



Geochemical Monitoring of Volcanical Activity: Methods and Trends

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Abstract: The eruption of volcanoes remains one of the key natural hazards, which calls for real-time monitoring with an aim of issuing precautionary warning and alleviating risk involved. In this review, the modern advancements in geochemical monitoring of volcanic activity based on the study of gaseous products, utilisation of isotope fingerprinting approaches, and implementation of artificial-intelligence-assisted forecasting models are synthesised. There is a specific interest in the emerging trend of portable Multi-GAS systems to be able to do in-situ concentration measurements of CO₂, SO₂, and H₂S and thus improve precision and safety of on-ground measurements in challenging volcanic landscapes. These tools, combined with remote-sensing data obtained on drones, open a potentially transformative chapter of spatially and temporally defined sampling in area active volcano vents. The new empirical interest in compound-specific isotope-traceable forms of magmatic gas tracing, hydrothermal alteration process characterisation, and elucidation of the pre-eruptive dynamics of volcanic systems have all become possible. The embedding large-scale and multifactor datasets in machine-learning algorithms enhance the abilities of eruption forecasting since it translates intricate measurements into usable information. In retrospect, the future of volcanic observatory is most feasibly predicted to be characterized by autonomous sensor networks, cloud-hosted data frameworks, and standardization of high-resolution gas profiling, consequently inciting more global consistency and improving both proactive and reacting surveillance policies.

Keywords: Geochemical monitoring, Volcanic gas emissions, Multi-GAS sensors, Isotope fingerprinting, Passive gas spectroscopy.

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Introduction

Eruptive processes of volcanoes cause massive risks to human life, ground constructions, and climatic processes. Modern volcanology therefore aims to explain the preliminaries of such events. In terms of monitoring methods, seismology, ground deformation, remote sensing, and geodetic observation have been fundamental to date, but geochemical surveillance has proved to become irreplaceable as well since it is directly linked to magmatic processes occurring on a lower level (Aiuppa *et al.*, 2021; Schmid *et al.*, 2023). Carbon dioxide (CO₂), sulfur dioxide (SO₂), hydrogen sulfide (H₂S) and water vapour (H₂O) are volcanic emissions that form sound indicators of magma degassing and transport. Change in gas composition, both the chemical concentrations and mass flux often pre-event preceding eruptions and hence should be significantly considered. Also, the geochemical characteristics of such emitted gases provide informative data that gives information about the depth of the magmatic reservoir, oxidation state and even zapora.

Gas sampling in the past was restricted to ad hoc, manual campaigns done at the fumaroles or at crater rim, an operation in itself very risky to the field workers. However, a revolution in the discipline has taken place during the past 20 years with *In Situ* sensor networks, remote sensing instruments and laboratory approaches. Methods using a number of parameters, including Multi-GAS (Multiple Gas Analyzer Systems) and Open-Path FTIR (Fourier Transform Infrared Spectroscopy), now yield substantive real-time gas composition and ratios information (Mori *et al.*, 2021). Later on, these evolutions were marked by the improvement of mobility, autonomy and integration. Measurements through hazardous areas or inaccessible locations via Unmanned Aerial Vehicles (UAVs) with miniaturized sensors are now capable of gas analysis, therefore enabling the measurement of plumes dropped by lava lakes or other such active sources (de Moor *et al.*, 2022). They are combined with satellite-based sensors such as TROPOMI and OMI, performing standardized measurement of monthly global data on the level of gas emissions with high time coverage (Carn *et al.*, 2022).

In addition to measurements of bulk gas, isotopic compositions give a clearer view of the magma source regions as well as the degassing pathway. Isotopic fingerprinting method results can be used to attribute volcanic volatiles to mantle source, thus the models related to volcanic eruption forecasting are more accurate (Villasante-Marcos *et al.*, 2023). Also, new studies of rare gases (e.g., neon, argon, xenon) and metal volatiles (e.g., mercury, lead, arsenic) have diversified geochemical monitoring, especially to monitor deep-seated degassing or environmental contamination caused by volcanic processes (Weis *et al.*, 2022).

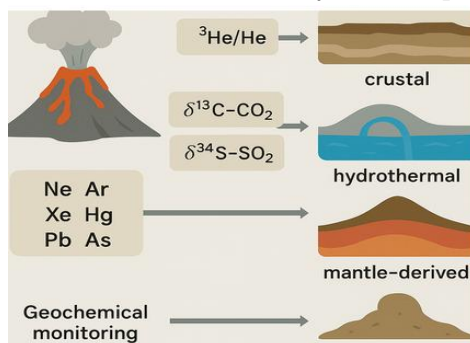


Figure 1: Isotopic Fingerprinting and Geochemical Monitoring of Volcanic Gas Sources

Multi-GAS and Drone Integration

Most recently, volcanic geochemistry has improved hand in hand with the introduction of Multi-GAS (Multiple Gas Analyzer System) and the judicious use of drones. Despite the conventional ground-based measurement methods still being sound, their use is either limited by accessibility, safety, and/or low spatial resolution (Aiuppa *et al.*, 2021). The combination of Multi-GAS sensors and unmanned vehicles (UAVs) provide access to high-resolution data acquisition in inaccessible areas, including active craters, steep crater flanks and areas near vents. The recent Multi-GAS instruments are not bulky and heavy and can be mounted on drones easily. Installation of these systems means they can automatically measure gas levels of volcanically important species such as CO₂, SO₂ and H₂S on a continuous basis. The data can be tele-metred in real time to ground stations allowing timely analysis to efficiently detect anomalies and predict the behavior of eruptions. Together with Multi-GAS, the deployment of the drones therefore increases spatial coverage and allows vertical-horizontal profiling of the gas plumes, further improving the flux and emission rates estimates (Galle *et al.*, 2022). In addition, the method is less personnel risk based and less disruptive to the natural plume dynamics producing a safer and more scientifically sound system. More recently, the integration of a GPS and Inertial Measurement Units (IMU) to the Multi-GAS sensors has allowed accurate mapping of ground location and altitude in which the measurements have been obtained (Arellano *et al.*, 2023). The more recent development of volcanic gas monitoring systems has seen autonomous navigation and the capability to fly within a predetermined flight path thus making repeatable and search-based missions possible. Moreover, the combination of artificial-intelligence and edge-computing functionality, on-board the drones, allows processing of the collected information and the possibility to make an autonomous decision. This trend puts the existing systems in a state of complete operational autonomy within the short-term future (de Moor *et al.*, 2023). Hand in hand with such displacements, the implementation of Multi-GAS sensors partnered with drone systems is revolutionizing the capabilities of volcanic gas monitoring as they gain capabilities to access real-time, high-resolution data sets while being safe to use by their nature. This leads to a complete data set which is reinforcing in terms of eruption forecasting and providing important insight into the mechanisms of volcanic degassing and the time development of magmatic processes underneath the surface.

Real-Time Gas Detection with Portable Multi-GAS Systems and Drones

One of the most popular technologies that are used to determine volcanic gas releases in real time are portable multi-gas analysis systems. In such systems, which usually consist of infrared sensors of carbon dioxide (CO₂), electrochemical sulfur dioxide (SO₂) and hydrogen sulfide (H₂S), also have complete (complex) modules of pressure - temperature and - humidity (PTU). The small, weather-resistant platforms allow ongoing collection of gaseous ratios (e.g., CO₂/SO₂ and CO₂/H₂S), thereby enabling them to detect changes in magma degassing activity and precursors to an eruption. Permanent monitoring instituted over time in programs including the Deep Earth Carbon Degassing Project (DECADE), have been operational long-term and have been invaluable in the identification of precursors of eruptions at volcanoes where sustained measurements have been maintained (De Mazière, and Ireland, 2001; Furnes *et al.*, 2001; Scarrow *et al.*, 2001; M rquez *et al.*, 2001). Especially notable in this respect are volcanoes possessed of permanent installations, especially Masaya and Tutumaca.

Drone-Based Platforms: Enhancing Access and Spatial Coverage

Existing studies typically use small multi-gas sensors attached to unmanned aerial vehicles (UAV)s to sample fumarolic emitters miniGAS and Sniffer4D Mini 2. Such sub-kilogram small drones, weighing below 300 g, can measure CO₂, SO₂, H₂S (and in some versions, PM), thus providing a rich chemical portrayal of cavity space samples and plume emissions, keeping field participants out of dangerous gases.

A very recent field campaign carried out on Turrialba and Poas Volcanoes (Costa Rica) proved the effectiveness of Sniffer4D-Mini2-equipped drones: the approach provided concentration data that matched those measured using a classic ground-sampling approach and allowed repeated cost-effective surveys of the volcanoes. Similarly, small, unmanned aircraft flights over Bagana Volcano demonstrated that UAV surveys can provide detailed compositional data even in inaccessible and hard to reach locations, but that current flight times are not yet as extended as those possible using continuously deployed permanent stations.

System Features and Real-Time Data Integration

Contemporary multiGAS systems carried by drones (such as the Sniffer4D platform) use modular platforms that allow it to detect nine gas or particulate species over a single flight (e.g., SO₂, CO₂, CO, VOCs, PM 2.5). Transmission of data is done real-time by cellular, or telemetry connection and tile instruments are set to log at 1 Hz to be analyzed offline. The systems also are compatible with 2D, and 3D mapping and can transmit fast mission reports on cloud-based dashboards. Such capabilities allow volcanologists to re-route flight paths on the ground, as well as optimizing plume characterisation, and enhancing area coverage of hazards, without jeopardising safety.



Figure 2: Real-Time Volcanic Gas Monitoring Using Drone-Mounted Multi-GAS Systems

Scientific and Hazard Monitoring Applications

Deployment of the Unmanned Aerial Vehicles (UAVs) has also become a valid solution in providing monitoring of volcanic gases and its resolutions have shown to be better than the ground-based techniques. Some effectiveness claims that are identified by the recent research refer to practical advantages such as low access of the staff to dangerous areas, high spatial resolution, and speed of system installation. An example would be the volcano of Stromboli whereby infrared images revealed two separate stratified plumes, that differed significantly in terms of their CO₂ SO₂ ratio. These findings showed that there was a discrepancy in the formation of gas bubbles that was time and space dependent. Moreover, the UAV routes at Poas Volcano allowed simultaneous monitoring of atmosphere dilution of CO₂, including even the fumarole driven levels, and the information showed high correlation with an *In Situ* molar-monitor level, thus increasing the level of safety and working efficiency.

The main advantages of UAV-based gas monitoring are safety, fast data collection, access to otherwise unreachable vent sources and high-resolution concentration maps. These capabilities deal with the possibility of entry risks, allow increasing the sampling rate, and promote better eruption forecasts. However, there are some limitations, and they are still connected primarily with the limiting flight time, the chances of UAV getting lost somewhere in plumes, and the inability to cover the time period during the flight operation compared to the stationary stations. Recent studies are overcoming such downfalls by formulating appropriate systems (e.g. the LoCUS program) based on swarms thereby utilizing redundancy and system resiliency.

With future UAV systems, swarm sampling to maximize plume overlap and therefore coverage, autonomous route planning using real time mission parameters, the addition of a thermal camera in concert with that of gas-sensing are to be expected and the deployment of an army of multimodal particulates sensors will provide the ability to perform an entire plume assessment.

Table 1: Overview of Drone-Based Volcanic Gas Monitoring: Sites, Observations, Tools.

Aspect			Details
Study Sites			Stromboli (dual CO ₂ /SO ₂ plume layers); Poás (CO ₂ dilution comparison with fumaroles)
Observed	Gas	Ratio	High spatial resolution differentiation of CO ₂ /SO ₂ ratios within and across plume layers
Technological Tools Used			Drone-mounted Multi-GAS sensors; real-time telemetry; GPS; LoCUS swarm algorithm
Advantages			Safe, rapid deployment; access to hazardous zones; spatial mapping; higher sampling frequency
Limitations			Limited flight time; risk of drone loss; shorter monitoring duration vs. fixed stations
Future Trends			Swarm algorithms (e.g., LoCUS); autonomous missions; multi-sensor integration (thermal, VOCs, PM)

Integration with AI and Machine Learning

Within the past 5 years, there has been a paradigm shift in the analysis of volcanic gasses data where machine learning (ML) and AI-based models have been implemented. Now, due to the support of neural networks and decision-tree algorithms, researchers can use large data sets of time series to visualize the smallest peculiarities, as well as gain a proper insight into the dependence between the fluxes of gases and eruptions (Pering *et al.*, 2022; Williams-Jones *et al.*, 2023). The latter tools allow real-time detection of patterns and allow abnormal degassing to be detected early, even in cases where surface activity does not occur. of note, volcanic observatory long-term gas data are also being used to train models to estimate eruption probability, predict volcanic plume height and forecast gas dispersion.

Global Relevance and Risk Mitigation

Effective geochemical monitoring is not only critical for scientific understanding but also for civil protection and disaster preparedness. Volcanic crises like those at La Palma (Spain, 2021) and Tonga (2022) have demonstrated the value of rapid geochemical surveillance in guiding evacuation decisions and informing the public. The development of international frameworks, such as the Global Volcano Model (GVM) and Deep Carbon Observatory (DCO), underscores the global effort to standardize monitoring practices, share real-time data, and improve response coordination across nations and observatories (Burton *et al.*, 2021).

Drone-Mounted Gas Sensors for Volcanic Monitoring: Advances, Applications, and Future Directions

In-plume measurements with unprecedented temporal resolution in dangerous or inaccessible areas is a revolutionary development in volcanic gas monitoring, brought by the integration of miniaturised applied to drone-mounted gas sensors. Recent experiments using the Mini GAS and MicroGAS devices (mass < 1.5 kg) have confirmed that the mini-systems yield similar gas quantifications as the larger and heavier Multi-GAS ones, and can therefore be used to detect low, and yet volcanically meaningful amounts of CO₂, SO₂, and H₂S (Aiuppa *et al.*, 2021). This smaller-size and weight is essential to the continuous, distant observation of isolated volcanoes or of volcanoes with steep sides. An existing use case at Johannes Gutenberg University demonstrates the effectiveness of utilizing ultra-light uncrewed aerial systems (UAS) with fewer than 900 g in weight and gas sensors, therefore significantly increasing both operation deploy ability and crew protection capabilities through the ability to conduct regular sampling without risk to crew members (Gouhier *et al.*, 2021).

In-Plume Measurement During Active Eruptions

A groundbreaking deployment during the 2021 Tajogaite eruption (La Palma) utilized drone-mounted tunable diode laser spectrometers to capture in-situ CO₂ concentrations and isotopic ratios directly from the eruptive plume. These measurements enabled estimation of CO₂ fluxes ranging between 1.8×10^3 and 2.2×10^4 t d⁻¹, providing novel insights into deep magmatic gas sources (Arellano *et al.*, 2022). This marked the first successful drone-based quantification of volcanic carbon fluxes during an active eruption.

2D and 3D Plume Mapping Capabilities

Modern drones also support georeferenced 2D/3D plume mapping in real time. Technologies like Sniffer4D Mini2 integrate gas sensors, telemetry, and GPS to deliver high-resolution gas concentration maps. These systems allow dynamic flight-path optimization based on real-time data, facilitating efficient plume tracking (Shinohara, 2022). Emerging algorithms such as LoCUS coordinate autonomous drone swarms that track concentration gradients in a fault-tolerant manner, crucial in complex volcanic environments (Cámara *et al.*, 2020).

Scientific and Hazard Monitoring Benefits

At volcanoes like Turrialba and Masaya, UAS platforms have enabled repetitive measurements of gas ratios (e.g., CO₂/SO₂), uncovering spatial and temporal heterogeneities in degassing not captured by stationary monitoring stations (de Moor *et al.*, 2019). Drone campaigns at Stromboli captured multi-layered plume structures with distinct gas signatures, revealing complex plume dynamics. Similarly, at Poás Volcano, drones dramatically reduced sampling time from hours to mere minutes while providing data quality comparable to traditional ground-based techniques (Arellano *et al.*, 2020).

Innovations and Future Outlook

Aerial volcano monitoring (AeroVolc, 2025) is the latest step in volcanic surveys using drones, which combine sampled ash and aerosol measurements in real-time with volcanic gases and species sampling in eruption columns. The extension of the in-situ characterization of volcanoes is impressive because of this combination. Future systems will use autonomous drone swarms, on-board thermal imaging, self-limited VOC/PM sensors and highly complex sensor-drift-correction mathematical algorithms, further increasing operational autonomy and data fidelity.

Sensor Architecture and Telemetry

The newly arranged sophisticated multi-gas platform based on drone MiniGAS PRO includes infrared CO₂ detectors, electrochemical analyzers of SO₂ and H₂S and the PTU (pressure temperature humidity) system with integrated telemetry and global positioning systems on board. By using a PTFE inlet specially designed not to cause rotor-induced turbulence, plume air is sampled by the system and forced through a parallel sensor linear array at a flow rate of around 1.2 L/min, powered by micro- pumps. Valuable

variables are sampled at 1 Hz and highly specific information in the geolocation and environmental metadata is automatically recorded (Shinohara *et al.*, 2023). A ground station interface is provided due to real-time transmission of data at up to 1.5 km and allows a real-time situation awareness.

Real-Time Data Logging and Visualization

High-frequency telemetry from in-flight drones provides continuous updates on gas concentrations, atmospheric data, and GPS position, which are visualized in 2D/3D plume maps using cloud-based dashboards. Onboard storage retains raw sensor outputs for calibration and validation post-flight (Aiuppa *et al.*, 2021).

Adaptive Flight Control and Autonomous Sampling

Drones equipped with real-time feedback systems enable adaptive flight patterns during missions, adjusting trajectories to target high-concentration plume regions. Swarm navigation algorithms like LoCUS allow coordinated sampling missions even when individual drones lose communication or fail (Cámara *et al.*, 2020).

Calibration, Maintenance, and Data Quality

Before deployment, sensors undergo zero and span calibrations, with software accounting for response time to synchronize gas concentrations with spatial data. Automatic drift correction and mid-mission recalibration procedures ensure high data accuracy in extreme volcanic conditions (de Moor *et al.*, 2019).

Integration with Satellite and Ground-Based Observations

Drone-collected data complements satellite platforms (e.g., TROPOMI, OMI) and fixed Multi-GAS stations, allowing multi-scale analysis of gas emissions. This integration enhances the temporal and spatial resolution of volcanic surveillance, critical for eruption forecasting and hazard response (Arellano *et al.*, 2022).

Stromboli: UAS campaigns revealed dual-layered plumes with distinct gas ratios, highlighting complex degassing processes.

Turrialba and Masaya: Drone measurements matched ground-based data but reduced dangerous, time-consuming fumarole sampling to a fraction of the time.

Challenges and Future Enhancements

Although powerful, drone systems face limitations including battery lifespan, sensor drift, and potential flight disruption from volcanic turbulence or corrosive gases. Future improvements include onboard thermal and particulate monitoring merged with gas sensing, real-time AI-driven anomaly detection for on-the-spot data validation and adaptive flight, deployment of autonomous drone swarms, and standardization via cloud-based data integration for global volcanic monitoring network.

Advanced Sensor Architecture and Telemetry

Modern drone-based Multi-GAS platforms, such as the miniGAS PRO, integrate infrared CO₂ sensors and electrochemical SO₂/H₂S detectors with onboard PTU (pressure-temperature-humidity) modules, GPS, and telemetry systems. Gas is sampled via a PTFE inlet positioned away from rotor downwash, then drawn through the sensor array with a micro pump at ~1.2 L/min. Each sensor records calibrated concentrations at 1 Hz, alongside timestamped location and environmental data. A radio link (up to ~1.5 km range) transmits data to a ground station in real time, enabling live monitoring and immediate analysis.

Real-Time Data Logging and Visualization

Every minute, in-flight platforms stream high-frequency data including gas concentrations, GPS position, and environmental metadata to a ground control console. This data is automatically incorporated into mapping dashboards capable of generating real-time 2D or 3D plume concentration models. Onboard loggers also preserve raw voltage and digital signals for post-flight recalibration and validation.

Dynamic Mission Control and Adaptive Sampling

Drone systems equipped with real-time feedback interfaces allow operators to adjust flight routes on-the-fly based on live plume concentration maps. This feedback loop permits targeted investigations of gas hot spots and transitional layers in volcanic plumes. Swarm algorithms (e.g., LoCUS) enable multiple UAVs to coordinate automatically, following gas concentration gradients while remaining resilient to drone loss or communication dropout.

Calibration, Quality Assurance, and Sensor Maintenance

Gas sensors undergo pre-flight calibration using zero/span gases, and software incorporates time response corrections so that each reported concentration matches the correct GPS timestamp. Automatic drift correction protocols ensure data integrity, while field routines allow for quick recalibration between flights vital for maintaining data quality over multiple missions in harsh volcanic conditions.

Integration with Satellite and Ground-Based Data

Data collected from drone-mounted platforms complements and validates satellite-based measurements (e.g., TROPOMI or OMI SO₂ retrievals) and ground-mounted Multi-GAS stations. Integrated datasets provide a more accurate, multi-scale representation of gas fluxes, enhancing the reliability of volcano surveillance systems.

Use Cases: Real-Time Implementation

At Stromboli, drone campaigns captured dual-plume layers with different CO₂/SO₂ ratios, revealing heterogeneity in degassing even within rapid flight times. During surveys at Turrialba and Masaya, realtime drone measurements not only matched ground-based Multi-GAS data but reduced logistically difficult fumarole sampling from hours to minutes, improving turnaround and safety.

Conclusion

The new and emergent geochemical volcanic monitoring represents a paradigm shift which was triggered by advances in portable Multi-GAS instrumentation, UAV delivery platforms, isotopic fingerprinting, and AI in data analytics. These technologies have led to significant improvement of detection of volcanic gases emissions, quantification and in real time interpretation which have been attained even under Hazardous working environment conditions and inaccessibility. The combination of Multi-GAS sensors with UAVs has achieved wide area coverage, improved safety of its operations and increased data resolution and isotopic analyses have given people a more in-depth understanding of magma sources, degassing pathways and pre-eruptive processes. The combination of AI and machine learning helps conduct surveillance of volcanic gases by quickly processing large multi-parameter data that allows enhancing both the timely and accurate prediction of eruptions. Moreover, the combination of in-situ drone measurements to satellite and ground-based monitoring networks provides a multi-scale high-fidelity view of the volcanic system thus enabling a more solid hazard assessment and civil protection tactics. Although issues like short drone endurance, sensor drift and the engineering risk of working in turbulent volcanic conditions persist, continued innovation: autonomous swarms, multi-sensor payloads, cloud based standard data integration is likely to incrementally improve volcano hazard monitoring. In the end, the combination of novel geochemical techniques, emerging sensing technology, and international data-sharing systems, is contributing toward an increasingly predictive, synchronized, and proficient system of reducing volcanic hazards on a worldwide scale.

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