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Eruptive evolution and 3D geological modeling of Camp dels Ninots maar-diatreme (Catalonia) through continuous intra-crater drill coring

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ABSTRACT

Camp dels Ninots is a mixed hard-soft maar-diatreme located in the Catalan Volcanic Zone (NE of Iberia), in which intra-maar lake sediments have preserved one of the most remarkable Pliocene fossil records in Europe. Geophysical surveys combined with the geological map and 11 boreholes, including two new continuous intra-crater drill cores, have enabled the construction of a 3D geological model of this maar-diatreme and its basement. The formation of this maar-diatreme started with a vent-opening phreatomagmatic explosion at the intersection between a regional fault and the Paleozoic groundwater level at a depth of 210 m. We infer and calculate the geometry, dip direction and dip angle of this regional fault. During the eruption, mixed Strombolian and phreatomagmatic episodes occurred, forming the tuff ring and filling the diatreme with minimum estimated volumes of 0.012 and 0.004 km³, respectively. The diatreme infill is composed of three main lithofacies that include tuff-breccias, welded scoriae, and mafic intrusions into the phreatomagmatic breccias. Thus, the stratigraphy of the diatreme succession suggests a progression of explosive events from deeper to shallower zones with short lateral migration of explosion vents, which control its final morphology, without evidence for significant deep enlargement of the diatreme during the later phases. This generated a wide funnel-shaped with low diatreme wall angles that differs from kimberlite pipes with great depths and sharp slope geometries. Hence, such 3D geological model helps to understand the complex architecture of maar-diatreme structures, highlighting the lack of geological modeling of this type of monogenetic system.

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1. Introduction

Maar-diatreme structures are common in monogenetic volcanic fields forming as a result of phreatomagmatic episodes caused by magma-water interactions (Lorenz, 1973). Several models exist on their formation and evolution (Lorenz, 1975, 1986; Geshi et al., 2011; Valentine et al., 2011; Valentine and White, 2012; Graettinger et al., 2014, 2015; Ross et al., 2017). Maar eruptions are mostly investigated through the study of the deposits forming their tuff or tephra rings (e.g., Pedrazzi et al., 2014; Valentine et al., 2015). Moreover, intra-crater successions also provide valuable information to understand the formation of such particular volcanoes and their diatreme architectures, where most of the studies come from kimberlite pipe exploration (e.g., Sparks et al., 2006; Lorenz and Kurszlaukis, 2007; Brown et al.,

2009; Seghedi et al., 2009) and from old exhumed maars or eroded structures (e.g., Suoana maar in Miyakejima Volcano, Japan (Geshi et al., 2011); Hopi Buttes, USA (White, 1991; Vazquez and Ort, 2006; Lefebvre et al., 2013; Latutrie and Ross, 2019, 2020), Missouri River Breaks volcanic field, USA (Delpit et al., 2014); Coombs Hills, Antarctica (McClintock and White, 2006; Ross and White, 2006), etc.). Numeric and analogue modeling of maar formation has contributed to the understanding of these processes and their diatreme architectures (Valentine et al., 2011; Ross et al., 2013; Graettinger et al., 2014; Le Corvec et al., 2018). However, only scarce research drilling has been carried out in maar intra-diatreme facies, commonly performed to calibrate geophysical prospecting (e.g., Pirrung et al., 2003; Schulz et al., 2005; Martín-Serrano et al., 2009; Bolós et al., 2012; Elliott et al., 2015; Jones et al., 2017), hence, the deepest regions of diatremes are still not well-understood. Despite the similarities in the eruptive processes involved in the formation of such these volcanoes, not all the resulting structures have similar shapes and dimensions. Measured diatreme dimensions

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range from deep narrow structures found in kimberlite pipes (e.g., Pittari et al., 2008) to shallower and wider funnel-shaped structures found in basaltic to andesitic maar volcanoes, such as the completely exposed Suoana maar-diatreme in Japan (Geshi et al., 2011). The diatreme morphology is influenced by differences in magma composition (e.g., volatile content), in the way magma/water interaction is produced, the mechanical characteristics of the substrate on which these volcanoes form (Bolós et al., 2014; Németh and Kósik, 2020), and by the lateral migration of explosion locations during eruptions (Ort and Carrasco-Núñez, 2009; Jordan et al., 2013; Blaikie et al., 2014; Saucedo et al., 2017; Graettinger and Bearden, 2021).

The Camp dels Ninots maar-diatreme (CNMD) is an example of an eroded tuff ring from which the external structure has been completely dismantled (Vehí et al., 1999). Its recognition as a maar structure is constrained by geophysical evidence (Oms et al., 2015) and the study of the intra-crater deposits, which were drilled by nine boreholes (total depths between 15 and 80 m) made for research and hydrological purposes (Jiménez-Moreno et al., 2013; Rodríguez-Salgado et al., 2021). In particular, its lacustrine sedimentary infill contains one of the richest fossil records of Pliocene fauna in Europe (3.06 Ma) (Campeny and Gómez de Soler, 2010; Gómez de Soler et al., 2012; Claude et al., 2014; Campeny et al., 2015; Přikryl et al., 2016). Two more recent boreholes

(CP1 and CP2) (Fig. 1d) were drilled inside the maar crater to a depth of 113 and 145 m, respectively, aiming to obtain a volcanic record of the diatreme infill succession as well as constraining the necessary data to generate a 3D geological model. Continuous core recovery (recovery wireline ratio > 95%) was carried out for both boreholes, thus providing the required information to study the evolution of the CNMD and its internal architecture.

This study is one of the few cases in which a non-kimberlitic maar-diatreme structure is drilled to sufficient depth to study its structure and evolution. These observations provide the necessary evidence to state the main differences between the well-known diatreme structures of kimberlite pipes and other maar types such as the CNMD. We have integrated the existing borehole records with surface geology and geophysical data in a 3D geological model, which helps to define the geometry and orientation of the main fault that controlled the magma's rise to the surface, the morphology of the diatreme, its internal facies, and the layout and thicknesses of the country rock basement.

2. Geological setting

The CNMD Pliocene lacustrine infill has been dated from 3.3 to 3.1 Ma (Jiménez-Moreno et al., 2013; Carrancho et al., 2012), and

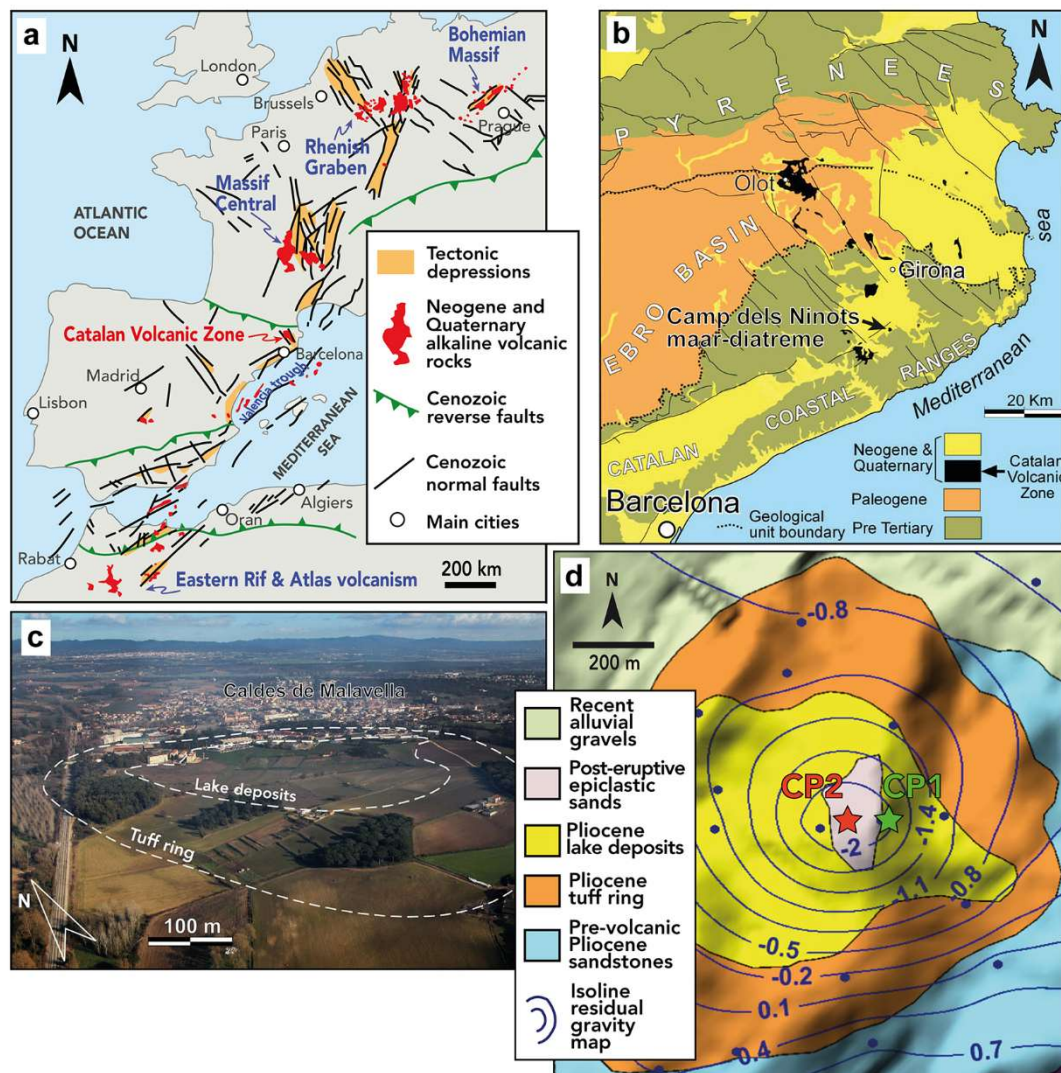


Fig. 1. Geological setting of the CNMD. a) Location of the Catalan Volcanic Zone in the European Rift System (modified from Martí and Bolós, 2019); Geological map of eastern Catalonia and location of the CNMD (modified from Oms et al., 2015); c) Aerial view of the CNMD studied area showing the main surface geological contacts (dashed lines); d) CNMD geological map displaying the location of CP1 and CP2 boreholes and the residual gravity isolines (modified from Oms et al., 2015).

therefore the eruption is slightly older. It is located in the town Caldes de Malavella (Girona province, Catalonia) and forms part of the Catalan Volcanic Zone (CVZ), one of the volcanic provinces of the European Cenozoic Rift System (Martí et al., 1992; Martí and Bolós, 2019) (Fig. 1a). The tectonic evolution of this volcanic region was controlled by the Neogene extensional fault system, which was responsible for the formation of several fault-bounded basins (Bolós et al., 2015) (Fig. 1b). The CNMD belongs to La Selva Basin, a tectonic depression bounded by ENE–WSW and NW–SE fault systems that also contain a younger maar, La Crosa de Sant Dalmaí volcano (Bolós et al., 2012; Pedrazzi et al., 2014). The CNMD was built astride two different substrates (i.e., mixed setting), Paleozoic granites and pre-volcanic unconsolidated Pliocene sediments corresponding to the as much as 200 m thick succession that infills La Selva Basin (Fig. 1d), and which contains the main Pliocene groundwater aquifer in the area. The tuff ring of the CNMD has been mostly eroded, and the remaining volcanic products that infill the diatreme are now covered by the post-eruptive lacustrine sedimentary infill of the crater (Vehí et al., 1999) (Fig. 1c).

3. Methodology

The 2015 coring campaign was planned in order to log the lacustrine deposits and the inner diatreme of the CNMD. The CP1 borehole reached a total depth of 113 m and was located near the inferred center of the diatreme, as determined by the minimum gravity anomaly and electrical resistivity data (Oms et al., 2015) (Fig. 1c). This drill core shows the complete post-maar lacustrine sequence, and part of the eastern wall of the diatreme, penetrating more than 10 m into the basement granites (Fig. 2). The CP2 borehole was drilled 80 m to the west of the CP1 borehole and achieved a maximum depth of 145 m (Fig. 2). CP2 intercepted the inner diatreme, providing the deepest record of the intra-crater volcanic succession made for this volcano. Cores were described, photographed, and sampled for petrographical studies and were later stored at room temperature at the Geology Department at the Universitat Autònoma de Barcelona (ref. boxes CP1 and CP2, store C2/207). Core samples were cut and processed into thin sections for petrographic analyses at the petrography laboratory of the Institute of Geophysics, Unidad Morelia at the Universidad Nacional Autónoma de México (UNAM).

Additional data including a detailed geological map, nine boreholes (15–80 m) drilled for paleoclimate research and hydrological purposes (Jiménez-Moreno et al., 2013; Rodríguez-Salgado et al., 2021), and geophysical data (Electrical Resistivity Tomography (ERT) profiles and gravity data) (Oms et al., 2015), were combined to perform a 3D geological model of the inner diatreme structure by Schlumberger's Petrel E&P software. The workflow started with the digitization and interpretation of the main geological boundaries from 1D and 2D input data. These boundaries include the maar crater and the surrounding host rocks (Pliocene pre-volcanic sandstones and Paleozoic granitic basement) and, within the maar crater, the surfaces representing the base of the lacustrine infill/top of the diatreme, and the base of the drilled section of the diatreme (Table 1). The uppermost limits of the diatreme were also established. In addition, two-dimensional (2D) ERT profiles (Oms et al., 2015) were used to define the deepest parts of the crater, the upper diatreme, the major normal fault on which the maar stands, and the basement unconformity. Using the interpreted data as an input, the model surfaces were reconstructed using a convergent interpolation algorithm with a regular grid size of 5 × 5 m, this being the resolution of the model.

4. Results

4.1. Volcanic-facies descriptions

The description of the CP1 and CP2 drill cores permits the identification of three groups of lithofacies. The first lithofacies (L1) consists of a

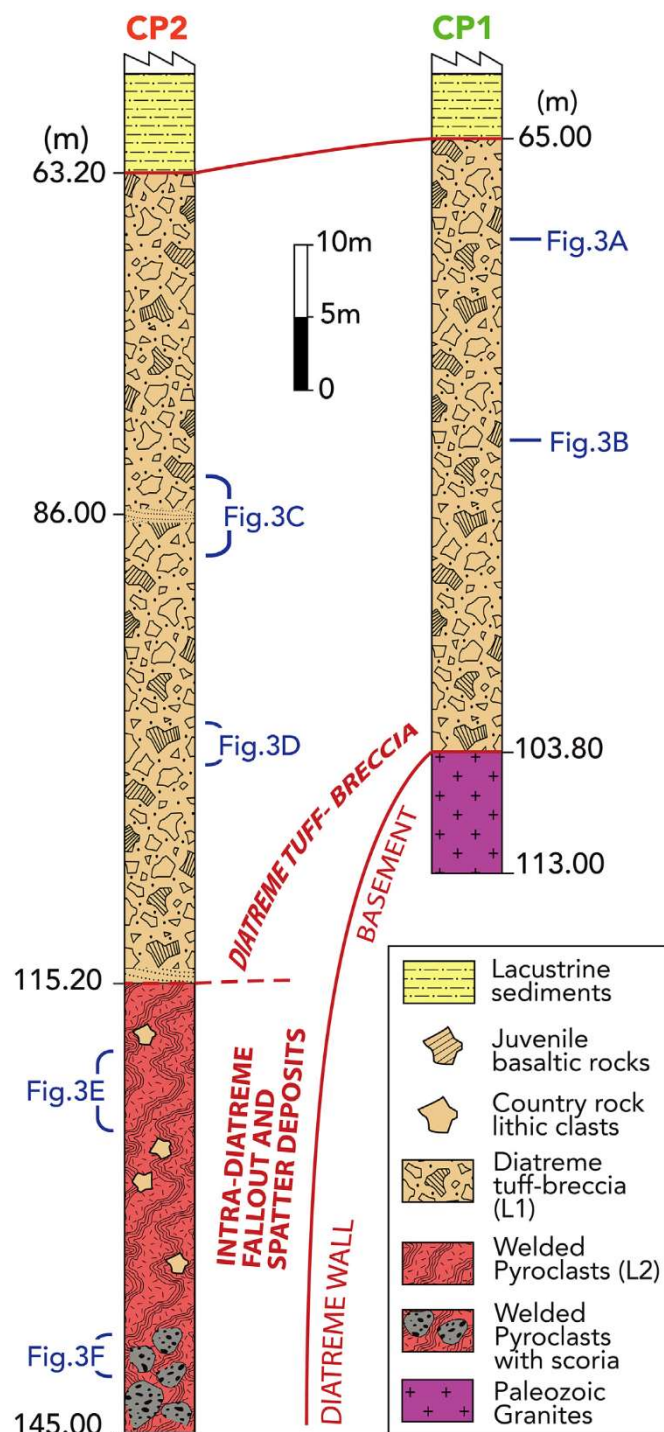


Fig. 2. Stratigraphic correlation of the CP1 and CP2 drill cores. The location of these drill cores is shown in Fig. 1d.

tuff-breccia intra-diatreme deposit (Fig. 3a, b, c), which is the most predominant in the drill cores. In CP1 it forms 91.1% of volcanic succession and 9.9% corresponds to Paleozoic granitic basement (Fig. 2), while in CP2 volcanic successions are identified from 63.2 to 115.2 m (i.e., 52 m in total), accounting for 63.5% of the core (Fig. 2). The rest of CP2 (0 to 63.2 m) corresponds to lacustrine sediments. The total estimated volume of the L1 from the 3D model reconstruction is 0.004 km³ (Table 2). The breccia deposit is matrix-supported. This matrix is fine-grained and largely composed of juvenile ash and Pliocene soft sedimentary basement (wackes) particles. Larger clasts are composed of both lapilli size

Table 1

Summary information of the eleven boreholes. Coordinates, ground levels, total depths, and the lithology contacts measured from the drilling floor in meters.

BOREHOLES	X (WGS-84 UTM)	Y (WGS-84 UTM)	Ground level (m.a.s.l)	Total depth	Quaternary	Lacustrine crater fill	Tuff ring	Diatreme	Pre-volcanic Pliocene	Paleozoic granites
CA	483,273	4,631,412	101.9	31.2	–	0	9.7	–	15.93	–
CC	483,386	4,631,766	103.1	75.6	–	0	–	48.4	–	–
CP1	483,491	4,631,660	112.2	113	–	0	–	66	–	104
CP2	483,414	4,631,645	110.2	145	–	0	–	63	–	–
P1	482,960	4,631,494	82.7	14	–	–	0	–	–	–
P2	483,453	4,631,845	104	27	–	0	–	–	–	–
P3	483,389	4,631,542	103	55	–	0	–	–	–	–
P4	483,180	4,631,822	96.4	101	–	0	–	–	30	–
S1	483,117	4,631,515	99.9	30	–	–	0	–	29	–
S2	483,554	4,632,286	89.3	16	0	–	–	–	13	–
S3	483,450	4,631,828	104.5	29.05	–	0	–	–	–	–

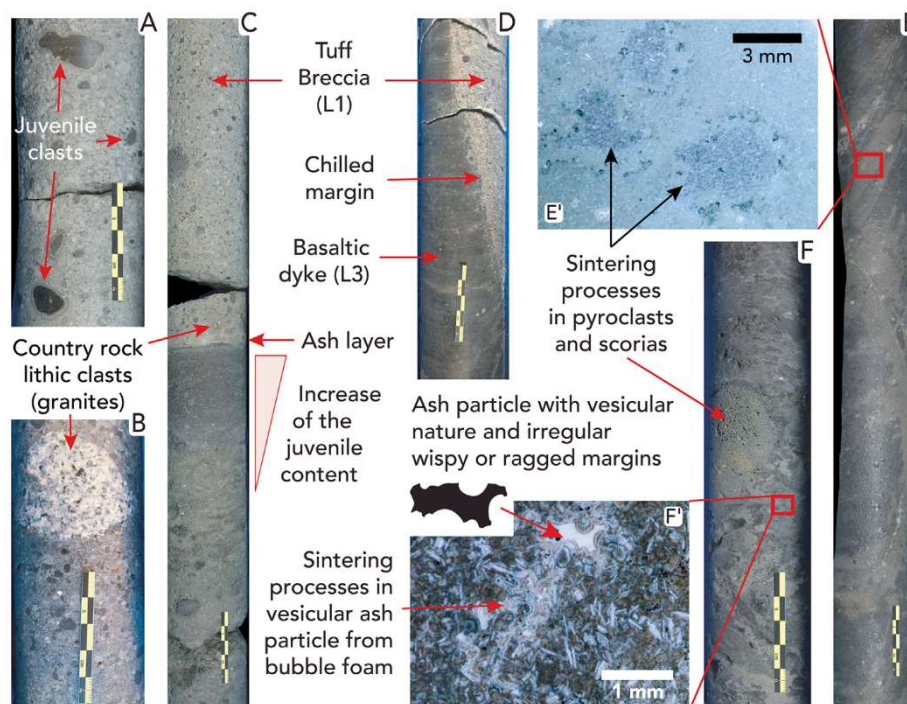


Fig. 3. Detailed pictures of the CP1 and CP2 drill cores showing the three lithofacies identified. The location of the drill core pictures is shown in Fig. 2. a, b and c) L1 Lithofacies (tuff-breccias) filling the main part of the diatreme; d) L3 Lithofacies (mafic intrusions into the tuff-breccias); e) L2 Lithofacies showing welded pyroclasts; e') Thin section under optical microscope of the L2 welded pyroclasts; f) Welded pyroclasts with scoriae of the L2 Lithofacies; f') Thin section under optical microscope of the welded pyroclasts with scoriae. The scale ruler has 5 cm.

Table 2

Attribute summary of the 3D geological model.

	max. diameter (m)		max. height (m)	number of cells (cell size = 25 m ³)	volume (km ³)
	base	top			
Lacustrine sediments	300	600	72	211,523	0.0053
Diatreme	5	500	138	161,508	0.0040
Tuff ring	500	1000	31	460,679	0.0115
Pre-volcanic Pliocene	n/a	n/a	85	1,175,821	0.0294
Paleozoic granites	n/a	n/a	223	1,254,300	0.0314

juvenile basaltic-scoria fragments and lithic clasts derived from country rock (60 and 40% vol., respectively). Such lithic clasts are granite blocks of up to 80 cm across (maximum thickness of the lithic clast penetrated with the drill core) (Fig. 3b) as well as soft blocks and small particles of sand from the Pliocene wackes. Juvenile scoria generally presents secondary alteration rims due to hydrothermal alteration (Fig. 3a). Locally,

at depths of 86 m and 115 m in CP2, this breccia facies shows intercalations of ash layers that do not present a lateral correlation with CP1.

The second lithofacies (L2) corresponds to a welded scoria, which varies from a scoriaceous agglomerate to a strongly welded spatter (Fig. 3e and f). L2 was identified from 115.2 m to 145 m (core bottom) in the CP2 borehole. It is not possible to estimate the volume of this

deposit because we only detected this lithofacies in CP2, thus there is a lack of geometric data at depth and laterally. In the L2, among the scoria clasts, there is some interstitial ash. In general, scoria pyroclasts tend to be more common and larger toward the deepest part of CP2. This lithofacies also presents some small lithic clasts (< 1 cm). The degree of welding changes among the scoria fragments and the interstitial ash (Fig. 3e, e', f and f'). Under thin section (Fig. 3e', f'), ash particles with blocky morphology show wispy or ragged margins (Fig. 3f'). Moreover, the analysis of the thin sections shows sintering processes in scoriae and vesicular ash particles from bubble foam.

The third lithofacies (L3) found in borehole CP2 is intersected at a depth of 100 m. It corresponds to massive, fine grained basalt that intrudes the intra-diatreme breccia deposit, showing chilled margins at its contact (Figs. 2 and 3).

4.2. 3D geological modeling

The 3D geological model integrates the available geological (surface mapping and 11 boreholes) and geophysical data (gravity and ERT), which provides new information on nine key features:

- 1) The structure of the pre-volcanic basement (i.e., Paleozoic granites and Pliocene sands) offset by a main normal fault (Fig. 4).
- 2) The dip angle (75°), dip direction (322°), and geometry (Figs. 4 and 5) of this regional fault, which has been determined from the geological surface and boreholes data (Fig. 4).
- 3) The resulting morphology of the diatreme, its internal structure, and the relation with the basement (Fig. 5).
- 4) The dip angle frequencies of the diatreme, which are controlled by the soft (Pliocene sands) and hard (Paleozoic granites) sides of the substrate, where the hanging wall shows a dominant dip angle of 30° and the footwall has a mild bimodal distribution with two dominant dip angle frequencies of 30° and 50° , respectively. This mild bimodal distribution coincides with the lithological contrast between the hard-granites composing the basement in the deepest part and the overlying poorly-consolidated Pliocene sands and gravels (Fig. 6). This inner morphological data was obtained introducing the borehole information of the diatreme wall-boundaries with their depths to the 3D model, combined with the gravity and ERT data of Oms et al. (2015).
- 5) The minimum diatreme volume (including juvenile and country rock lithics), which is 0.0040 km^3 (Table 2), and excludes the root zone due to the lack of data.
- 6) The minimum volume of the eroded tuff ring, which is 0.0115 km^3 (Table 2).
- 7) The minimum volume of the partially eroded lacustrine sedimentary infill (0.0053 km^3), which is greater than the diatreme volume (Table 2).
- 8) The morphology and depth (72 m) of the explosion crater (i.e., top of the diatreme) that allowed it to be completely filled by lacustrine sediments (Fig. 4b and 6a).
- 9) The intersection between the main fault and the hypothetical root zone where the first phreatomagmatic explosion into the Paleozoic granitic basement took place, which is speculated to be at a depth of 210 m meters below the current surface (Fig. 5).

5. Discussion

The continuous intra-crater succession recognized inside the CNMD provides the clues to reconstruct the eruption that generated this maar structure (Fig. 7). The onset of the eruptions (i.e., the opening crater phase) was marked by an intense phreatomagmatic phase resulting from the fuel coolant-interaction of basaltic magma with water contained in the highly fractured and faulted Paleozoic granitic rocks of the basement (Fig. 7a – Stage 1). The deposits generated by this initial explosion (i.e., root zone) are not observed in the boreholes

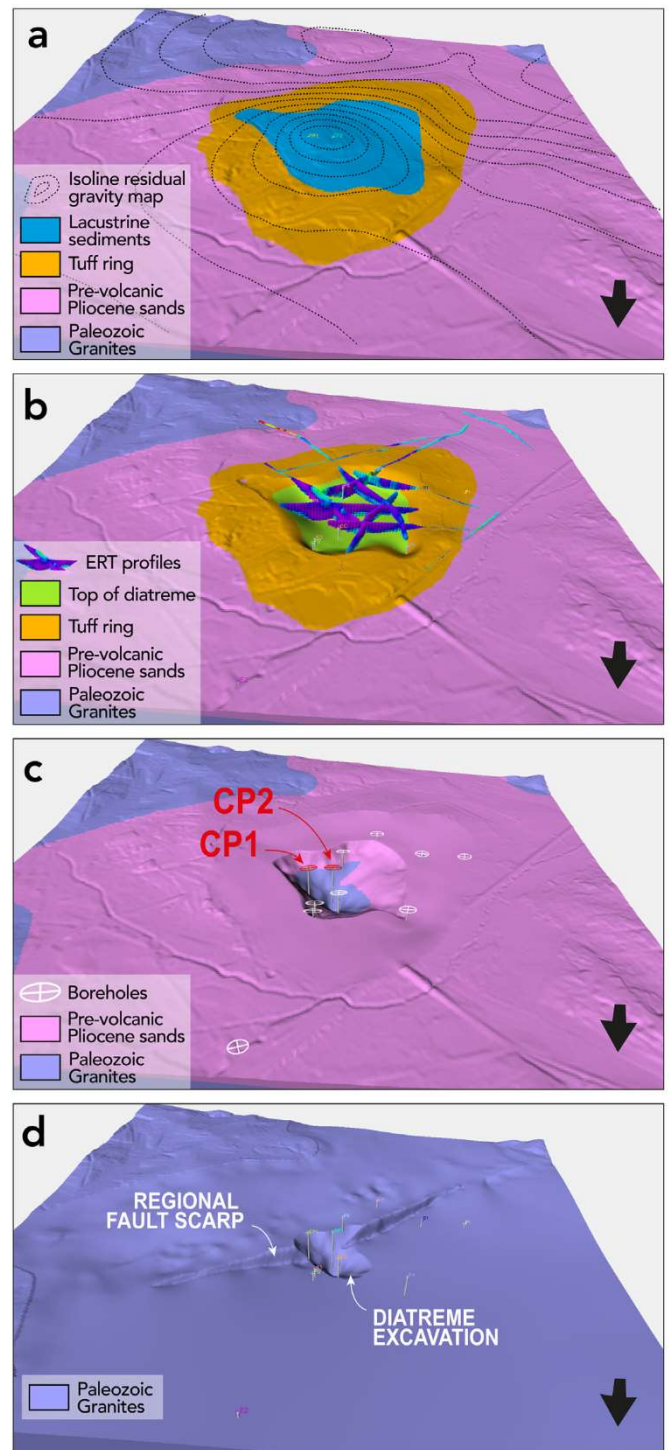


Fig. 4. 3D geological model of the CNMD area (view to the south). a) All units display residual gravity isolines from Oms et al. (2015); b) Display of the paleomorphology of the crater, the volcanic deposits (i.e., top of the diatreme and tuff ring), and the ERT profiles (Oms et al., 2015) without the lacustrine sedimentary infill; c) Displaying the basement units (pre-volcanic unconsolidated Pliocene sediments and Paleozoic granites), the diatreme excavation, and the eleven boreholes; d) Paleozoic granites of the substrate, showing the fault scarp and the diatreme excavation.

and it remains a challenge for future investigations. However, phreatomagmatic deposits are exposed at the base of the remnant tuff ring sequence (Oms et al., 2015), containing splinter-shaped ash particles and lithic fragments from the country rocks. Therefore, we infer that the deepest part of the newly formed crater was partially filled with a

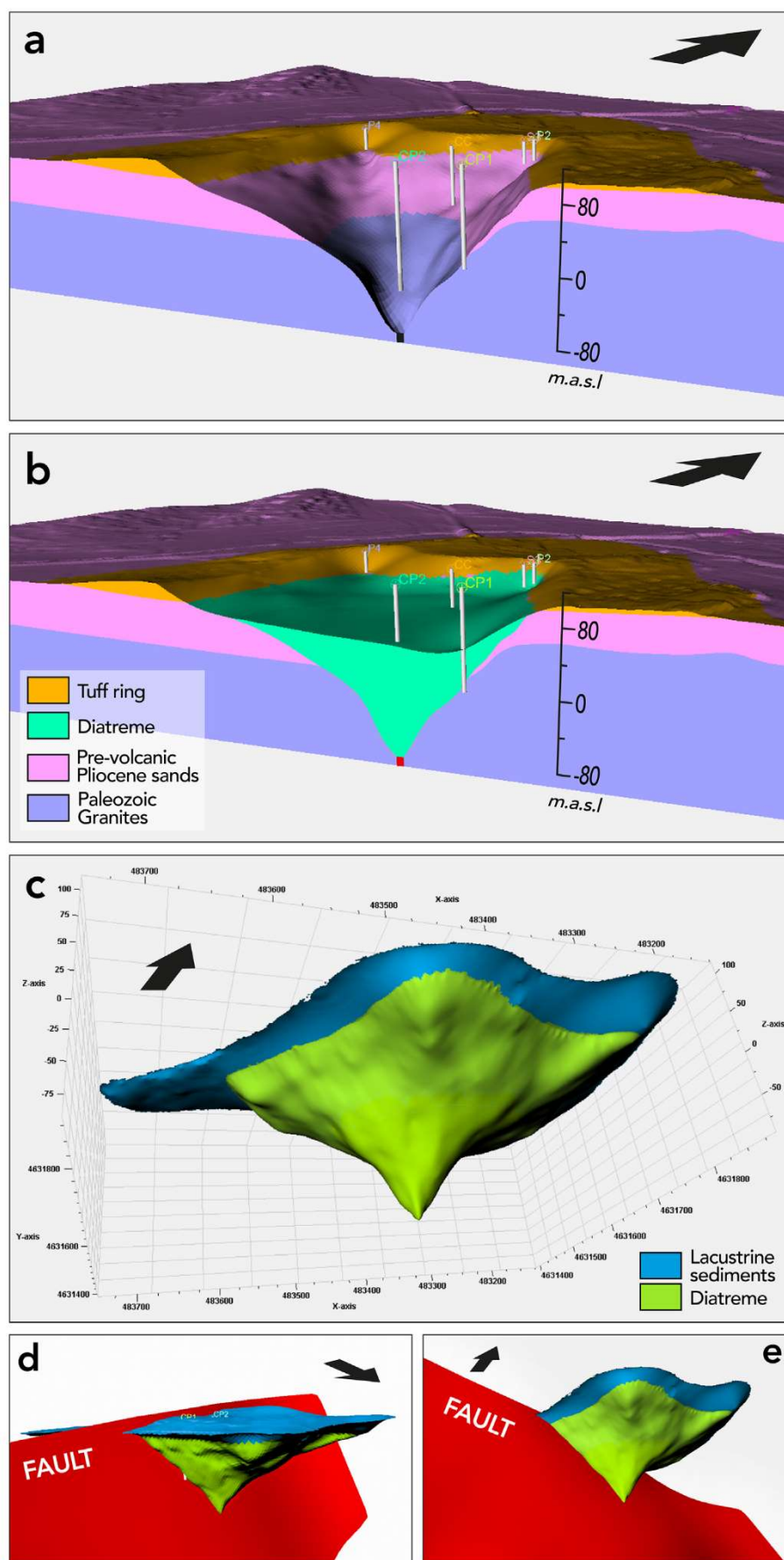


Fig. 5. a) 3D cross-section cutting into the CP1 and CP2 direction and displaying the diatreme excavation morphology and its depth. White lines show the location of boreholes; b) Diatreme infill with the same view as (a); c) 3D geological model of the diatreme and the lacustrine post-volcanic sediments; d) and e) 3D geological model of the CNMD, displaying the main fault.

lithic-rich coarse-grained explosion breccia (L1) similar to the one observed at the base of the remains of the tuff ring. This first excavation phase is deduced to have dug a 210 m deep crater with a symmetrical shape and steep angles (55°), entirely hosted into the Paleozoic hard-granites of the deepest part, and at low angles (30°) to the soft Pliocene basement at upper levels showing an irregular morphology (Fig. 6c). It formed a diatreme along the regional normal fault, dividing the soft and hard substrate, and through which the basaltic magma rose. This rheological contrast (soft gravels and hard granites) controlled the asymmetrical-shape blasting of the diatreme between the hanging wall and the footwall of the fault (Fig. 6). “The Paleozoic hard granites that constitute the footwall and bottom of the diatreme have greater lithological competence than the poorly consolidated Pliocene sand and gravels conforming the hangingwall. Therefore, contrast on the angles of the maar crater is observed, being lower in the hangingwall (poorly consolidated granitic sediments) than in the footwall (unaltered granite) (Fig. 6c). Although the precise relationship between the regional fault and the feeder dyke cannot be addressed in detail due to the lack of deeper data, we infer that occurs at 210 m depth into the Paleozoic hard-granites, taking into account the dip angle of the fault, the angles of the diatreme walls detected by the boreholes data, and the fact that most of the lithic clasts of L1 are fresh and angular granites.

Once the groundwater hosted in the granitic aquifer was locally depleted with absence of available water pathways into the diatreme, the eruption continued with a magmatic Strombolian phase, which was responsible for the deposition of the L2 intra-diatreme welded scoria (i.e., spatter facies) (Fig. 7b – Stage 2). These L2 pyroclasts and the derived lithic clasts generated by the intra-diatreme explosion, drove the ejected fragmentation vertically and accumulated nearly in situ under atmospheric pressure conditions (Fig. 7b') (Seghedi et al., 2009; Re et al., 2016). Subsequently, new phreatomagmatic explosions were fueled by the interaction of the ascending magma with new water supplies from the Pliocene groundwater aquifer, generating new intra-diatreme explosions and recycling its breccia infill. The lack of correlation between the ash layers and bedded breccias of the upper part of both drill cores (CP1 and CP2) (Fig. 2) and the fact that the welded scoria deposits (L2) are not disturbed, suggests that these new explosions occurred in different sectors and at shallower levels of the diatreme (Fig. 7c). This is reinforced by the final morphology of the crater (i.e., top of the diatreme) that shows an irregular shape with three major-excavation axes (i.e., three footprints) of decametric scale at the northwestern, northern, and east-southeastern parts of the crater (Fig. 6b). These last, suggest these shallow intra-diatreme explosions with short lateral vent migrations (e.g., Graettinger and Bearden, 2021). Moreover, the presence of a basaltic dyke (L3) crossing the intra-diatreme succession, suggests the occurrence of intrusion sites at different positions, indicating the continuous magma ascent after the major excavation phase (Stage 1). On the other hand, the presence of at least two ash deposits interbedded with breccias in the upper part (Figs. 2 and 3c) indicates that these new explosive phases were pulsating, rather than continuous. Finally, post-eruptive processes occur immediately after the volcanic activity thereby remobilizing the pyroclastic material and forming lacustrine sediments.

According to the proposed eruptive dynamics for the CNMD where explosions took place at a near-surface intra-diatreme level with short lateral vent migrations during the eruption, we ratify the revised model of Valentine and White (2012). They considered that intra-diatreme dykes follow irregular paths, ascending through a heterogeneous and unconsolidated breccia fill, such as our L1 and L3 lithofacies. Thus, it can promote the magma-water interaction with wet diatreme parts under the water table, producing new phreatomagmatic eruptions without the progressive excavation of the country rock basement at depth, such as explained in the classical model by Lorenz (1986). Hence, our results support the Valentine and White (2012) model, providing a case study for complex interactions between the evolving diatreme with different rheological host properties (i.e., soft and hard

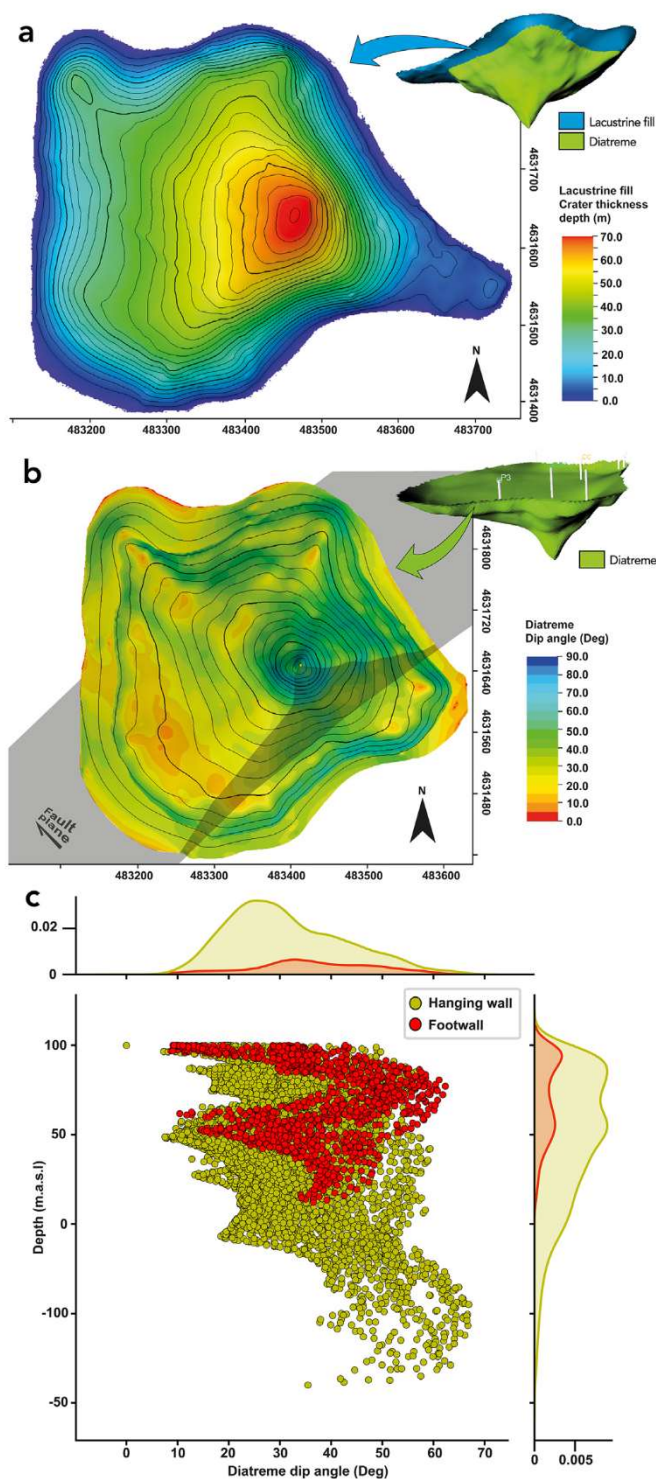


Fig. 6. a) Crater thickness depth filled by the post-volcanic lacustrine sediments; b) Dip angles of the diatreme wall; c) Scatter plot of the dip angle (x-axis) vs. depth (y-axis), showing the difference between the hanging wall (yellow) and footwall (red) angles. The histograms show the Kernel Density Estimate. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

substrate), giving as a result, a complex and shallow diatreme morphology with a small volume (0.004 km^3).

The 3D model for the CNMD presents a wide funnel shape with a low angle diatreme wall (30°–50°) showing a shallow total depth (210 m) with a low-diatreme volume compared with kimberlite pipes

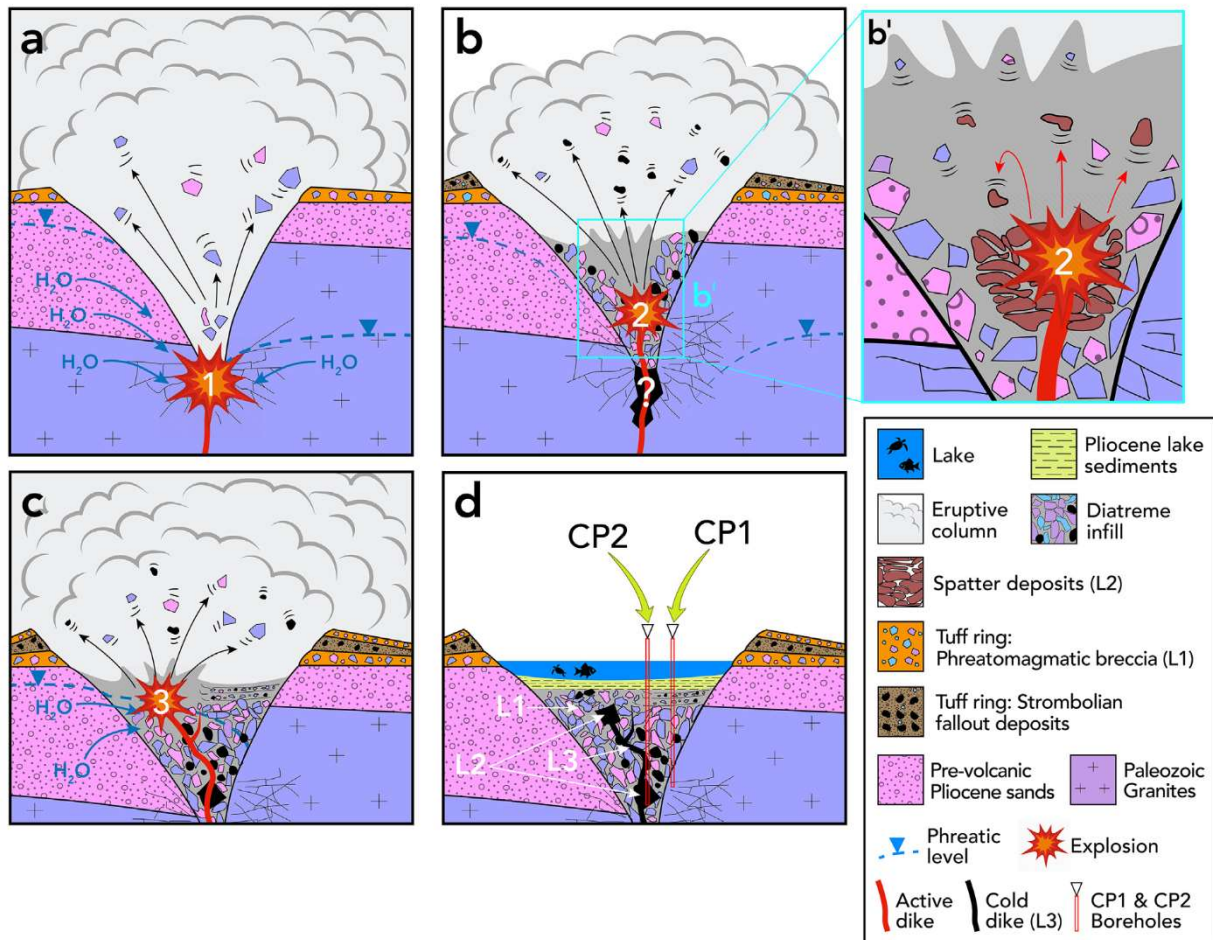


Fig. 7. Three main eruptive stages in the evolution of the CNMD: (a) Stage 1: initial vent-opening explosive phreatomagmatic event, excavating the basement Paleozoic granites; (b) Stage 2: intra-diatreme Strombolian explosions with fallout magmatic activity; (b') detailed view of Stage 2 showing the spatter deposits of the L2 lithofacies; (c) Stage 3: intra-diatreme phreatomagmatic activity at shallower depths, which recycle the breccia deposits; (d) post-volcanic lacustrine sedimentation showing the location of the CP1 and CP2 boreholes.

(e.g., Pittari et al., 2008; Kurszlaukis and Lorenz, 2017). These differences seem to be related to changes in magma composition (e.g., gas content), and the mechanical properties of the substrate on which these volcanoes form (Kurszlaukis and Lorenz, 2017; Németh and Kósik, 2020). The CNMD shows similar features compared with non-kimberlitic maar-diatremes worldwide due to intra-diatreme eruptions at shallower depths with lateral migration of explosion locations (e.g. Blaikie et al., 2014; Graettinger and Bearden, 2021). This makes the CNMD a relevant example to be compared with other similar maar-structures with less information of their inner diatreme.

Most of the knowledge on the inner diatreme structure is based on the rare case of kimberlite pipes (e.g., Sparks et al., 2006) because of their economic value. However, during the last decades, the study of exhumed or eroded maar-diatremes (e.g., White, 1991; Ross and White, 2006; Geshi et al., 2011; Latutrie and Ross, 2019, 2020), the use of geophysical prospecting methods (e.g., Bolós et al., 2012; Blaikie et al., 2012, 2014), and research drillings (e.g., Pirrung et al., 2003; Elliott et al., 2015) have evidenced complex eruptive dynamics and diatreme structures with a wide range of morphologies compared to kimberlite pipes. The CNMD is the first 3D geological model of a non-kimberlitic maar-diatreme type that combines observations from multiple geophysical methods, surface geology and borehole data. This represents a step forward to improve the understanding of this type of volcanoes, allowing the visualization and calculation of all the parameters needed for their characterization. Furthermore, this study evidences the lack of geological modeling of monogenetic systems and the need to use and develop new 3D geological models in well-constrained maar volcanoes, which

are the second most common volcano type on Earth (Vespermann and Schmincke, 2000; Schmincke, 2004; Lorenz and Kurszlaukis, 2007; White and Ross, 2011).

6. Conclusions

The compilation of all the available geophysical data combined with surface geology and 11 boreholes including two new drill cores (113 and 145 m depths), extracted near the inferred center of the diatreme of CNMD, allows us to construct a robust 3D geological model of the inner diatreme fill and the eruptive evolution of this partially eroded volcano. The final 3D morphology of the diatreme confirms a geometry that results from the mechanical behavior during the eruption of a mixed soft and hard substrate, affected by a regional normal fault with a dip angle of 75° and a dip direction of 322°. This diatreme morphology differs from kimberlite pipes. Instead of the kilometeric depths and high slope geometries of the classical model represented by kimberlite pipes, the studied diatreme is inferred at 210 m depth with a wide funnel and low diatreme wall angles (30° to 50°). A minimum volume of 0.0040 km³ calculated for the diatreme (including juvenile and country rock lithics), which represent less volume compared to the post-eruptive lacustrine sedimentary fill of the crater (0.0053 km³). Hence, this allows us to reconstruct the paleo-surface of the crater. This crater morphology, together with the description of three types of lithofacies, including tuff-breccia (L1), welded scoria (L2) and mafic intrusions (L3) at depth, and the lack of correlation between the ash layers and bedded breccias of the upper part of the drill cores, suggests a progression of explosive events

from deeper to shallower levels into the diatreme, supporting the [Valentine and White \(2012\)](#) model for maar-diatreme eruptions. Moreover, magma supply seems to have been continuous throughout the eruption, while groundwater was interrupted several times during the whole process, thus giving rise to alternating Strombolian and phreatomagmatic phases.

The eruptive evolution proposed and the comprehensive view of the diatreme architecture of CNMD highlight the importance of the three-dimensional geological modeling in this type of volcanoes that their structure remains buried into the subsoil. Thus, this case study represents a relevant example that differs from the simplified deep cones that dominated past conceptual models.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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