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BRIEF REPORT

From magma to macrophage: the grand challenges of volcanic environments

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Abstract

The interdisciplinary study of volcanic processes, which extend across all timescales and lengths, requires a multitude of approaches, ranging from analogue and numerical modelling to observations and fieldwork and extending to mathematics. A conference was held at the East African Institute for Fundamental Research, affiliated with the University of Rwanda, a country which, along with the Democratic Republic of Congo, presents a unique geodynamic context. Located along the East African Rift, an active seismic region, Rwanda is close to two of Africa's most active volcanoes, including Nyiragongo, which overlooks Lake Kivu, a deep volcanic lake rich in dissolved carbon dioxide and methane, the latter of which is used for electricity generation. In this context, the conference addressed many "classic" volcanological topics and their modern advances, such as multiphase lava flows, subsurface magma propagation, seismic and deformation signals from a volcano, modelling of volcanic emission dispersion, and volcanic lakes. Yet, it broadened the discussion to the volcanic particle-water interface and its impact on soils, volcanoes and climate change, and volcanoes and health. This article aims to highlight and share the richness of the integration and interconnectedness of the various questions related to a volcanic environment, as well as their impact on society. Ultimately, this conference also demonstrated the importance of promoting science in Africa and developing countries so that the next generation of African researchers is equipped to address the challenges facing their nations.

Keywords Volcanology · Volcanic eruptions · Volcanic processes · Natural Hazards · Climate change · Volcanic soils · Environmental Health

Introduction

Since 1841, when the first volcanic observatory was founded on Mount Vesuvius (Italy), monitoring has been at the heart of volcanic hazard assessment. Increasingly, field observations are integrated with satellite remote sensing, laboratory analysis and analogue and computational modelling to deepen our understanding of volcanoes and the magmatic systems that feed them. It is estimated that up to 800 million people worldwide are threatened by volcanoes. Hazards include lava, pyroclastic and mud flows, ash clouds and fallout, seismicity and exposure to gas and particulate plumes. Past eruptions have resulted in substantial loss of life, and infrastructural and economic damage. On the other hand, volcanoes and volcanic landscapes provide agriculturally-productive Andisols, geothermal resources and geotouristic potential.

From Cameroon to Eritrea, eastern and central Africa host many volcanoes that represent both risk and reward, yet the pace of disaster preparedness and development of resource opportunities has been slowed by wider challenges faced across much of the continent: conflict, health and economic inequality and impacts of climate change (Lenhardt and Oppenheimer 2014). A unique conference exploring

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these themes was held at the East African Institute for Fundamental Research in Kigali (https://eaifr.ictp.it) in September 2025. It drew locally-based staff, students and health professionals, regionally-based geophysicists, and scientists of diverse persuasions from Asia, Europe and North America (Fig. 1). A primary aim was to provoke discussion between students and experts and to showcase the research capacity in the region. Here, to stimulate further international engagement, we provide a digest of the topics covered by the meeting and highlight the tremendous potential for new collaborations aimed at tackling both fundamental and applied aspects of volcanic risk management, methane harvesting, agronomy and environmental health.

Studying volcanic processes and their implications

Volcanic processes involve complex multiphase flows, ranging from subsurface mixtures of melt, crystals and bubbles, controlled by viscous stresses, to much faster-moving, inertia-controlled flows of fragmented solid particles suspended in hot, pressurized gas. Important phase transitions occur as the continuous phase changes from liquid to gas by decompression, or from liquid to solid by cooling and crystallization (Edmonds & Woods 2018). Understanding how these mixtures evolve under changing conditions has advanced considerably through the development of models for phase transitions as the melt cools, decompresses, and progressively crystallizes on ascent. In addition, models have been developed for the saturation and exsolution of volatile compounds that accompany cooling and crystallisation. A key future development is the integration of these models with magma intrusion models.

A key challenge for hazard assessment is forecasting of the location, timing and nature of eruptive phenomena, which requires reliable models for the subsurface storage, transport and degassing of magma. Today, analogue, theoretical and numerical approaches that simulate magma trajectories from depth to the surface in different tectonic regimes, accounting for the influence of regional stress fields, topographic loading and unloading, magma buoyancy, viscous stresses, fracture resistance and solidification. An example of recent success has been the use of static models to capture the subsurface path of the Nyiragongo (East African Rift) magmatic intrusion (Pinel and Mériaux 2025). Further

Fig. 1 Group Photo of the conference. Photo Credit: Philbert Ntivuguruzwa

recent developments have enabled exploration of the relationships between magmatic intrusion and the associated spatio-temporal patterns of seismicity and ground deformation. However, magma cooling and phase transitions during tortuous dike propagation in complex stress settings remain largely unexplored.

Seismic activity and surface displacements are crucial indicators of subsurface magma propagation. Surface displacements can be directly measured using geodetic techniques (InSAR, GNSS). The increasing availability of satellite data and improvements in time-series analysis enable measurement of displacements of just a few mm/yr over areas 100 s km wide every few days (Pagli et al. 2014). Displacements are rapidly analyzed via 3D inverse models to estimate the geometry and stress changes of the source of displacement (Smittarello et al. 2019). Identification of high frequency (volcano-tectonic) earthquakes provides a proxy for magma ascent, while low frequency seismicity can reveal processes in the volcanic conduit and deep pulses of volatile-rich basaltic magmas rising from the mantle. Today, improved computing power and machine learning are facilitating automated data processing, accelerating analysis and revealing fine structures around pressurized magma bodies. Such monitoring and analytical capabilities can provide vital early warnings of volcanic unrest and potential eruptions.

Volcanoes release ash, gas, and aerosols into the atmosphere forming plumes that can spread great distances with the winds. Atmospheric chemistry-transport models are used to simulate ash cloud dispersion, sulfate aerosol formation and tephra fallout. Different strategies are adopted for short-term forecast vs long-term hazard assessment, the former driven by weather prediction models and real-time observations, the latter by wind statistics and stratigraphic and sedimentological data. Advances in short-term forecasts include ensemble-based runs, assimilation of satellite and real-time monitoring data, and modelling of ash resuspension. For long-range hazard assessment, High Performance Computing (HPC) models allow full probabilistic treatments. Digital twins, AI and novel software engineering technologies promise further support for operational forecasting. In particular, Machine Learning and Deep Learning can reveal rules and patterns from data without explicit human supervision (Corradino et al. 2024). The uptake of these emerging approaches demands multidisciplinary skills and deeper understanding of underlying processes.

The Virunga region is renowned both for the prevalence of lava lakes at Nyiragongo and Nyamuragira volcanoes, and the vast, strongly stratified Lake Kivu. Magma degassing can result in accumulation of bubbles in subsurface sills and microlite formation. The near-surface increase in melt viscosity can provoke intermittent gas explosions (Strombolian eruptions). In contrast, water-filled lava lakes contain dissolved CO_2 or CH_4 at depth, which, if destabilized, can release hazardous bubble plumes. The possibility of such limnic eruptions being triggered by subaqueous fissure eruption at Lake Kivu (DRC-Rwanda) has been a particular concern. There is also interest in the potential impacts of methane harvesting, which is underway on the lake, for energy generation. Bubble plume modelling has evolved from pioneering work that described the bulk motion of turbulent buoyant plumes to double-plume models incorporating stratification, bubble expansion and dissolution, and chemical reaction, and computational fluid dynamics (Cardoso and Cartwright 2024).

Volcanic soils result from both the bio-weathering of bedrock (e.g. basalt) and atmospheric inputs of tephra (e.g., containing titanomagnetite) and volatiles (S, Se, halogens, trace metals). The acidity of these soils favors dissolution of primary particles by plants and microorganisms. Bioalteration rapidly releases plant nutrients, combining with good water retention, friability to contribute to the high fertility of these soils, but also transforms ash and pumice into secondary minerals such as aluminosilicate nanospheres, nanorolls, and nanotubes (Dahlgren et al. 2004). Coupling intensive analysis of pair distribution functions and reactive transport models with advanced observational techniques (e.g., scanning electron microscopy, laser-induced breakdown spectroscopy) is revealing the important mechanisms controlled by these nanoparticles.

Volcanism influences our planet's environment across a vast range of spatial (local to global) and temporal scales (from less than a year to 100 million years) and through numerous processes, such as, but not limited to, Large Igneous Provinces (LIPs), and short-lived large-scale explosive eruptions (Mather 2015). Explosive sulfur-rich volcanic eruptions are a leading cause of external forcing of climate and can perturb the Earth system for timescales ranging from years to decades. The stratospheric sulfate aerosol generated by major eruptions increases planetary albedo, resulting in surface cooling by radiative forcing and potential interactions with internal modes of climate variability such as ENSO. Climate observations, reconstructions, and simulations reveal complex dynamic responses in the coupled ocean–atmosphere-sea ice system. Consideration of volcanic forcing has not only contributed to interpretations of world history (Büntgen et al. 2026), it is now recognised as essential for future climate projections (Marshall et al. 2022).

Health risks associated with volcanic eruptions include trauma, respiratory effects of ash and gas inhalation, skin and eye irritation, and asphyxiation (from catastrophic CO_2 release associated with limnic eruptions or accumulation of CO_2 from soil degassing in sheltered terrain). Less understood are the impacts of chronic exposure to acid atmospheric plumes sourced by persistent degassing, e.g., from Nyiragongo lava lake), and exposure to mineral particles, which can lead to conditions such as podoconiosis, a non-filarial form of elephantiasis caused by long-term barefoot exposure to soils of volcanic origin and their nanotubes. Podoconiosis affects more than 4 million people worldwide, in severe cases leading to chronic lymphoedema of the lower legs and inflammation (Deribe et al. 2018). Recent studies have found elevated aluminium, silicon, and titanium in affected tissues, suggesting absorption of soil mineral particles. Macrophages play a key role in the immune response by internalizing these particles, but when the digestive vesicle ruptures and releases toxins, inflammation is triggered. Podoconiosis exemplifies an environmental disease rooted in the interactions between volcanic soil particles, genetic predisposition, and sociocultural factors including footwear and hygiene. Addressing it requires an interdisciplinary approach integrating volcanology, biomedical research, and public health.

Concluding remarks

Throughout the Kigali conference, the importance of integrating different approaches to understand the processes and impacts of volcanism was evident, including analogue and computational modelling, observations and fieldwork, and mathematical theory (See Supplementary Information). The diverse applications of this knowledge—from analysis of hazards and risks, to evaluation of energy futures, crop yield experiments, soil bio-weathering, and environmental toxicology—were striking. We invite readers of this report to engage in more strategic and integrative thinking about the challenges and opportunities of the geosciences, aimed at supporting risk management, land use planning, sustainable development of energy and geo-resources, environmental health, and agronomy in volcanic regions, and encourage especially new thinking and collaborative research on these topics in eastern and central Africa.

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Declarations

Competing interests The authors declare no competing interests.

References

Büntgen U, Di Cosmo N, Esper J, Frachetti M, Khalidi L, Mauelshagen F, Rohland E, Oppenheimer C (2026). Volcanoes, climate, and society. Annu Rev Earth Planet Sci 54:1.1–1.31. https://doi.org/10.1146/annurev-earth-032524-013254

Cardoso SS, Cartwright JH (2024) Bubble plumes in nature. Annu Rev Fluid Mech 56(1):295–317. https://doi.org/10.1146/annurev-fluid-120720-011833

Corradino C, Jouve P, La Spina A, Del Negro C (2024) Monitoring Earth's atmosphere with Sentinel-5 TROPOMI and artificial intelligence: quantifying volcanic SO2 emissions. Remote Sens Environ 315:114463. https://doi.org/10.1016/j.rse.2024.114463

Dahlgren RA, Saigusa M, Ugolini FC (2004) The nature, properties and management of volcanic soils. Adv Agron 82:113–182

Deribe K, Cano J, Trueba ML, Newport MJ, Davey G (2018) Global epidemiology of podoconiosis: a systematic review. PLoS Negl Trop Dis 12(3):e0006324. https://doi.org/10.1371/journal.pntd.0006324

Edmonds M, Woods AW (2018) Exsolved volatiles in magma reservoirs. J Volcanol Geotherm Res 368:13–30. https://doi.org/10.1016/j.jvolgeores.2018.10.018

Lenhardt N, Oppenheimer C (2014). Volcanism in Africa: geological perspectives, hazards, and societal implications. In A. Ismail-Zadeh, J. Urrutia Fucugauchi, A. Kijko, K. Takeuchi, & I. Zaliapin (Eds.), Extreme Natural Hazards, Disaster Risks and Societal Implications. Cambridge University Press pp. 169–199. https://doi.org/10.1017/CBO9781139523905.018

Marshall LR, Maters EC, Schmidt A et al (2022) Volcanic effects on climate: recent advances and future avenues. Bull Volcanol 84:54. https://doi.org/10.1007/s00445-022-01559-3

Mather TA (2015) Volcanoes and the environment: Lessons for understanding Earth's past and future from studies of present-day volcanic emissions. J Volcanol Geoth Res 304:160–179. https://doi.org/10.1016/j.jvolgeores.2015.08.01

Pagli C, Wang H, Wright TJ, Calais E, Lewi E (2014) Current plate boundary deformation of the Afar rift from a 3-d velocity field inversion of InSAR and GPS. J Geophys Res Solid Earth 119(11):8562–8575. https://doi.org/10.1002/2014JB011391

Pinel V, Mériaux CA (2025) Subsurface lateral magma propagation from Nyiragongo volcano in the Western Rift Zone of the East African Rift. J Afr Earth Sci 226:105569. https://doi.org/10.1016/j.jafrearsci.2025.105569

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