International Association of Volcanology and Chemistry of the Earth's Interior

Commission on the Chemistry of Volcanic Gases

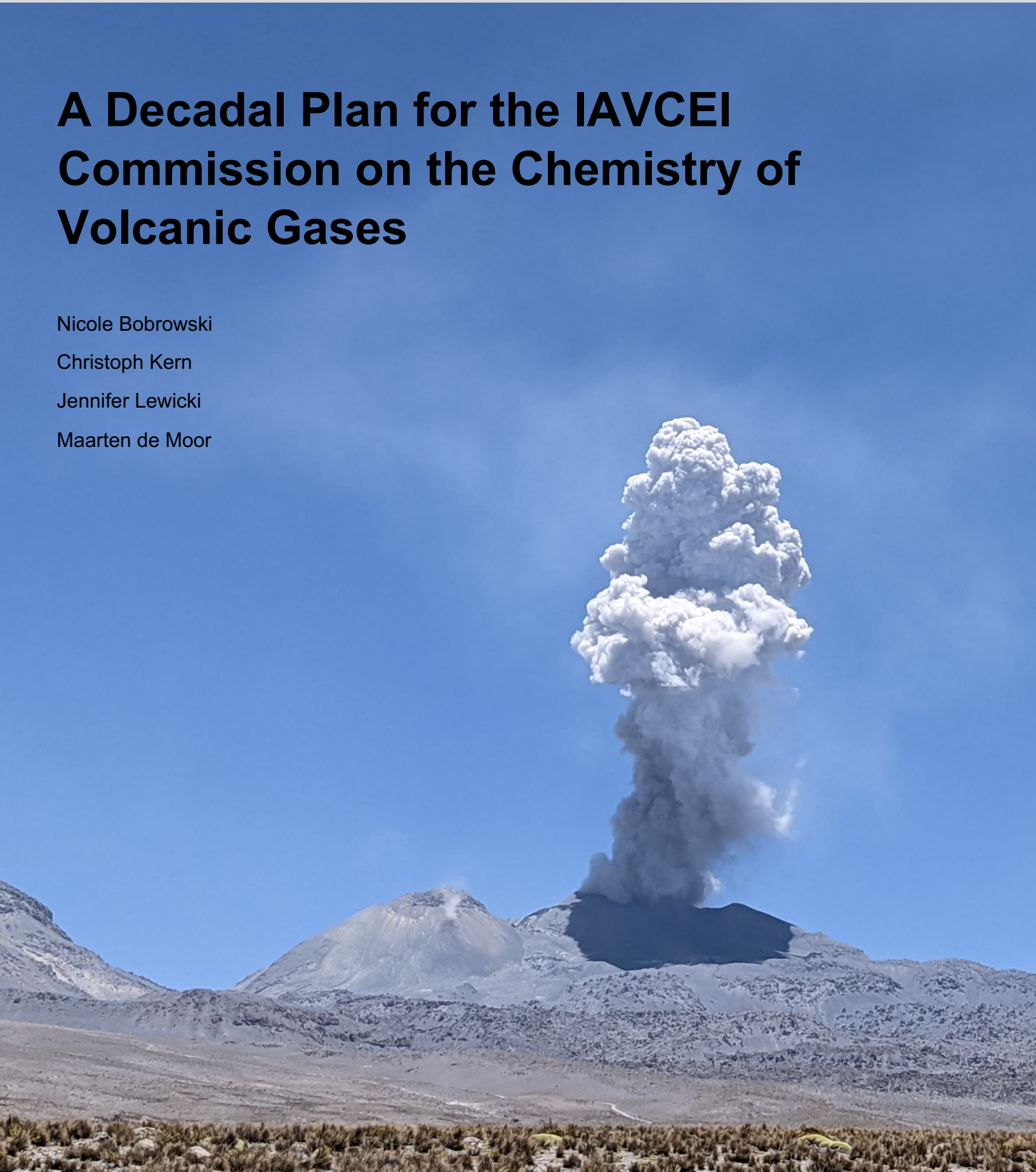
A Decadal Plan for the IAVCEI Commission on the Chemistry of Volcanic Gases

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Cover. Photograph of an explosion occurring at Sabancaya Volcano, Peru, on November 11, 2022. Photograph by Christoph Kern

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Introduction

The year 2032 will mark the 50th anniversary of the founding of the IAVCEI Commission on the Chemistry of Volcanic Gases (CCVG). During the 14th CCVG Field Workshop held in Arequipa, Peru, in 2022, a panel was tasked with developing a plan to guide the Commission's efforts in the next 10 years leading up to this important milestone. This document makes recommendations for improving the Commission's ability to advance the science of volcanic gas geochemistry and communicate that science effectively while fostering an inclusive, productive, and innovative environment for the advancement of the next generation of volcanologists. Below, we list specific goals that we believe should be prioritized over the next decade. Many of the goals are ambitious and cannot be expected to be fully attained in 10 years. However, wherever possible, we list specific recommendations on how progress might be achieved. The goals and recommendations are divided into four categories broadly focusing on research, resources, education, and outreach.

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Section 1: Fostering Research and Innovation

Volcanic gases contain information about processes that occur within active volcanic systems. Improving our ability to measure gases and interpret these observations will advance our understanding of volcanic systems, aid in forecasting volcanic events, and yield insights into the impact of volcanism on Earth System as a whole. We recommend the following actions to foster original research and pioneer innovations that will improve the state of our science.

- ***Identify reliable geochemical indicators of unrest and eruption.***
  - Advocate for more gas geochemical studies to expand our knowledge base. Repeated or continuous measurements are especially valuable, as they allow establishment of baseline conditions and detection of anomalous signals departing from these. Also encourage repeat/high frequency measurements of new parameters (e.g., trace gases, isotopes, aerosols) that have not previously been tracked.
  - Provide guidelines for practical techniques in volcanic gas monitoring, including strategies and examples for monitoring volcanoes in different phases of unrest.
  - Provide tools and resources to facilitate volcanic gas monitoring. This could include shared instrumentation (instrument pool) and freely available and rigorously tested (ideally open source) codes for data processing.
- ***Improve links between measurements and models.***
  - The use of petrologic models for interpretation of gas observations shows great promise, but uncertainties are large. Improve coordination with petrologists and experimentalists to prioritize measurements that yield the most useful information for interpretation of gas data. For example, CCVG might request a summary document from petrology experts outlining the opportunities and challenges of petrological modelling to better align our efforts with the highest potential benefits.
  - Thermodynamic gas-water-rock reaction models exist but are lacking some key aspects: Many of these models can either examine relatively low-temperature hydrothermal processes or high-temperature volcanic processes, but not both. Also, many of the existing models lack user-friendly interfaces. In the next decade, these shortcomings should be addressed such that gas geochemists can utilize wholistic gas-water-rock reaction models to draw robust conclusions from measured data and gain insights into their uncertainties.
  - Improve collaboration with experts in atmospheric chemistry and prioritize measurements and instrument development to address key questions. For example, high-temperature chemistry occurring immediately as gases mix with background air appears to be important when interpreting redox equilibria. And the removal of SO_2 from the atmosphere through oxidation and deposition of sulfate

appears to occur on a large range of time scales the cause of which is not yet fully understood.

- ***Conduct community science experiments.***
  - CCVG Workshops provide an excellent opportunity for large-scale experiments. Significant resources, both in instrumentation and personnel, are available to address important research questions during these workshops
  - Community experiments require coordination ahead of future workshops, including conceptualization of the research questions, development of the experiments, and logistical planning. This could be handled by the workshop's Scientific Committee and must include local expertise. Future meeting sites could be chosen, in part, based on short proposals solicited for experimental concepts.
  - If successful, the results of community experiments should be published in Bulletin of Volcanology. Ideally, a primary investigator / lead author should be selected ahead of time to increase the likelihood of success.
- ***Explore new technologies and methods.***
  - Unoccupied aircraft systems (UAS), autonomous boats, and subaqueous drones are all promising technologies that could allow previously impossible measurements. These technologies are particularly promising for volcanic observations, as they allow access to areas that would otherwise be hazardous or impossible to reach. To facilitate their application, the community should improve communication with technology experts, as they are often looking for applications but do nothave a good understanding of what is useful. For example, a list of questions that could be answered by autonomous measurements should be developed.
  - Artificial Intelligence / Machine Learning is another new technology that is rapidly developing and could have applications to gas geochemical data analysis and interpretation. Since we are often data-limited in our field, care must be taken not to overfit existing data, which would lead to failure to make correct predictions on new data. When considering the use of AI / Machine Learning, subject matter experts should be consulted (see Section 4 of this document).
  - Additional new technologies and methods are constantly being developed. For example, the last few years have brought improvements in real-time isotopic measurements (CRDS systems), passive IR remote sensing, high resolution spectroscopy, and Fabry Perot interferometric imaging, and environmental hardening of these and other systems to facilitate application in extreme environments. We suggest that a portion of each future workshop be dedicated to discussing new technologies and methodologies.

Section 2: Providing Important Resources to the Volcanology Community

Scientific progress will be most efficient if appropriate resources are readily available to the research community. Although scientists will generally need to obtain funding for their work from their respective science agencies and government institutions, the CCVG has an important role in organizing the sharing of resources and information among its members.

- ***Develop and publish standard operating procedures for data collection and error assessment.***
  - Continue to organize intercomparison exercises at workshops to allow groups to learn from one another and adopt best practices for collecting samples, making measurements, and analyzing data. Conduct round-robin analyses of known gas mixtures for the direct sampling group and conduct round-robin analyses of identical remote sensing data to compare remote sensing methodologies.
  - Solicit input from the entire CCVG community, develop documents that describe standard operating procedures for common sampling, measurement, and analysis techniques. Include discussion of problematic conditions, pitfalls, and potential solutions.
  - Where possible, also develop standardized methodologies for assessment of uncertainty in measurements. Fundamental science practices require a realistic range of uncertainty be reported with every measurement.
  - Publish consensus documents describing best practices, for example on the CCVG website.
- ***Adopt standardized data formats and repositories.***
  - Interpretation of volcanic gas measurements is generally a data-starved problem. Robust insights are often only obtainable by considering current measurements in the context of previously reported global datasets. Therefore, every effort should be made to optimize the FAIR principles: Findability, Accessibility, Interoperability, and Reuse.
  - The CCVG community should work towards standardization of data formats for each of the gas measurement techniques such that data can easily be shared and compared. Definitions of standard data formats should be posted on the CCVG website.
  - When findings are published in research papers, the data on which these findings are based should always be made available to the community, either as supplemental information or by uploading it to an accessible repository.
  - While we believe it is beyond the scope of CCVG to host its own database of gas measurements, several such databases already exist (e.g., WOVOdat,

EarthChem, MaGa, etc). We recommend the CCVG form a subcommittee tasked with exploring available database options with the goal of producing formal recommendations to members on where to upload results for future comparisons.

- ***Promote open sharing of analysis tools, software, and models.***
  - Scientific progress will be more efficient if we better share our digital tools with one another and enable each other to use them. Also, as data analysis methods and models become more sophisticated and complex, care must be taken to ensure reproducibility of experiments and results. For these reasons, CCVG should advocate for sharing software and models as they are developed and utilized in research studies. Sharing such tools necessarily also entails testing these and producing documentation with use cases for others to follow. .
  - Platforms already exist for hosting digital resources. Open-source computer code and software can be uploaded to GitHub. There are also valid reasons for not providing open-source code, e.g., when a tool is still under development or part of a student's research project. In such cases, software and models can be shared in compiled form.
  - We recommend the CCVG develop a list of digital tools available to the community and post this on the website. Each entry should have a brief description of the intended application, limitations, contact person(s), and a link to where it can be obtained. In cases where a consensus can be achieved, certain tools may be recommended for specific applications. A process for keeping this list up to date is needed as it will evolve rapidly over time.

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Section 3: Peer Training and Collaborative Learning

Ensuring progress in the field of volcanic gas geochemistry and its application to monitoring, hazard analysis, and fundamental research requires that CCVG prioritize training of its members on the continuously evolving technology and improvements in data analysis and interpretation methods. Knowledge transfer from one generation of geochemists to the next is of particular importance.

- ***Continue to organize regular field workshops.***
  - Perhaps the most important training opportunity for the community occurs through the regular field workshops organized by CCVG. Ensuring that these workshops continue to be held at regular intervals should be prioritized. The timing of these workshops should be such that early career researchers (ECRs) can attend at least one during their time as graduate students, and potentially a second one if they advance to post-graduate studies.
  - Whenever possible, funding should be sought such that ECRs and can be offered scholarships to attend workshops. Even partial travel support is significant in the early career stage. Also ensuring that participants from historically underprivileged countries and institutions are adequately represented. ,
  - As time during the main field workshops is often limited, the community should consider offering optional short intensive courses on a variety of subjects related to volcanic gas geochemistry before the main workshops begin. By arriving only a few days early, participants could thus obtain additional training on foundational topics of their choice.
- ***Provide training resources outside of the field workshops.***
  - Numerous training opportunities exist outside of the umbrella of the CCVG. Examples include the Vulcano International training Summer School of Geochemistry, the Commission on Volcanic Lakes (CVL) summer course and regular field workshop, the International Training School on Convective and Volcanic Clouds (CVC), and the annual International Course of the Center for the Study of Active Volcanoes (CSAV). Compiling and announcing such training opportunities in a central place, e.g. on social media and/or the CCVG website, would make it easier to for people to connect to the opportunities that they require to advance in their research pursuits.
  - Many developing countries with active volcanism have limited educational opportunities in Earth sciences, hindering the advancement of gas geochemistry and volcano monitoring. The CCVG should seek to connect students from historically underprivileged countries and communities with graduate opportunities in countries with established Earth Science programs.

- We recommend the CCVG community be polled to identify key areas in which members feel there is a need for additional training. Such training could then either be organized and conducted by CCVG itself, or external partners could be brought in to provide training (also see Section 4 of this document).
- Digital resources which could provide more effective training opportunities are currently underutilized by CCVG. This could be improved, for example by posting short training videos on the website. Producing such videos can require significant time and effort, but some of them might even be produced on-site during the field workshops. Screen-shot videos of someone performing data processing tasks are also a powerful tool for training on specialized software tools.
- The CCVG website might also be used to share software tools, along with documentation on their use, to the community. Oftentimes it may be preferrable to host the software on other platforms (e.g., GitHub). In such cases a link could be provided on the CCVG website.

➢ ***Ensure early career and DEIA representation and celebrate accomplishments.***

- Several recommendations for ensuring that ECRs and researchers from historically underprivileged groups have access to the resources and opportunities that CCVG has to offer are listed above. However, we fully realize that this is not a comprehensive list, and that any such list must develop over time, adapting to evolving funding opportunities and institutional support.
- Besides hands-on training on a variety of field-based methods, the workshops offer ECRs the opportunity to interact with the research community. This aspect is important and workshop activities that promote such interactions should continue to be prioritized. For example, ECR participants should always be given explicit opportunities to ask questions, present their own research, and take on tasks related to workshop and field work planning.
- We recommend that an ECR representative be elected to join the CCVG leadership panel. Not only can this person speak to the needs and desires of ECRs, but such a position also represents an opportunity to gain experience in leading a professional organization / research community. The community could either decide to dedicate an existing position to be filled by an ECR (thus keeping the team smaller) or add an ECR to the leadership team.
- The CCVG should consider how accomplishments from ECRs within our community could be better celebrated. For example, we might create an ECR award for outstanding accomplishments in the last 2 years, to be awarded at each field workshop. A small “awards” panel within CCVG should also compile a list of existing ECR (and other) awards (e.g., IAVCEI, IUGG, AGU, EGU) and consider nominating deserved CCVG members for these. This is not only a great help to those potentially receiving awards, but also increases the visibility of our community beyond the field of volcanic gas geochemistry.

- We also recognize the need for continued improvement on diversity, equity, inclusion, and accessibility (DEIA) topics. We urge the community to examine these topics further and ensure that DEIA continues to be considered in CCVG planning and programming. The community may elect to include a DEIA representative on the leadership team if this is not viewed as stigmatizing or a burden to the individual in this role. Alternatively, or additionally, a time slot dedicated specifically to DEIA topics could be scheduled as part of every future field workshop. Recognizing that simple solutions do not exist, we encourage polling of the CCVG community for additional ideas on how to affect meaningful change in this field.

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Section 4: Connecting with other research communities and the public

Connecting with other research communities will promote advances in volcanic gas research and monitoring. CCVG is well situated to develop links and foster communication with many complementary research communities and should actively seek to do so.

- ***Improve integration of satellite-based remote sensing of volcanic gases into CCVG activities.***
  - Satellite-based remote sensing of SO_2 emissions at volcanoes, particularly those in remote locations, can provide key information about the onset of volcanic unrest or an otherwise-undetected low-level eruption, and the ability to monitor emissions on a global scale. While some CCVG members utilize satellite data alongside ground- or airborne-based SO_2 emission measurements in their own research, to date the satellite remote sensing community has not been well integrated with CCVG activities, potentially missing opportunities to compare contemporaneous data sets and present the most current methods to the CCVG community.
  - We recommend that CCVG organizes with members of the satellite-based remote sensing community prior to future CCVG field workshops to arrange data acquisitions during the workshops when SO_2 emissions are expected to be measured via ground-based techniques. Plans to jointly analyze and compare the complementary data sets should be made, with a specific end-product in mind.
  - Adding a scientific session on satellite-based remote sensing of volcanic gases to one or more future CCVG workshops and inviting members of the community to present current research and methodological developments could foster coordination efforts. Given time constraints for scientific sessions at workshops, the CCVG community should polled in advance on whether such an addition is of broad interest.
  - We recommend that CCVG approaches the CVC to eventually coordinate joint activities like inviting CVC members to CCVG workshop or for online seminars such as the regular CCVG Broadcast.
- ***Find opportunities to integrate geophysical proxies of degassing into CCVG activities.***
  - Magmatic degassing and fluid migration, and subsequent interactions with shallow hydrothermal, ground, and surface water systems are often invoked to explain geophysical observations in volcanic systems, but processes linking gas geochemical/emissions and geophysical data sets are often ambiguous. CCVG field workshops and community experiments may provide valuable opportunities to collect and analyze contemporaneous geophysical and gas data sets to better elucidate these processes.

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- CCVG should consider including geophysical measurements in our field workshops and community experiments. This could be as simple as inviting geophysicists from the local host organization(s) to participate in measurements, data analysis, and discussion. In addition, geophysicists with interest in gas-related topics could be invited from the broader community to participate in these events.

- **Integrate current petrologic techniques into data collection and interpretation.**
  - As already mentioned in Section 1, petrologic measurements and models are of fundamental importance when attempting to derive information on subsurface volcanic processes from gas measurements. Therefore, close ties to the petrology community are of great importance.
  - Many CCVG members have expertise in petrology or already collaborate closely with petrologists, but CCVG should seek to introduce those that do not to at least the fundamental concepts of volatile behavior in magmas. This could occur by organizing or recommending short courses, recommending literature, and/or adapting tools for petrologic data interpretation as they become available.

- ***Investigate opportunities and challenges that machine learning may provide to the CCVG community.***
  - The rapid development of machine learning algorithms and strategies holds enormous promise for the field of volcanology, including advances in real-time monitoring and hazards and risk assessment. These algorithms can analyze large amounts of multi-parametric (e.g., seismic, gas emissions, ground deformation) data for purposes such as automated real-time data processing and analysis, signal detection and classification, estimation of the probability of an episode of unrest or eruption, and development of early warning systems, among many other applications. Challenges also exist with the use of machine learning in volcanology, such as incomplete or inconsistent data sets, which can limit the ability of algorithms to learn effectively.
  - Because the development of applications of machine learning to analysis of volcanic gas data sets is still in its infancy, we recommend polling the CCVG community on what it thinks the prospects and challenges of implementation are, and CCVG's potential role in this process over the next 5 to 10 years.
  - Input on machine learning implementation to volcanic gas data analysis could also be sought directly from data scientists. For example, a data scientist could be invited to a future CCVG workshop to solicit opinions on potential prospects, challenges, and paths forward.

- ***Find opportunities to collaborate more closely with IAVCEI's Commission on Volcanic Lakes (CVL).***
  - Natural synergies exist between CCVG and members of CVL studying degassing of volcanic lakes. As such, a number of researchers are members of both commissions and participate in field workshops hosted by CCVG and CVL.

- Forecast of often-hazardous, gas-driven (aka, phreatic) eruptions remains a major challenge in the field of volcanology. CVL, under the leadership of Bruce Christenson (GNS, New Zealand), is forming a formal multi-disciplinary working group on gas-driven eruptions. The goal of this working group is to coordinate research being conducted by scientists around the world working on various aspects of gas-driven eruptions to identify factors/behaviors common (and not common) to the volcanic environments in which these eruptions occur and improve ability to forecast these eruptions. CCVG members with expertise (or the interest to develop such expertise) in the study of gas-driven eruptions should take advantage of upcoming opportunities to participate as members of, and/or in activities sponsored by this working group.
- Meetings jointly sponsored by CCVG and CVL on research topics of common interest would provide the chance to leverage expertise and resources from both commissions. The first such joint meeting, took place in summer 2024 in Romania on the topic of diffuse degassing and can serve as a model for continued cooperative efforts.

➢ ***Foster technology developments***

- Recent technological advances have greatly improved our ability to make autonomous, real-time, high-rate measurements of volcanic gas fluxes and compositions. CCVG has an important role to play to foster continued advances.
- We recommend CCVG reach out to industry partners and academic groups working on novel gas measurement technologies to develop links between engineers/developers and potential end users. Engineering groups currently working on volcanic applications, as well as those new to these applications should be considered. For example, one or more engineers could be invited to CCVG workshops to demonstrate state-of-the-art equipment in the field and discuss current community needs.
- Many ongoing short- to long-term instrument deployments still require technological and procedural improvements to increase robustness and reliability. Input should be solicited from the CCVG community and documents that describe standard operating procedures for common types of deployments, problematic conditions, and potential solutions should be developed and made publicly available on the CCVG website.

➢ ***Sharing our science with the public***

- Most of our scientific endeavors are funded by the public, whether it be through grants from national or international science foundations, government agencies, or other science institutions (e.g., AGU, EGU, IAVCEI, UNESCO). The public will be more willing to fund our research if they are at least broadly familiar with the outcomes. We are lucky in that our work is generally viewed as exciting and interesting by many, and we should aim to keep it that way. As a community, we will do better if the public is interested in and aware of what we do.

- We understand that communication of our results and interpretations with the public can be a sensitive topic, especially during volcanic crises. It is not within the mandate of CCVG to force the communication of results to the public. However, CCVG can help with dissemination of information where appropriate, and a few general recommendations can be made.
- CCVG should encourage community members to participate in outreach and public communication of their research as they are able. Public communication is a skill that can be learned and (almost always) improved upon. Working with public relations and media experts, CCVG could provide tips for public communication, for example on the Commission's website.
- More and more information today is being shared through social media. As a community, we should explore whether we would benefit from a more organized social media presence. This could require significant effort on the part of one or more dedicated people to regularly reach out to community members asking for plain-language content on their recent work. For example, members could be asked for a short, plain language summary with a single photograph or plot each time they publish a paper, and these could be posted to social media (and the website, see below). For some examples of engaging volcano news articles, see, e.g. https://www.usgs.gov/observatories/hvo/news or https://www.ingv.it/en/press-and-urp/Press/News. Because such content requires significant work to create, the community should first be polled on what level of public engagement is appropriate and how/whether members are willing to contribute.
- The CCVG website could also be updated to include a news section where new content is posted regularly. As it stands, the only current information on the website is related to the field workshops.

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