Petrology of the opening eruptive phase of the 2021 Cumbre Vieja eruption, La Palma, Canary Islands

Matthew J. Pankhurst (✉ mpankhurst@iter.es)

Instituto Tecnológico y de Energías Renovables

Jane H. Scarrow

Department of Mineralogy and Petrology, University of Granada <https://orcid.org/0000-0001-8585-8679>

Olivia A. Barbee

Department of Geological and Mining Engineering and Sciences, Michigan Technological University

James Hickey

University of Exeter <https://orcid.org/0000-0002-5391-3415>

Beverley C. Coldwell

Instituto Tecnológico y de Energías Renovables

Gavyn Rollinson

Camborne School of Mines, University of Exeter

Jose A. Rodriguez-Losada

Department of Animal Biology, Edaphology and Geology

Alba Martín-Lorenzo

Instituto Tecnológico y de Energías Renovables

Fátima Rodríguez

Instituto Volcanológico de Canarias

William Hernández

Instituto Volcanológico de Canarias

Pedro A. Hernández

Instituto Tecnológico y de Energías Renovables

Nemesio M. Pérez

Instituto Tecnológico y de Energías Renovables (ITER)

Brief Communication

Keywords: petrology, Cumbre Vieja, volcanic processes

Posted Date: October 13th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-963593/v1>

Abstract

The first products of the current Cumbre Vieja eruption comprise simultaneous tephra fall from near-continuous, gas-rich eruption plumes and lava flows. From combined field, petrographic and geochemical analyses we identify: low percentage mantle melts with a variably-equilibrated multimineralic crystal-cargo and compositional fractionation by eruptive processes. Hence petrology can untangle complex magmatic and volcanic processes for this eruption, which through further study can assist in active decision making.

Main

On 19th September 2021, Cumbre Vieja volcano (La Palma, Canary Islands, Fig. 1a) erupted after 50 years of quiescence (day 0). How and why magmatic systems reactivate is still a critical question for monitoring and hazard mitigation efforts during first response and ongoing volcanic crisis management. To consider this, here we present petrographic, XRD, QEMSCAN®, EPMA, and whole-rock major and trace element geochemistry results for the first 2021 La Palma volcanic eruption effusive and explosive products (see supplementary materials).

Understanding the lithologically varied Canarian archipelago origins and evolution (Fig. 1a), has long attracted international research efforts^{1,2}. La Palma has experienced several magmatic episodes: Basal Complex (~4.0-3.0 Ma); Garafia, Taburiente, Cumbre Nueva and Bejenado volcanoes (~1.7–490 ka); and Cumbre Vieja (~125 ka-present), and is the most active system in historical times: ~1480; 1585; 1646, 1677, 1712, 1949, 1971 and 2021^{3,4,5} indicating a ~230-20 year return period.

The current eruption began with explosive activity at a new vent that produced lava and near-continuous ash plumes driven by vigorous gas jets, and fire fountains from a fissure. Samples presented here were collected during the first week of activity from initial lava flow (CAN_LLQ_0001, 2, 3, 4) and tephra fall (chronologically, increasing in distance from the vent: CAN_TLP_0008, 9, 11) (Fig. 1b-f).

Petrology provides insight into volcanic plumbing systems as they assemble before, and evolve throughout, eruption^{6,7}. Current initial eruption products contain coarse minerals identifiable by hand-lens and provide a rapid real-time guide to system evolution. A multimineralic cargo is observed (Fig. 1g), which raises the potential to extract detailed system information and serves as a baseline to track possible trends that may be used to help forecast eruptive behaviour and evolving hazards.

X-ray diffraction analysis confirmed major mineral phases are clinopyroxene, plagioclase, and amphibole. Feldspathoids are notably absent.

Thin sections show the lava is hypocristalline and porphyritic with ~15% vesicularity (Fig. 1g). Clinopyroxene is the most common coarse mineral (~15-20% vol.) and is present as euhedral-subhedral solitary crystals (1-3 mm diameter) or in mono- and polymineralic (Cpx, Ox ± Ol ± Amp) clusters (up to 7 mm), including possible xenoliths with 120° grain boundaries (Fig. 1gi). Cpx commonly displays

concentric and sector zoning, with some embayments and abundant Fe-Ti oxides and apatite inclusions; sieve-textures are rare. Amphibole crystals (~4% vol.) are anhedral-subhedral, 0.5-2.5 mm, and have distinct reaction rims (Fig. 1d). Olivine (~1% vol.) usually forms euhedral-anhedral isolated crystals (0.5-1.5 mm). Fe-Ti oxides (~1% vol.) are subhedral-anhedral and 0.5-1 mm. Groundmass minerals include abundant plagioclase, oxides, clinopyroxene, and olivine. Tephra is mineralogically comparable to the lava but with a fragmented, hypocrySTALLINE texture (Fig. 1g).

QEMSCAN® analysis of 27 mm² of CAN_LLIP_0001 representing ~8 M points measured in <17 hr with a 5 µm pixel size highlights three dominant groups accounting for 90.07% modal mineralogy (Fig. 2a): Ca-Fe-Al silicates (49.54%) and Ca-Mg-Fe silicates (20.94%), interpreted to be groundmass+amphibole and clinopyroxene, respectively, and plagioclase (19.59%). The next most abundant minerals are olivine (2.70%), Ti-Magnetite (2.12%), ilmenite (1.95%) and biotite (1.65%). Plagioclase is present as groundmass crystal laths, whereas olivine, Ti-magnetite and ilmenite are present as both equant and microlitic crystals. Groundmass with textures finer than excitation volume contributes to total Ca-Mg-Fe silicates, hence the elevated value with respect to petrographic analysis.

Whole-rock XRF and ICP-MS analyses show products have restricted, primitive, metaluminous, alkaline whole-rock compositions (Fig. 2b-e); lava (SiO₂ 44.27-44.59 wt%) is slightly more primitive than tephra (44.82-45.61 wt%). Normalised to NMORB, all rocks show positive anomalies, relative to adjacent elements, in Ba, Th, U, La, Ce and Eu (Fig. 2c). Relative to chondrite, LREE are enriched relative to HREE (La_N/Yb_N 23.9-26.5), Eu anomalies are absent. All rocks have ~15.5-16% normative nepheline. In both rock types Al₂O₃, Na₂O and K₂O, Zr plus large ion lithophile elements correlate positively with differentiation index SiO₂, whereas FeOT, MgO, CaO and TiO₂ plus Sc and V correlate negatively (Fig. 2d-e).

EPMA confirms clinopyroxene as titanaugite, and demonstrates no clear major element difference exists between cores, corroded crystals and monomineralic clusters. Rims, however, are generally richer in SiO₂ and MgO, and poorer in TiO₂, Al₂O₃, and Na₂O. Large olivine grains have uniform compositions, Fo₇₈₋₈₀, Cr-spinel is present as inclusions. Ti-magnetite (3-5 wt% TiO₂) is present both as discrete grains and in the groundmass with slightly higher Ti concentration. Amphibole is kaersutite; no core-rim zoning was detected. Groundmass plagioclase is An₅₈₋₆₇, two grains have higher Na, An₃₂₋₄₃.

Geochemically, eruptive products plot as basanite-tephrites (Fig. 2b), yet mineralogical observations lead to their classification as *alkali basalts*⁸, implying comparatively higher degree mantle melting⁹. Petrography and mineral chemistry illustrate a complex crystal cargo. In addition to euhedral clinopyroxene phenocrysts, rare variably resorbed clinopyroxene is observed. Anhedral olivine is recognised both as ripened-skeletal and also rounded-embayed forms. Amphibole has marked reaction rims and a variably oxidised appearance (Fig. 1gii). We suggest the current eruption is tapping melt-mush magma mingling zones.

Major and trace element trends together with petrographic observations indicate limited cpx (~85 %) and titanomagnetite (~15 %) fractionation, interpreted as winnowing^{1,10}, between lava and tephra with increasing distance from the vent (Fig. 1g and 2b-e).

Olivine abundance is being keenly tracked at the time of writing and appears to be rising, coincident with overall lava production, and flow aspect ratio lowering. End-member interpretations are: earliest eruption products represent older, reactivated magma that is being depleted as newer magma arrives at the vent and now solely drives the eruption. Alternatively, all volcanic products are derived from the same parental magma that traversed colder crust in stages for ~1 week, involving reactive flow¹³ gas charging, and crystallisation. Having now warmed the country rock, parental magma can ascend more efficiently. These models will be addressed by continued petrological eruption tracking.

Declarations

Acknowledgements

Antonio Alvarez, Jaime Martin, and Adrian Jones are thanked for field support and loan of equipment. Comunidad de Regantes Dos Pinos are thanked for hosting the petrology base. JHS thanks laboratory staff and colleagues at the UGR for helping expedite production of results.

Author contributions

M.J.P. initiated the study, contributed to writing the manuscript, collected samples.

J.H.S. contributed to writing the manuscript, prepared figures, collected samples.

O.B. contributed to writing the manuscript, prepared figures.

J.H. contributed to writing the manuscript.

B.C.C. initiated the study, contributed to writing the manuscript, collected samples.

G.R. contributed to writing the manuscript, prepared figures.

J.A.R.L. contributed to writing the manuscript.

A.M.L conducted fieldwork and processed samples.

F.G.R. conducted fieldwork and processed samples.

W.H. cartography.

P.H. conducted fieldwork and processed samples.

N.P. initiated the study.

Competing interests

The authors declare no competing interests.

References

1. Morgan, W. J. Hotspot tracks and the early rifting of the Atlantic. *Tectonophys.* **94**, 123–139 (1983).
2. Turner, S., Hoernle, K., Hauff, F., Johansen, T. S., Klügel, A., Kokfelt, T., Lundstrom, C. 238 U– 230 Th– 226 Ra disequilibria constraints on the magmatic evolution of the Cumbre Vieja Volcanics on La Palma, Canary Islands
3. *J. Pet.*, 56, 1999–2024 (2015).
4. Hernandez-Pacheco, A., & Valls, M. C. The historic eruptions of La Palma island (Canaries). *Arquipélago. Série Ciências da Natureza* **3**, 83–94 (1982).
5. Romero Ruiz, M. C. Las manifestaciones volcánicas históricas del Archipiélago Canario. PhD thesis, University of La Laguna, Tenerife, Canary Islands, Spain (1990).
6. Global Volcanism Program, Smithsonian Institution, <https://volcano.si.edu/>.
7. Kahl, M., Chakraborty, S., Pompilio, M., & Costa, F. Constraints on the nature and evolution of the magma plumbing system of Mt. Etna Volcano (1991–2008) from a combined thermodynamic and kinetic modelling of the compositional record of minerals. *J. Pet.* **56**, 2025–2068 (2015).
8. Pankhurst M. J., Morgan D. J., Thordarson T. and Loughlin S. C. Magmatic crystal records in time, space, and process, causatively linked with volcanic unrest. *Earth Planet. Sci. Lett.* **493**, 231–241 (2018).
9. Le Maitre, R. W. *Igneous Rocks a Classification and Glossary of Terms Recommendations of the International Union of Geological Sciences, Sub-Commission on the Systematics of Igneous Rocks*. Cambridge University Press, 236 p. (2002).
10. McKenzie D. & Bickle M. J. The volume and composition of melt generated by extension of the lithosphere. *J. Pet.* **29**, 625–679 (1988).
11. Cas, R., & Wright, J. *Volcanics Successions Modern and Ancient. A Geological Approach to Processes, Products and Succession*. Springer, Netherlands, 528 (1988).

12. Klügel, A., Galipp, K., Hoernle, K., Hauff F & Groom, S. Geochemical and volcanological evolution of La Palma, Canary Islands. *J. Pet.* **58**, 1227–1248 (2017).
13. Hofmann, A. W. Chemical differentiation of the Earth: the relationship between mantle, continental crust, and oceanic crust. *Earth Planet. Sci. Lett.* **90**, 297–314 (1988).
14. Jackson, M. D., Blundy, J. & Sparks R. S. J. Chemical differentiation, cold storage and remobilization of magma in the Earth's crust, *Nature* **564**, 405–409 (2018).

Methods

Lava samples were collected from active flow fronts either warm (CAN_LLIP_0001), or for all other samples, hot incandescent, and immediately water quenched; suitable sampling points were identified with a thermal camera. Tephra was collected from direct fall deposits. Each sample was viewed using a ZEISS Discovery V20 stereomicroscope for initial assessment.

All samples were powdered in an agate automatic mortar and pestle grinder.

Whole-rock major element determinations were performed by X-ray fluorescence, after fusion with lithium tetraborate. Typical precision was better than $\pm 1.5\%$ for an analyte concentration of 10 wt.%. Zirconium was determined by X-ray fluorescence on glass beads, with a precision better than $\pm 4\%$ for 100 ppm Zr.

Whole-rock trace element determinations were done by ICP-mass spectrometry (ICP-MS) after HNO₃+HF digestion of 0.1000 g of sample powder in a Teflon-lined vessel at $\sim 180^\circ\text{C}$ and 200 psi for 30 min, evaporation to dryness, and subsequent dissolution in 100 ml of 4 vol.% HNO₃. Instrument measurements were carried out in triplicate with a PE SCIEX ELAN-5000 spectrometer using rhodium as an internal standard. Precision, as determined from standards WSE, BR and AGV run as unknowns, was better than $\pm 2\%$ and $\pm 5\%$ for analyte concentrations of 50 and 5 ppm, respectively.

Whole-rock X-ray diffraction of the agate milled sample produced diffractograms using a PANalytical X'Pert Pro diffractometer (CuK α radiation, 45 kV, 40 mA) equipped with an X'Celerator solid-state linear detector, using a step increment of $0.008^\circ 2\theta$ and a total counting time of 10 s per step. Data were processed using HighScore software to identify key mineral peaks, d spacing Å: clinopyroxene 2.55-2.99; plagioclase 3.19-3.21; amphibole 8.35-8.44.

Major element analyses of minerals were obtained by wavelength dispersive analyses with a Cameca SX-100 electron microprobe, using mainly synthetic standards. Accelerating voltage was 20 kV, and beam current was 20 nA. Spot size was 5 microns.

For automated mineralogy, sample CAN_LLIP_0001 was mounted in a 30 mm diameter epoxy resin block, polished to a 1 micron finish, carbon-coated to 25 nm, then analysed by a QEMSCAN® 4300 at the University of Exeter (Gottlieb et al., 2000). Sample measurement and data processing used iMeasure v4.2SR1 and iDiscover 4.2SR1 and 4.3 (Rollinson et al. 2011). The QEMSCAN® settings used 25kV, 5nA, a 1000 X-ray count rate per pixel, a WD of around 22 mm under high vacuum and beam calibration every

30 minutes. Sample measurement used the fieldscan measurement mode (Pirrie & Rollinson, 2011) to analyse the samples at an X-ray resolution/pixel spacing of 5 microns and a 1000 micron² field size (x68 magnification).

References

Gottlieb, P., Wilkie, G., Sutherland, D., Ho-Tun, E., Suthers, S., Perera, K., Jenkins, B., Spencer, S., Butcher, A., & Rayner, J., Using quantitative electron microscopy for process mineralogy applications. J. Min. Metals Mat. Soc. 52, 24–25 (2000).

Pirrie, D. & Rollinson, G.K. Unlocking the applications of automated mineral analysis. Geology Today 27, 235-244 (2011).

Rollinson, G.K., Stickland, R.J., Andersen, J.C., Fairhurst, R. & Boni, M. Characterisation of supergene non-sulphide zinc deposits using QEMSCAN®. Min. Engineer. 24, 778-787 (2011).

Samples in order of collection and also distance from the vent.

CAN_LLP_0001 21/9/2021, 28.618758, -17.884791 (El Paraíso)

CAN_LLP_0002 21/9/2021, 28.618613, -17.903585, First active lava (Todoque)

CAN_LLP_0003 22/9/2021 28.618585, -17.904383, Second active lava

CAN_LLP_0004 23/9/2021 28.618711, -17.904324

CAN_TLP_0008 Tephra Station 1a: 22/9/2021, 28.624518, -17.884743

CAN_TLP_0009 22/9/2021: mobile collection on north side of volcano, within 5 km of vent

CAN_TLP_0011 25/9/2021 06.00-08.30: 28.661182, -17.914099

Figures

Figure 1. Pankhurst et al.

Figure 1

(a) location of tephra samples, and historic eruptions^{3,4,5}; (b) selected flow extent snapshots and lava sample locations; CAN_LL_P_0001 (sampling: c; hand specimen: d); e) CAN_TLP_0001 coarse particles; f) CAN_TLP_0011 stereomicroscope image including ultra-rare restingolite (pending confirmation). g. Ash, tephra and lava photomicrographs.

Textural and compositional analysis

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Samplesmetadata.xlsx](#)
- [Wholerockmjrsandtraces.xlsx](#)
- [Mineralchemistry.xlsx](#)
- [QemscanCANLLP0001QEMSCANPankhurst2021.xlsx](#)
- [DiffractogramsCANLLP00014TLP0008911.pdf](#)
- [QemscanCANLLPTLPALP0001.jpg](#)