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VICTOR—A new cyberinfrastructure for volcanology

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Abstract

We introduce the Volcanology Infrastructure for Computational Tools and Resources (VICTOR), a cloud-based cyberinfrastructure designed to modernize computational workflows and data access in volcanology. Built around a scalable JupyterHub environment, VICTOR provides users with an array of pre-installed modeling tools, remote sensing data access workflows, geochemical calculators, and the pyVICTOR utility library for geospatial and visualization tasks. The platform drives educational efforts through courses, modular teaching materials, and multilingual documentation. VICTOR promotes open science by making tools findable, accessible, interoperable, and reproducible (FAIR) and enables innovative workflows including multi-model intercomparisons and inversion schemes. We describe its architecture, current tool suite, community engagement activities, and plans for model coupling, machine learning integration, and expanded observatory support. VICTOR exemplifies a community-driven approach to infrastructure that empowers researchers, educators, and stakeholders in volcanic hazard science.

Keywords: Cyberinfrastructure; FAIR science; Cloud computing; Numerical models; Volcanology.

1 Introduction

The VICTOR project was launched in 2022 to address persistent challenges in volcanology—such as limited access to computational models, lack of standardization, and low interoperability—by creating a modern cyberinfrastructure aligned with community needs outlined in seminal National Academies of Sciences report "Volcanic Eruptions and Their Repose, Unrest, Precursors, and Timing" [ERUPT, NASEM 2017]. Since its launch, VICTOR has grown rapidly and now serves hundreds of users and makes tens of tools accessible in a user-friendly, open platform. This section reviews the motivation and preparation steps that led to the creation of VICTOR.

1.1 Motivation

New modeling and data analysis tools are required to answer many of the questions that stand open in volcano science, as depicted in the ERUPT report. Numerical models of volcanic processes, from within the crust through the magmatic plumbing system to the eruptive products, are essential for deciphering precursors and providing process-based forecasts [Sparks 2003; Segall 2013; Cassidy et al. 2018; Poland and Anderson 2020]. Importantly, forecasts of volcanic eruptions and their impacts require a careful orchestration of modeling and analysis of available data to quantify the uncertainty [Selva et al. 2012; Papale 2017; Tierz 2020].

Computational approaches play a critical role in forecasting and mitigating the impact of volcanic eruptions [Fink et al. 2023] and have been in use by communities for decades [e.g. Peck et al. 1977; Wohletz et al. 1984; Valentine and Wohletz 1989; Vignaux and Weir 1990] including early attempts at creating a shared data and computing resource [Palma et al. 2014]. Nevertheless, most tools and models remain rigid and monolithic because they are designed for a narrow set of research questions, are difficult to find and access, and are individually developed codes (i.e. "Hero codes") that are hard to link with other tools due to lack of standardization, documentation, and testing [Charbonnier et al. 2018] and the lack of computational and methodological frameworks for such integration. Recent years have shown the start of a shift towards better software and access standards, which we aim to lead and accelerate. Several modern packages for volcanology have been built with openness, scalability, and interoperability in mind, for example MAGEMin [Riel et al. 2022] and VESICal [Wieser et al. 2022b], and recently, Orange-Volcanoes [Musu et al. 2025]. There have also been efforts to adapt generic open-source fluid mechanics software packages to magma and volcano applications, for example, MagmaFOAM [Brogi et al. 2021] which is based on OpenFOAM [Jasak 2009]. In parallel, the community has seen efforts to make data more open and accessible. For instance, the EU Geo-INQUIRE project[†] works across the geosciences to supply and inform on data management, modeling, and more, working across a consortium of more than 50 European universities. Also in the EU, FUTUREVOLC [Larsen and Guðmundsson 2025] provides a data portal for Icelandic volcanoes, which itself is linked to the broader European Plate Observing System (EPOS) data portal [Cocco et al. 2016]. Another instance is the VOLCANBOX platform [Martínez-Sepúlveda et al. 2024], which provides hazard assessment and risk mitigation tools. These initiatives both demonstrate an evolution and modernization of the geoscience and volcanology. VICTOR takes these ideas further, having the community serve as the perpetual focus, allowing it to be a dynamic, "living" platform.

The ERUPT report discusses the present status of research and novel additions to the study of volcanic eruptions. The report states that "Communal cyberinfrastructure supports com-

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† https://www.geo-inquire.eu/

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prehensive databases, model development, benchmarking, and implementation [...] Community facilities, such as NSF-funded CIG (Computational Infrastructure for Geodynamics*), help improve the accessibility and user-friendliness of computational approaches by enhancing code efficiency and offering resources not available to individuals" [NASEM 2017, p. 80–81]. Access to high-performance computing resources, either local or remote, remains limited for many researchers and practitioners who rely on them. Today, the volcanology community lags behind other fields (such as oceanography and cryospheric sciences) in its utilization of emerging modern computational platforms and tools such as cloud computing and machine learning. Volcanology Infrastructure for Computational Tools and Resources, or `VICTOR`, is a novel, modern cyberinfrastructure platform aiming to standardize and centralize tools for the volcano science community and enable the community to rapidly assimilate new computational and data science methods.

1.2 Predecessor Initiatives

The challenge of expanding access of volcanologists to computational tools is not new. A previous notable effort towards this goal was Vhub [Palma et al. 2014]. Vhub was a science gateway for the volcanology community building on the HubZero platform [McLennan 2008]. The project had many successes and the platform attracted up to 2500 regular users of the many modeling tools and data sets it supported. The low barrier of entry to use complex computer models like `Tephra2` [Bonadonna et al. 2005] or `TITAN2D` [Patra et al. 2005] attracted researchers to the platform. Many innovative tools were developed and made available along with early work on using workflows based on the `Pegasus` tool [Deelman et al. 2015] for uncertainty quantification [Jones-Ivey et al. 2022]. However, over time, the limitations of the rigid design and its high engagement and commitment required from the tool developers undermined its success. Updates of the tools fell behind. The rigid protocols for such updates, the necessity for engagement of software engineers at HubZero, and the need for significant licensing fees all created barriers to sustained use. Nevertheless, its use over ten years made Vhub a pioneer in community cyberinfrastructure and set a motivating precedent for the community of utilizing open science tools. `VICTOR` is building on that legacy and the lessons learned, such as the importance of continued community engagement and platform flexibility and simplicity. Since Vhub's inception, the increase in processing speed, and ease of scalability using products like `Terraform` and `Kubernetes`, made the initial implementation and deployment of the hub much simpler. This also allows the team to more rapidly respond to improvements or changes to infrastructure.

1.3 Planning for `VICTOR`

Noting the decline in usage and usability of Vhub and the scientific needs expressed through community reports and activities, our team of collaborators held a virtual workshop in 2019 aimed at envisioning a new community infrastructure for volcanology to begin to solve these problems. The workshop included 65 participants from a range of institutions and career stages, including volcano observatory staff from the US, Colombia, Nicaragua, and Italy. Thematic presentations were given by representatives from community organizations such as the Modeling Collaboratory for Subduction (MCS) of SZ4D, the United States Geological Survey (USGS) and EarthCube. Presentations were given by representatives from related cyberinfrastructure efforts, including Vhub, the Computational Infrastructure for Geodynamics (CIG), the Community Surface Dynamics Modeling System (CSDMS), and Pangeo, which are organizations dedicated to strengthening both computational and communication infrastructure around geodynamics, surface dynamics, and geoscience overall, respectively. Formal presentations were followed by break-out sessions to gather specific community insight about the necessary components of a modern cyberinfrastructure for volcanology. The discussions yielded more than one hundred specific recommendations that were used to inform the development of the `VICTOR` pilot. Common priorities expressed in these suggestions included: (1) development of tools to couple numerical models, generation of example workflows (e.g. probabilistic forecasts),ß and establishment of community projects to tackle technical barriers, including high-performance computing (HPC) and GPUs; (2) verification, validation, benchmarking, standardization, and documentation of models; (3) continued development of outreach, teaching/workshops at a variety of levels, and inclusivity, including multilingual documentation and democratization of access via web interfaces to models. These recommendations motivated and guided the creation of `VICTOR`. Specifically, guidance on a community governance structure for `VICTOR` led us to gather an advisory committee for `VICTOR`. The conclusion drawn from the workshop was that the community was looking to `VICTOR` to be an inexpensive, sustainable, and flexible platform, capable of accelerating the pace of volcano science and hazard mitigation.

Motivated by these challenges, a small group gathered that included both veteran infrastructure leaders with experience from Vhub, and members new to the endeavor, and sought funding from the National Science Foundation. Upon initial funding, the group reached out to members of the community to establish a five-member advisory committee, which represents both academia and government, and has both US and international members. The advisory committee guides the leadership and technical teams in selection of tools, platform design and features, and outreach efforts. As the project matures, the advisory committee membership will rotate and draw from the wider volcanology community. After two years of service, the committee is currently (at the time of writing) being replaced. The process includes a wide-reaching invitation to the community to nominate or self-nominate representatives. We will emphasize the representation of different sections of the community, including early-career scientists, observatory and academic professionals, international/US-based, and stakeholders such as emergency managers. Additionally, during webinars, workshops, and conferences, we actively poll for interest and advertise opportunities for membership.

*`geodynamics.org`

The current advisory committee and the leadership team will select the new committee using criteria that will be shared.

1.4 An Open Science philosophy

A key driving motivation behind VICTOR is to promote the principles of open science within the volcanology community. The community has been gradually becoming more used to making samples and sensor data Findable, Accessible, Interoperable, and Reproducible (FAIR) [Wilkinson et al. 2016], thanks to the availability of public data repositories such as EarthChem [Lehnert et al. 2007], the IRIS Data Management Center [Ahern 2003], and Zenodo*, and requirements by funding agencies and journal publishers to share the data.

FAIR principles have been articulated for Research Software by a dedicated working group in 2022 [Barker et al. 2022], These FAIR4RS principles state that (1) Software, and its associated metadata, is easy for both humans and machines to find; (2) Software, and its metadata, is retrievable via standardized protocols; (3) Software interoperates with other software by exchanging data and/or metadata, and/or through interaction via application programming interfaces (APIs), described through standards, and (4) Software is both usable (can be executed) and reusable (can be understood, modified, built upon, or incorporated into other software). In the design and implementation of VICTOR, we followed these principles and promote them for volcanological software. By creating a centralized facility, VICTOR makes many tools much easier to find, and their installation and usage protocols are unified through well-documented common protocols. The following sections describe in more detail how the principles of FAIR4RS manifest in VICTOR.

Adopting these principles offers significant benefits for the entire research community, such as making the computational methods used in research transparent and allowing other researchers to replicate results. Additionally, it supports enhanced sustainability by encouraging better development and documentation practices resulting in more robust and long-lasting software. Equally important, it creates consolidation, allowing researchers to find and reuse existing software instead of developing redundant tools.

In particular, an open platform like VICTOR benefits an important sub-community of volcanology: volcano observatories, many of which are underfunded and/or understaffed. Observatories are tasked with the continuous monitoring of volcanoes and responding to volcanic crises, often many times at high frequency. These responsibilities often take priority over the tedious tasks of keeping up with model versions, new tools, and code dependencies. An open and accessible platform that provides observatory scientists a way to quickly learn and use new tools while keeping them informed and avoiding "black boxes" has a direct benefit to their operations and the stakeholders that rely on their insights.

2 System components and structure

VICTOR has several components that make up its overall resources, and their relationship is depicted in Figure 1. At the core is the computational hub, built as a cloud-based JupyterHub†, which provides a highly interactive and versatile platform (Section 2.1). The hub includes a large number of built-in tools for a range of volcanological applications, from simulations of eruptive processes (Section *2.3.1*), to tools for remote sensing data access and analysis (Section *2.3.2*), and tools for computational geochemistry and petrology (Section *2.3.3*). The VICTOR hub also contains a Python library, named pyVICTOR, which was specifically developed to support the VICTOR user community. pyVICTOR provides a simplified interface to some common user activities on the platform (Section 2.4) such as visualization of model outputs and obtaining elevation data. The tools are embedded in and accessed by a collection of workflows implemented as Jupyter Notebooks [Kluyver et al. 2016]. These notebooks promote interoperability, as a much wider community can now use tools hosted on VICTOR regardless of the environment they have access to at their own institution or their familiarity with the various program languages. Through the lens of these notebooks, models, libraries, and datasets can be accessed through the same system calls and used freely. We hope that this exposure will promote the sharing of tools developed by the community, including workflows used in publications, to enhance reproducibility.

Beyond the hub are a number of supporting resources. The VICTOR website (Section 2.6) serves as the location for users to learn about the project, its components, and upcoming events. The VICTOR documentation (Section 2.7) is a key piece of the platform, providing technical descriptions for the computational models and custom libraries. Finally, users can join a forum (Section 3.2) to support open discussions about the platform, the tools, and computational volcanology in general.

2.1 JupyterHub/VICTOR Hub

The VICTOR hub (located at hub.VICTORproject.org) is built upon the JupyterHub framework, a product of the Jupyter Project [Granger and Pérez 2021]. A JupyterHub is a multi-user platform that provides centralized access to a variety of interactive computing environments—including Jupyter notebooks, terminals, and other web-based interfaces—through a web browser.

VICTOR is run as a set of Linux machines on Amazon Web Services (AWS) servers. AWS was chosen for two reasons. Firstly, many scientific datasets relevant to volcanology, such as NASA's remote sensing data, are stored on AWS, and this proximity makes data transfers more efficient. Secondly, there are pathways in place for users to bring in computing credits that allow for long-term support of the hub. In addition to the AWS deployments, a fully configured installation file is available on the VICTOR GitHub, with instructions for users who wish to create a local instance of our machines on their HPC or local servers.

Through custom configured software images, VICTOR instances come pre-installed with over 100 libraries, packages, and utilities that are commonly used in computational geoscience. These range from broad mathematical libraries such

*https://zenodo.org/

†https://jupyterhub.readthedocs.io/en/stable/#

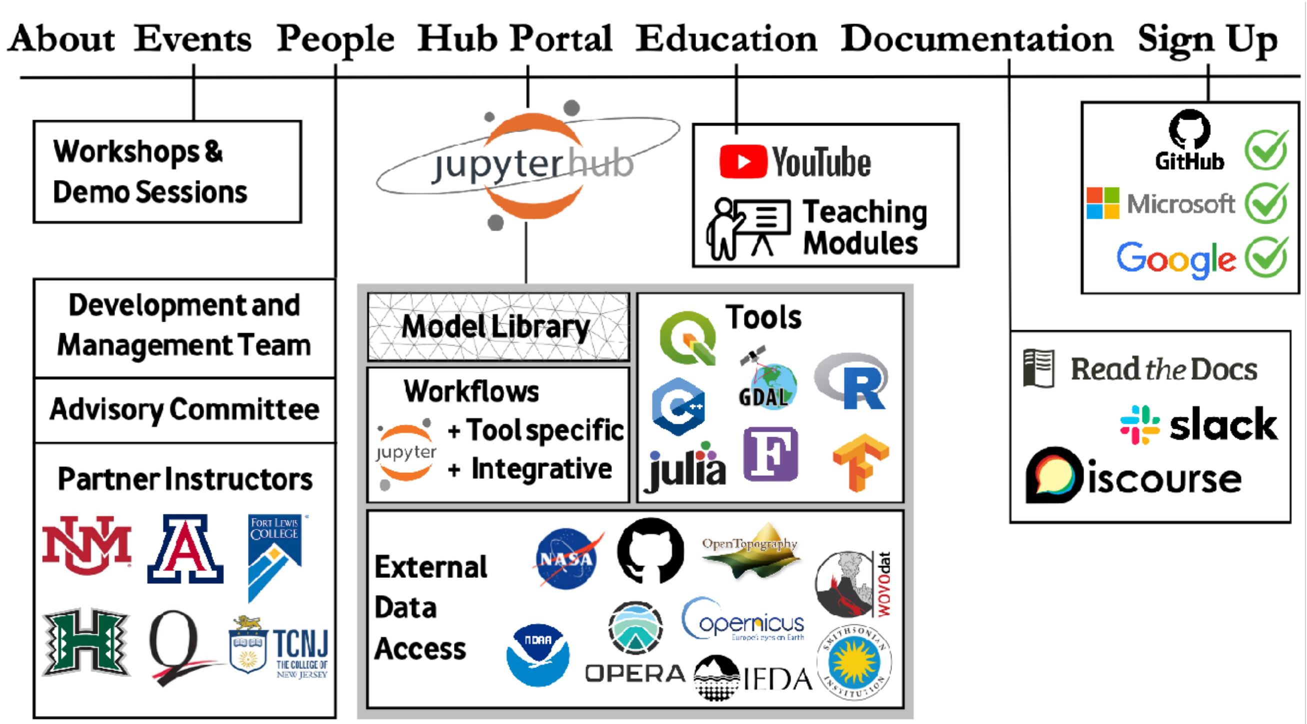

Figure 1: An overview of the components of the VICTOR platform and their relations. The top banner shows the tabs on the VICTORproject.org website, which leads to the various components, including platform registration, documentation, educational content, and the central JupyterHub. The website also includes information about events such as workshops and demo sessions, and details of project partners and participants.

as Numpy [Harris et al. 2020] or Pandas [The pandas development team 2020] to more specific tools such as EarthAccess and asf_search [Alaska Satellite Facility 2023] for retrieving InSAR data to calculate ground displacement. VICTOR also includes compilers for a variety of programming languages, like C, C++, and Fortran, which are often used in numerical modeling due to their high efficiency and scalability [Aruoba and Fernández-Villaverde 2014]. The VICTOR image can be customized to meet the needs of specific sub-communities, and we have been testing a heavier (larger image file, slower loading times) image that supports packages required for machine learning and artificial intelligence. The VICTOR image can, in principle, be deployed on any Linux machine, including locally at a user's desktop or cluster machines, but we have not tested this form of deployment yet.

Lastly, VICTOR provides a virtual graphical desktop environment, which supports and hosts a free and open-source mapping software (QGIS) and a general visualization tool (ParaView [Ahrens et al. 2005]) for complex data visualization. Figure 2 shows a screenshot of the virtual desktop, with QGIS and ParaView open and displaying visualization of model results.

Users take a few short steps to start interacting with VICTOR. After signing up and navigating to the site, the user is prompted to log in. After choosing their intended platform, another option appears. The hub provides scalable machines, ranging from lightweight options equivalent to a budget laptop to server-scale meant for large spatiotemporal simulations. For many of our educational activities provided through VICTOR, we recommend the choice of machine to match the computational complexity of the model or related data. The computing node will then spawn an environment for the user. Currently, the maximum size of a machine in terms of computational and memory requests are a 16-core, 128 gigabyte RAM machine. Various smaller machines are available with 2-8 cores, and 4-64 gigabytes of RAM. In terms of quantity of machines, this is theoretically limitless, but has not been tested beyond a few dozen users at once. They are first greeted by a launcher that provides quick-start options for creating Jupyter Notebooks, accessing a terminal, or editing a file in a text editor. Every user has a unique home directory that persists between sessions, which will be used to hold models and model outputs.

2.2 'Behind the scenes' infrastructure support

VICTOR and platforms like it owe much of their existence to the rise in cloud computing, and the overall accessibility of powerful remote machines. Currently, VICTOR uses computing resources on the AWS cloud. It is possible for VICTOR to work on any container-based cloud platform, but for reasons mentioned in Section 2.1 we have set our focus there. Much of the technical support of VICTOR is provided by the International Interactive Computing Collaboration*. They have organized the creation of many hubs for a variety of disciplines. The VICTOR team has developed a close relationship with 2i2c, working to push academic/research computing further. Another important part of our service is affordability.

*2i2c.org

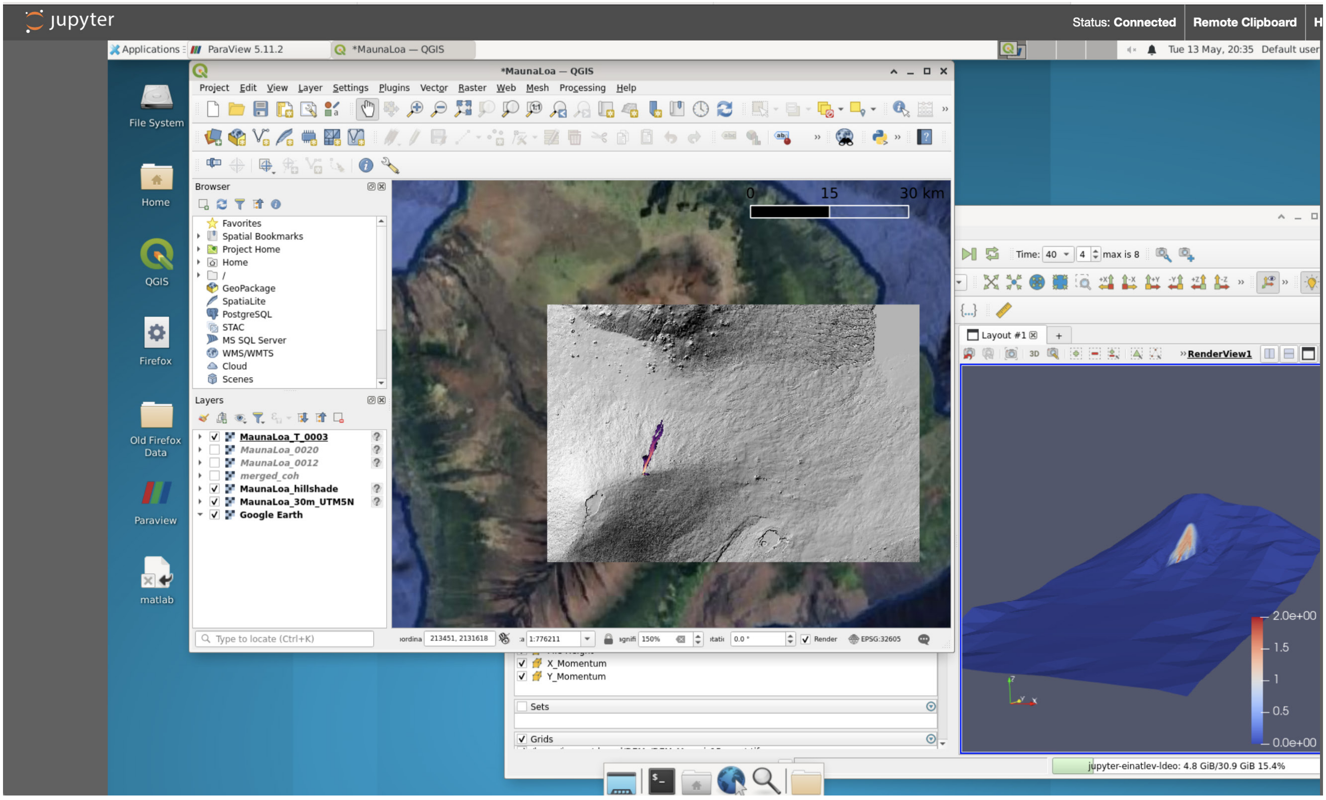

Figure 2: A demonstration of the virtual desktop. On the left, a QGIS project showing a Google Earth background, a digital elevation model (DEM) with hillshade, and a result of a lava flow emplacement simulation, for the Mauna Loa 2022 eruption on the island of Hawai'i. On the right, a three-dimensional ParaView rendering of the output of a TITAN2D model simulation of a pyroclastic density current (PDC) at Merapi. The bottom and side panels show shortcuts to other utilities available in the desktop environment, including a web browser, file navigator, MATLAB, and a terminal.

Cloudbank* has made it possible for NSF-supported projects to easily gain compute credits and apply them to one's project. This partnership has both allowed allocation of resources to other vital events such as workshops, but also continued to provide free access to all users of the platform. The VICTOR team will continue to work with existing and new organizations to provide simple and equitable access to cloud resources around volcanology.

2.3 An ever-growing collection of built-in tools

The centerpiece of the VICTOR hub is the model and tools library. Since the platform's inception, the VICTOR team has worked to collect new, promising simulation tools for volcanic phenomena. At this time, the platform includes more than 20 models relating to all aspects of a volcanic eruption. Additionally, nearly every model is completely open-source, allowing users to change code as they see fit to adapt existing structures to a novel approach. Due to their wide popularity, VICTOR does include a few tools [e.g. dMODELS [Battaglia et al. 2013] and Volcflow [Kelfoun and Vargas 2016]], that come as compiled executables built using the commercial software MATLAB. However, the code for these tools is still openly available on VICTOR. We also utilize the free MATLAB-substitute software Octave [Eaton 1997] to run some codes written as MATLAB source. VICTOR will always be committed to supporting open-source software, as it supports collaboration and innovation, and encourages community building.

The tools already included in VICTOR can be roughly divided into three categories: (1) Volcanic process simulations; (2) Petrological calculations; and (3) Remote sensing data access and processing. We briefly describe the tools in each category here, with complete descriptions available at the VICTOR documentation pages (see Section 2.7) and the respective publications that accompany each tool as provided by the developers.

The VICTOR team strives to expand the tool offerings on the platform to better reflect the needs of the community. To facilitate this, a 'tool suggestion/request' form is available on the VICTOR website. Responses can be submitted by either tool developers or interested users. This process enables the development team to evaluate and prioritize integration efforts that genuinely support the community.

2.3.1 *Eruption simulation tools*

Simulating volcanic and eruption processes is central to volcano science and to mitigating volcanic hazards. The volcanology community has shown in the past its readiness and support for running such simulations on a central computational platform. For instance, much of the use of Vhub was focused on eruption simulation tools, often by staff at volcano

* https://www.cloudbank.org

observatories around the world (e.g. usage information in Figure A1). Indeed, the ability to easily access and successfully run such tools with their appropriate documentations without having to spend time and efforts on code compilation, dependencies, updates and installation directly benefit users such as volcano observatories, especially those that are underfunded and/or understaffed. VICTOR expands on this capability by including a large set of simulation tools for a wide range of volcanic processes: magma ascent in the conduit; dispersal of ash clouds and gases; deposition of tephra; and inundation of landscapes by pyroclastic density currents (PDCs), lava flows, and lahars. Table 1 provides a list of the simulation tools of volcanic phenomena currently available on VICTOR, noting that the collection grows constantly. The variety of tools in Table 1 is evident, and covers most volcanic processes.

Each of these tools, regardless of the programming language it is built in, is accompanied by a Python Jupyter Notebook, which provides a clear and flexible workflow for running the tool. The overall structure of these tool-specific workflow notebooks begins with importing the necessary libraries, requesting input information and parameters from the user, setting up the input files for the tools, executing the tool, and visualizing the results. The source code for the base tool, as well as the notebook, are all available for the users to modify as needed by their use case. Notebooks are currently being developed mostly by the VICTOR software engineer, ideally in consultation with the tool developers. As more developers adopt the Python and Jupyter environments, it will be preferable that they, as the experts on their tools, provide workflows. When available, the notebooks are based on examples provided with the tool by the developers or the community.

2.3.2 *Streamlined access to remote sensing data*

Satellite remote sensing is a critical tool in monitoring volcanoes, especially those located far from infrastructure or population centers. Satellite monitoring of volcanoes utilizes a full band of wavelengths, including radar (used in SAR and InSAR), UV (in emission monitoring), visible (e.g. for terrain/vegetation change detection), and thermal infrared (in detecting thermal anomalies). The abundance of remote sensing data, the diversity of data types and collecting agencies and platforms, and the specialized jargon associated with it, make it challenging for new users to find, access, and analyze remote sensing data. VICTOR is aiming to help with this by providing simple, open-source workflow exemplars.

With the VICTOR platform operating in the cloud comes an added benefit: proximity to cloud-hosted and other online data repositories. For example, NASA stores many remote sensing datasets, both raw and high-level products, on AWS. Satellite remote sensing provides aerial coverage and repeating visits that are often not available with ground-based methods. However, not many in the community get practice in accessing and analyzing remote sensing data as part of their volcanology education [Donoho et al. 2009], perhaps due to lack of specific training.

VICTOR has begun to address this challenge by providing workflows that demonstrate access to volcano-relevant remote sensing products. Examples include notebooks that show queries to a NASA project which provides Observational Products for End-Users from Remote Sensing Analysis (OPERA). One such notebook demonstrates how a user can interactively select a region of interest and a time range, obtain a list of products available for the region and time, select the type of product (for example, a ground disturbance product, or DIST), and then perform on it preliminary analysis, such as segmentation of an area of disturbance, which may reflect a recent lava flow or PDC deposit. Figure 3 shows screen captures of the DIST workflow example. As additional higher-level product suites (e.g. surface displacement, vertical land motion, water extent), are released by the OPERA project, VICTOR will integrate them into workflows.

2.3.3 *Petrology and geochemistry calculators*

Volcanology extends far beyond eruption processes, to the entire magmatic system. Its study through petrology and geochemistry requires computational tools. The communities of petrology and geochemistry are transitioning from relying on Excel and similar platforms towards more open-source, interoperable, and reproducible tools [Barker et al. 2022]. For example, the ENKI portal* is a closely related effort to provide scientists with web-based access to thermodynamic computations based on the MELTS [Ghiorso et al. 2002] family of codes. VICTOR provides an ideal infrastructure for supporting this transition by making tools accessible and findable to users of all digital abilities. VICTOR already includes several tools for igneous geochemistry and petrology, listed in Table 2.

2.3.4 *Volcano statistics tools*

An emerging category of tools that is being added to VICTOR includes statistical tools related to volcanic hazard assessment. Currently on the platform are pyBET [Tonini et al. 2016] which provides a toolbox for building Bayesian event trees for eruption likelihood, and pyVOLCANS [Tierz et al. 2019], which matches volcanoes with analogues based on characteristics such as eruption style and frequency, tectonic settings, and geochemistry using an objective, structured and reproducible method.

2.4 The pyVICTOR library

Many of the workflows on VICTOR share common steps, such as visualization of flow model outputs and access to geospatial databases. Thus, VICTOR includes a Python library, pyVICTOR, whose functionality can primarily be split into two sections: Visualization and Connectivity/API Access. Additional helper functions are available, such as stitching outputs together for time series, or conversion between coordinate systems. We briefly describe these capabilities here. A typical user workflow will begin with the library's data access functions (e.g. obtaining a digital elevation model, or DEM), use the library's tool for geographic coordinate manipulation (e.g. from latitude/longitude to the Universal Transverse Mercator, or UTM, coordinate system, as needed by many simulation tools), and after running their tools of choice, end with the library's visualization functions (e.g. to plot a simulated flow's thickness

*http://enki-portal.org/

Table 1: Tools for the numerical modeling of magmatic and eruptive processes currently available on VICTOR. The available tools span a wide range of volcanic processes, from magma ascent in the conduit, through lava flows and lahars, to ash and gas dispersal. The table is sorted alphabetically by category.

Category	Model name	Description	References
Tephra dispersion and deposition	Ash3D	A 3-D Eulerian model to predict airborne volcanic ash concentration and tephra deposition during volcanic eruptions.	Schwaiger et al. [2012]
Tephra dispersion and deposition	Hazmap	Used for simulating sedimentation of volcanic particles from discrete point sources and to obtain the corresponding ground deposit or probability.	Macedonio et al. [2005]
Tephra dispersion and deposition	Hysplit	Used to compute air parcel trajectories to determine how far and in what direction a parcel of air and air pollutants, will travel	Stein et al. [2015].
Tephra dispersion and deposition	Plumeria_wd	A one-dimensional model for wind-driven volcanic plumes	Mastin [2014]
Tephra dispersion and deposition	Fall3D	A three-dimensional model for atmospheric passive transport and deposition of particles, aerosols, and radionuclides based on the advection-diffusion-sedimentation (ADS) equation.	Folch et al. [2009b]
Conduit Ascent	ConFort	A numerical model for flow in eruptive conduits during steady-state pyroclastic eruptions	Campagnola et al. [2016]
Degassing	Sulfur_X	A model of sulfur degassing during magma ascent	Ding et al. [2023]
Gas Dispersion	DISGAS	Eulerian model for passive dispersion of diluted gas and fine dust particles	Costa et al. [2005]
Gas dispersion	TWODEE	A shallow layer model for heavy gas dispersion	Folch et al. [2009a]
Lahars	LaharZ	An open-source modeling tool for various flow hazards, primarily lahars, based on the 'energy cone' concept. A Python tool with a GUI	Iverson et al. [1998], Schilling [2014], and Blair [2023]
Lava flow	IMEX_LAVA	Shallow water model for lava flow with vertical profiles of velocity and temperature and temperature-dependent viscosity.	Biagioli [2023]
Lava flow	Lava2D	A new two-dimensional depth-averaged finite volume model of lava flow propagation over natural terrain which accounts for bulk rheological changes due to thermorheological stratification	Hyman et al. [2022]
Lava flow	MOLASSES	A cellular automata fluid flow simulator to estimate the area inundated by lava flows.	Connor and Connor [2006]
Lava flow	MrLavaLoba	A stochastic gridless model for lava flow	de' Michieli Vitturi and Tarquini [2018]
Lava flow	pyFLOWGO	A 1-dimensional thermo-rheological model of lava flow in a channel	Chevrel et al. [2018]
PDC	TITAN2D	Simulating deposition of geophysical mass flows over DEM of natural terrain	Patra et al. [2005]
PDC	VolcFlow	A depth-average fluid flow model. Versions are available for lava flows (including temperature), debris flows, and pyroclastic density currents	Kelfoun [2017]
Tephra dispersion and deposition	TEPHRA2	A tephra dispersion simulation to estimate the mass of tephra that will accumulate at a site or over a region, given explosive eruption conditions.	Bonadonna et al. [2005]

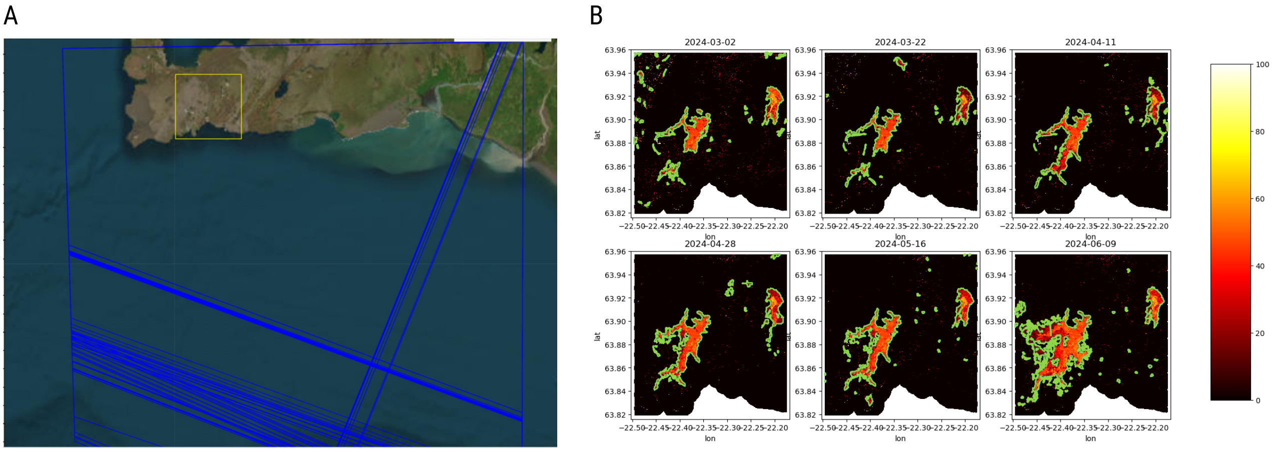

Figure 3: Steps from a workflow demonstrating access and analysis of remote sensing data. [A] Sentinel-1 granules (blue outlines) overlapping the user's chosen region (yellow square). [B] A timeseries showing surface disturbance (red-yellow) caused by lava flow eruption on the Reykjanes Peninsula in Iceland, with automatically-detected outlines (green) from which the extent of the flow over time can be calculated.

Table 2: Tools for petrology and geochemistry currently available through VICTOR.

Tool name	Aim	References
alphaMELTS	An interface for interacting with various models of thermodynamic equilibrium in silicate systems.	[Antoshechkina and Asimow 2016]
Perple_X	a collection of Fortran77 programs for calculating phase diagrams, manipulating thermodynamic data, and modeling equilibrium phase fractionation and reactive transport.	[Connolly 2005]
Thermobar	An Open-Source Python3 Tool for Thermobarometry and Hygrometry	Wieser et al. [2022a]
Sulfur_X	A model of sulfur degassing during magma ascent	Ding et al. [2023]
PyIRoglass	A Bayesian Monte Carlo-based Python algorithm for determining H_2O and CO_2 species concentrations in the transmission FTIR spectra of basaltic to andesitic glasses.	[Shi et al. 2024]

on top of hillshaded DEM). Full documentation of the library is available on the VICTOR Documentation site.

2.4.1 *Visualization*

Visualizing the results of simulation and data analysis tools is an essential step in many workflows, and helps to convey the results to users and to stakeholders more broadly. The tools available on VICTOR return outputs in a variety of formats and file types. Previously, users would have to struggle to write scripts, apply mapping tools, and reformat data. The pyVICTOR library aims to smooth this process by providing generic post-processing functions. For example, a user can call plot_flow with the file names of the topography and model output files, to plot the results of a variety of flow simulation codes. Building on the back of existing packages that elevate the use of rasters, it becomes much more practical to create complex figures, such as the one in Figure 6.

2.4.2 *Connectivity/API access*

Many datasets relevant to volcanology, such as those holding topographic and meteorologic data, are available on the internet, and are used by the tools available on VICTOR. Thus, efficient access to them is an important component of the platform. The pyVICTOR library provides concise and generic routines for accessing key data services, such as OpenTopography* and Copernicus† projects, taking advantage of the application programming interface (API) they provide. For example, using the function get_dem, a user can provide just the coordinate of a bounding box and the name of a topography dataset in a single line of code, and easily obtain a digital elevation model of their region of interest, ready to employ in a simulation. Additional options are given for file type and data provider for user flexibility. A separate function accesses ArcticDEM, which provides high resolution DEMs for high latitudes, including volcanically active regions in Iceland and

*https://opentopography.org/
†https://dataspace.copernicus.eu/

Alaska. Another important dataset the library provides access functions to is that of the Smithsonian Global Volcanism Program [Global Volcanism Program 2025], which holds names, locations, and other information on a large set of the world's volcanoes. Other databases relevant for volcanology, such as the petrological databases in EarthChem [Lehnert et al. 2007] or PetDB [Lehnert et al. 2000], provide APIs, and the team is planning to work with curators and users of these databases to develop example notebooks and workflows that access their data sets. We are also working with developers of databases that do not have APIs, such as the USGS FlowDat [Ogburn 2025], to develop demonstration workflows that will rely on downloading the database into VICTOR, and are anticipating developing workflows to access the API that will be provided by PDCD-DAT, a future iteration of this database [Brown et al. 2025]. Lastly, VICTOR does not offer any outward-facing APIs, prioritizing the ability to access data within the platform.

Functions often link together in useful ways. For example, a user can search for a volcano using the Smithsonian's Global Volcanism Program GVP database [Global Volcanism Program 2025], use the coordinates to set boundaries to download a DEM, and then visualize it, all within a few seconds. This flexibility is key to having pyVICTOR act as the adhesive for the platform. Most importantly, much of this content comes from community discussions and requests.

2.5 User management

The VICTOR onboarding process is designed to be minimal and straightforward. An interested user may navigate to any of the sites in the ecosystem, and will be directed to a simple Google form. Users are asked for their name, email, organization, and job/role, as well as their chosen method of signing up. VICTOR currently supports Github, Google (Gmail), and Microsoft (Outlook) accounts through CILogon. After the admin team verifies the user, the latter will be notified about their full access to the hub and VICTOR resources. Future advancements of the platform are planned to include user groups and variable user usage limits.

2.6 The VICTOR website

The VICTOR website* is a central access point to the many resources associated with the VICTOR platform. It provides easy-to-find links to the VICTOR hub, the platform documentation site and user communication channels, and the library of training and education content. In addition, the site provides information about the project, upcoming event such as workshops, conferences, and seminars/webinars, as well as information and recordings from past events. Lastly, the website includes a list of personnel, including both the primary leadership and development team and the advisory committee.

2.7 Documentation and usage guides

2.7.1 *Textual documentation*

VICTOR's documentation† provides long-form, written descriptions of the hub, its functionality, the models within it, and the pyVICTOR library. The Usage page instructs prospective users on how to register for the platform, common first steps, and how to run models or access the virtual desktop. It also includes contact information and quick links to citations for all models available on VICTOR. The Models page provides a list of all available tools and models, and for each tool, a brief description of it, its associated workflow, and the relevant reference(s). Finally, the pyVICTOR page provides complete descriptions of each function in the VICTOR library.

2.7.2 *Tool-specific tutorials and procedural guides*

To help onboard new users and support existing users as they learn how to utilize the tools available on VICTOR, we provide a collection of video tutorials. These include a general introduction to the platform, as well as tutorials for many individual tools. These tutorials show an on-screen walk-through of the relevant workflows and notebooks, accompanied by narration in either English or Spanish. Figure 4 shows a screenshot of the tutorial library page on VICTOR's YouTube channel‡ where videos are organized in playlists by theme.

2.8 Issue reporting and feature integration

For any user-facing platform, it is important to have methods for users to raise issues they may face when using the platform and guide its evolution. Issue reporting for VICTOR is done through GitHub, where the majority of our content, from the hub image itself, to our documentation and supported models, is held. Users can simply create an "issue", which describes problems they encounter or changes they want to implement.

3 Community Engagement

To fulfill VICTOR's mission as a community-serving facility, it is critical to actively promote its use by the community. We achieve this through community engagement activities of multiple types, described in this section.

3.1 Workshops and Seminars

One key activity for promoting community engagement has been workshops, which have ranged from short (1–3 hours) sessions at large and small geoscience conferences, to dedicated multi-day gatherings. Held by members of the VICTOR team, these sessions allow for more direct interaction, allowing us to demonstrate functionality that prospective users may not have known existed. To gauge the impact of these events on community awareness of the platform, we tracked the number of participants in all the events as well as noted any changes in the usage levels of the hub.

3.1.1 *Conference sessions*

A critical channel for introducing VICTOR to the community has been through short (1–3 hours) hands-on sessions held in conjunction with volcanology conferences. Thus far, sessions have been led by members of the VICTOR team at 2023 and 2025 scientific assemblies of the International Association for Volcanology and Chemistry of Earth Interior (IAVCEI), Cities on Volcanoes 2024, Cascades24, and Fall meetings and Chapman conferences of the American Geophysical Union

*www.VICTORproject.org
†docs.VICTORproject.org
‡https://www.youtube.com/@volcanocyber

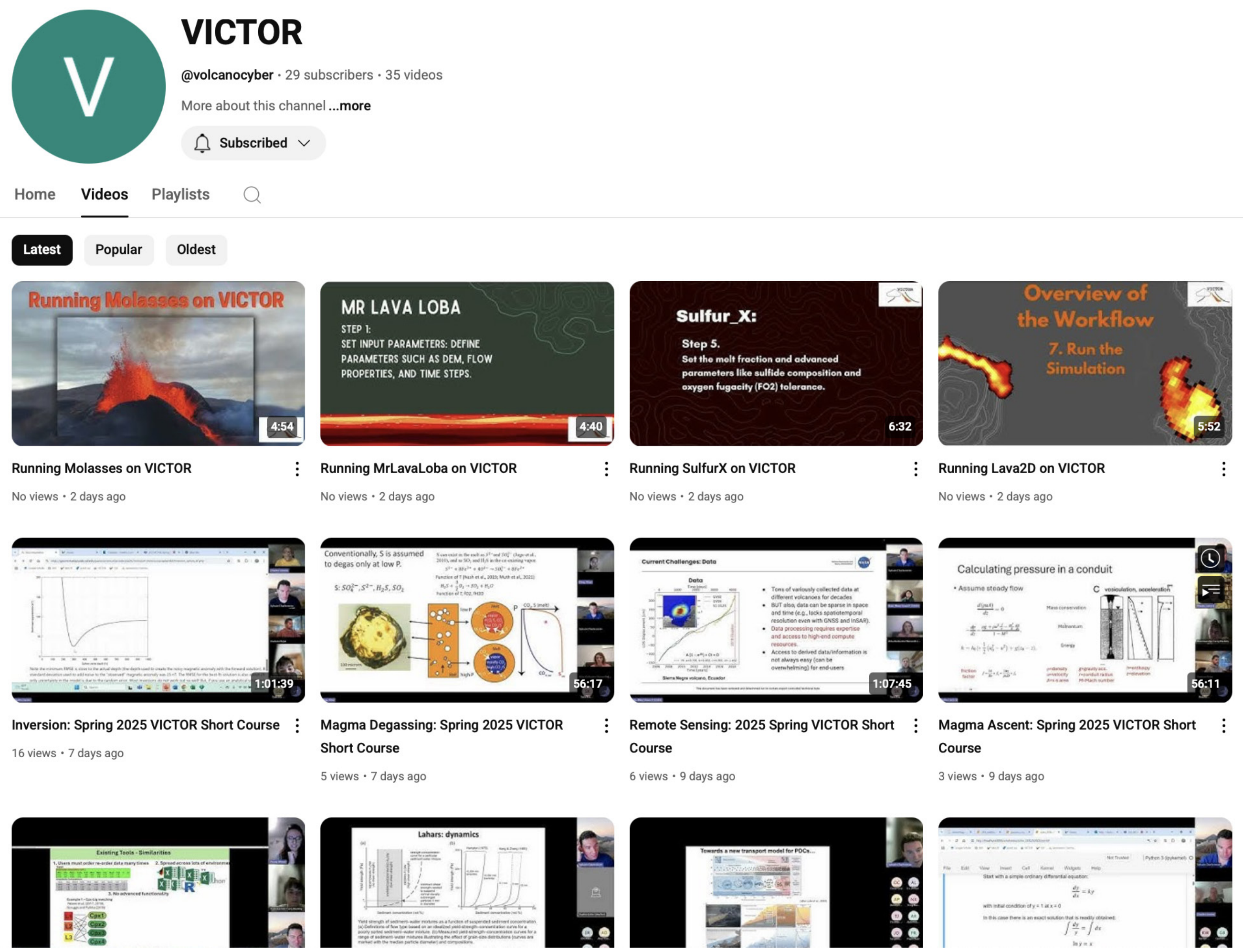

Figure 4: A screenshot of the VICTOR library of tutorial videos available on YouTube. The library includes recordings of sessions of the Computational Volcanology with VICTOR virtual course, tool-specific tutorials, and general introductory videos.

(AGU). These sessions consist of a brief introduction to the platform and its goals, followed by guided tutorials on the basic functionality of VICTOR and its models. Short participatory activities (formatted as in-room problem sets) act as knowledge checks and increase engagement. Session sizes generally range from one to two dozen people, with a variety of early and late career scientists, including both academics and observatory staff. Participants at larger conferences tended to skew younger (e.g. graduate students), and geological location often factors into observatory staff attendance. We find that these meetings and workshops are associated with jumps in the number of registered users and of compute hours used, showing their impact in increasing excitement around the project and its impact.

3.1.2 *Inaugural Workshop*

In August 2023, just over half a year after the VICTOR hub's creation, the first workshop to train researchers and encourage computational volcanology was held at Tufts University. Two dozen attendees from diverse geographic backgrounds, career stages, and technological literacy, participated in a three-day workshop where they were introduced to VICTOR and its capabilities, given practice problems to familiarize themselves, and subsequently broken into groups by discipline to experiment with new and unused models. By the end of the workshop, many participants had plans to use VICTOR resources in their current or future research. The team maintained a strong connection with many participants, integrating new models and tools into VICTOR to assist with research.

Through surveys both before and after the workshop, as well as discussions throughout, a clear picture emerged. Participants appreciated the platform and its potential, but were overwhelmed by the number of options and wanted more guidance. This confirmed two thoughts the team had. First, there was a necessity for training content, particularly for early career scientists and the less technologically literate. Thanks to a grant from NASA, we hired a professional education coordinator, and are actively in development of digital written and video content. Jupyter Notebooks remain universally popular, and will continue to function as technical walkthroughs. Second was that the inaugural workshop was targeted at more of a general audience. There was a need to support the "power users", the developers and highly technical contingent that would make VICTOR shine. These users would exemplify

VICTOR as a community-driven platform, and deserved specialized support.

3.1.3 *Developers summit*

In August 2024, 15 developers of volcanological software tools from 8 countries and 12 institutions gathered at the Lamont-Doherty Earth Observatory for three days of programming and technical talks. Attendees ranged from developers of new tools to researchers using models already on VICTOR to develop higher-level tools, such as machine learning workflows. The summit was structured to resemble a hackathon, prioritizing individual and group work over lectures. The two planned talks highlighted the importance of open source software and how to access and utilize high performance computing clusters. In addition, best practices in software engineering, such as proper version control, was taught to participants. The workshop concluded with three new models already adapted to and deployed on VICTOR and follow-up steps set for the tools yet to be finished. The developers summit provided technical leaders in computational volcanology an opportunity to share ideas and code, and develop professionally.

3.2 Forum and newsletter

As part of a commitment to transparency across the community, VICTOR encourages and facilitates open communications both among users and between users and developers through the Discourse forum platform. Various sections are provided, such as one specifically for the VICTOR hub's structure, and another focused on model implementation.

Another communication channel is an email newsletter, sent to all registered users every other month. The newsletter provides news, updates and highlights to the users community. Updates are also distributed through social media and sent to the widely-used volcano email listserv.

4 VICTOR FOR EDUCATION

Thus far, VICTOR has been discussed primarily in the context of research and observatory operations. Another major strength of this cloud-based platform is that it serves as an ideal education resource. Since its launch, VICTOR has been used in a variety of fashions to educate and train students and learners of all levels. We demonstrate this through our experience in using VICTOR in virtual multi-week courses and the development and use of VICTOR-based individual teaching modules.

4.1 Online courses

For the past three years, the VICTOR team at the University of South Florida have conducted an annual spring semester virtual class in Computational Volcanology which relied on VICTOR as a computation platform for demonstrations and hands-on activities for students. Participants were primarily graduate students and observatory staff from around the world. Topics included fundamentals, such as an introduction to Python and Jupyter Notebooks, differential equations, satellite remote sensing, and inversion, and more focused volcanological topics such as lava flows, PDCs, lahars, magma evolution, and volatile diffusion. To promote engagement and participation, the students were given in-class exercises that utilized built-in workflows on VICTOR, and shared their results through online sites such as Padlet or Google Slides. Classes also included presentations by guest speakers who covered topics and software tools they developed. At the end of each semester, interested students presented their own research, gaining an opportunity for brainstorming and exposure for early career scientists.

During the semester, participants engaged with each other and with the instruction team through the VICTOR Discourse forum, so questions and answers were available to everyone. After the conclusion of each course, students provided feedback through a Google form regarding the content, the user experience and the performance of the platform, leading to iterations and improvements to both the platform and the course structure itself. Lastly, since the classes were conducted virtually, lessons were easy to record, and the full catalog of lessons is available on the VICTOR YouTube channel. This allows other interested individuals to review the material at their own pace in the future.

4.2 Modular VICTOR-based teaching materials

The accessibility and modularity of VICTOR lends itself to its adoption by educators who wish to use it for a part of a course, to demonstrate a concept or a technique. The built-in resources save the major burden of installing software and handling dependencies on individual students' computers, while still allowing students to experience the computational process and become familiar with modeling and coding.

Over the past year, the VICTOR team has worked with several professors at a range of institutions to develop and implement VICTOR-centered learning materials for their students. The initial discussions involved identifying learning objectives and establishing learners prior knowledge and motivations. Following this planning effort, the team developed a library of teaching modules, each focused on a single topic (e.g. lava flows, tephra dispersal). Modules are comprised by video tutorials, lecture slides, and lab assignments that apply the learned content to real-world examples and enabled learners to work hands-on with VICTOR workflows. Students shared their results through the Padlet online platform, which allowed students to see results from different institutions, creating a larger sense of community. An example of a successful lab assignment developed for Fort Lewis College students during the Fall 2024 semester applied hazard modeling using Tephra2 on VICTOR in the context of infrastructure resilience, as the majority of students were engineering majors. The assignment asked students to use Tephra2 on VICTOR to determine if the roofs of buildings in Bend, OR would collapse in the hypothetical event of an eruption at South Sister volcano. Students chose the area of interest themselves using Google Maps, and were asked to modify input parameters, examine the visual model outputs, and make both quantitiative and qualitative assessments. A module for an introductory level class at the University of Hawai'i simulated lava flows for an eruption at Mauna Loa, similar to the one in winter 2022 which many of them had experienced. Students were asked to vary the eruption volume and assess the volume and timing it would take

Figure 5: Photos from VICTOR workshops and events. [A] Participants in a VICTOR workshop during the Cascades24 conference in Bend, OR, summer 2024. Participants ranged from undergraduate students and local residents to senior experts. They used example workflows that simulated tephra dispersal, lahars, and volatile exsolution. [B] Participants at the 2024 VICTOR Developers Summit, who brought new tools and capabilities to the platform.

for the lava to reach a key road. These examples demonstrate how VICTOR facilitates learning about volcanic processes but also provides an appreciation of modeling, model uncertainty, and computation.

To evaluate the impact of the educational content, students and instructors were asked to fill out surveys (Google form) after the modules were used. Survey questions referred to the overall clarity and interest in the activity, to technical aspects, and whether the activity impacted the participant's view of modeling or their understanding of the volcanic process being addressed. The repeated use of questionnaires with VICTOR educational content is proof of our commitment to listening to the scientific community. Additionally, feedback from a wide range of learners allows the VICTOR team to shape a platform that is welcoming to everyone.

4.2.1 *Digital Content*

Through videos and documentation, VICTOR provides a variety of learning materials for prospective users. Much of this is available in English and Spanish to improve accessibility to volcanology communities across the world. Through the VICTOR YouTube channel, users can access tutorials of tools and models available on the platform, as well as highlights from the aforementioned short courses. The documentation provides a more technical description of the tools, as well as the relevant references and links to manuals and articles. Through this combination of materials, users at any level will be able to take their first steps in utilizing VICTOR resources. In order to understand the context in which all these tools may be used, researchers may require additional hands-on content.

5 Catalyzing innovation through a unified platform

The VICTOR platform exemplifies the idea that the whole is greater than the sum of its parts. It is not just a channel to run individual tools, but a comprehensive environment that brings significant added value by unifying the access and execution of tools.

5.1 Value added example: multi-model assessment

A key strength of VICTOR is that it goes beyond making individual models or tools more accessible. By placing many tools on the same platform and wrapping them in common interfaces (i.e. the Jupyter Notebooks), VICTOR makes it easy to combine individual tools into joint workflows. This is a significant advance over the VHub platform, which only allowed rigid predefined workflows set by the developers.

One such example is a series of workflows we developed to streamline the comparison and assessment of models with similar goals, for example lava flow emplacement. Lava flow emplacement models, which simulate the movement and emplacement of lava at a given topography and eruption conditions, are important tools in short and long term volcanic hazard assessment. It is paramount that flow models are assessed through benchmarking and model inter-comparison [Cordonnier et al. 2016; Dietterich et al. 2017]. Such comparisons allow scientists to validate and improve models, leading to better hazard assessment and mitigation strategies. VICTOR contains a set of notebooks that compare the performance of four lava flow models—MOLASSES, MrLavaLoba, IMEX_LAVA, and Lava2D—on idealized benchmarks and for a natural test case. Adding other lava flow models as they become available on the platform to this comparison is straightforward. A similar workflow suite for assessing and comparing models of pyroclastic density currents is available too. Figure 6 shows the output from a model comparison workflow that used the topography and vent information for the 2022 eruption of Mauna Loa volcano. The models shared the topography, vent location, and overall eruption volume/flux. The results highlight the different flow footprints predicted by the four models, stemming from the differences in their mathematical and physical approaches. We note that we did not optimize the input parameters for each model to yield a best fit to the observations or to the other models, as this is only for demonstration. Other information about each model, such as the computational cost of the calculation or the complexity of the inputs, is readily clear to the users who execute the workflow. We are actively adding features to this workflow, for example a quantitative assessment of the fit of model outputs to observations.

To run a model comparison, users provide inputs that are common to all the models, such as eruption flux, vent location, and topography (a DEM). They then provide inputs that are specific to each model (e.g. lava physical properties for physics-based models or calibration parameters for stochastic models). The models are run in sequence, and a simple visualization is displayed after each model is finished.

Once models have finished, the user can assess their performance qualitatively by visually comparing the models to each other or to an expected result (observed flow footprint, or an analytical solution). A quantitative assessment of the level of agreement between the models predictions with each other or with an expected results (a natural flow's footprint or an analytical solution) is currently calculated using the the Jaccard index. A more comprehensive quantitative assessment, using the `Best-fit Assessment for Numerical Models` (BAM) tool [Garin et al. 2024], is currently in development. In the future, the model comparison workflow will be integrated with, for instance, the tool mentioned above for flow detection from remote sensing observations, to offer a complete sequence, from observations to model assessment and uncertainty quantification.

5.2 Enhancing awareness of appropriate use of software

The `VICTOR` ecosystem is structured to provide new users a gentle introduction to programming and the hub overall. Much of the educational content pairs with an associated model or concept to guide individuals towards a more complete understanding of said tool. The team has begun creating resources for larger/more complex software tools, such as the benchmarking code mentioned above. We aim to continue making this content as `VICTOR` evolves in new ways. However, due to the size of the team and overall time commitment, we will turn to the community to supplement our work. Already, colleagues across the world have combined their existing teaching resources with our content. `VICTOR` thrives most when structured as a collaboration between its creators and the wider community.

This is closely related to the importance of multidisciplinarity across the platform. Computational/quantitative volcanology is far from a monolith, encompassing from deep in the mantle to the atmosphere, and from microscopic particulate to flows in the cubic kilometers. Through this breadth of knowledge, new conversations can be started between scientists, propelling research in a unique and collaborative way.

Oversimplification is not expected to be a concern in the long term. Though `VICTOR` and its workflows can serve as a high-level introduction to many of these models, but our commitment to open-source code and collaborative science encourages users to inspect the program more closely, while also providing references and related research/papers to expand the understanding of such processes.

6 On-going and future directions

As `VICTOR` transitions from infancy to a more robust and popular platform, our eyes are focused on novel research and development directions that can be added. An active direction we are pursuing is to provide tools and workflows for inversion of observational data for eruption conditions or other important parameters. For example, `VICTOR` hosts an example workflow that inverts tephra deposit measurements (layer thickness and extent) to assess eruption parameters, including plume height, flux, and grain size distribution. It follows the work presented by Yang et al. [2021] that used the Metropolis-Hastings algorithm, and we are adding to it new inversion algorithms, such as simulated annealing and ensemble Kalman filter. This workflow will provide users a streamlined way to find best fitting parameters and the uncertainty associated with the process.

With such a wide range of volcanic processes represented by models already available on `VICTOR`, a next logical step would be to couple models of different subsystems to each other. For example, it is now much easier to create a workflow where the output from a conduit ascent model such as `CONFORT` is the input to a plume model such as `Plumeria_wd`, which then feeds into gas or ash dispersal models such as `DISGAS` or `Ash3D`. This kind of model coupling has been difficult to achieve, with each individual tool requiring users to find, install, and become familiar with its interface: all steps that `VICTOR` and its pre-installed workflows either eliminate or greatly simplify. Figure 8 shows this vision of coupled models, which can open the door for more quantitative forecasts and assessments of uncertainty.

Another direction where `VICTOR` can play a key role is to facilitate the transition of volcanology into the age of machine learning and artificial intelligence (ML/AI). The `VICTOR` image can include packages required for ML/AI, such as `FlowTorch`. A natural area of potential development would bring the power of machine learning to reduce data of a variety of types into the study of volcanoes, which are routinely monitored by a variety of techniques and sensor types [Carniel and Guzman 2021]. ML technique are already being applied to monitoring data of various types, from seismic [Thelen et al. 2022] to cameras [Witsil and Johnson 2020]. In addition, applications of ML in volcanology are already extending beyond monitoring, to "static" datasets such as petrology and geochemistry [e.g. Petrelli et al. 2020] and volcanic stratigraphy [Jutzeler et al. 2024]. As the community develops tool in these directions, `VICTOR` will be ready to host them and provide an open, accessible, and FAIR environment for applying these methods and training a new generation on their usage.

6.1 Evaluating the impact of `VICTOR`

During the first phase of `VICTOR`, we have been evaluating its impact in multiple ways. The most direct and quantitative measure of reach has been tracking the level of usage of the platform and the number of registered users. These have increased steadily, with jumps often associated with community events and classroom usage (Figure 9).

More qualitative assessments we performed was through surveys and conversations that asked participants about their

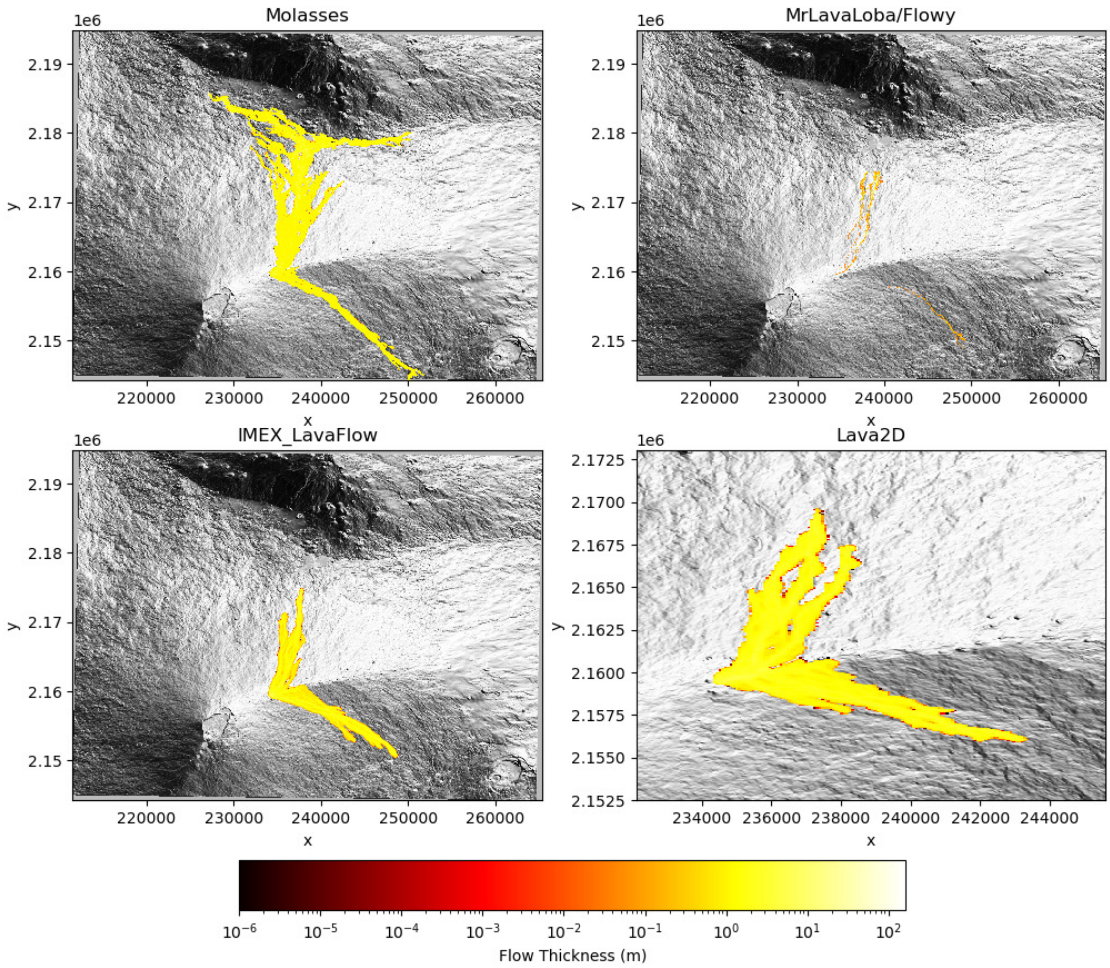

Figure 6: An example output from the lava flow model inter-comparison tool available on VICTOR. Within a single Jupyter Notebook, users can set common parameters (e.g. DEM, vent location, volume and effusion rate), run multiple lava flow models, and examine the differences in model predictions both visually and quantitatively. Being compared here are MOLASSES, MrLavaLoba, IMEX_Lava and Lava2d. All were provided with the DEM for Mauna Loa, the location of fissure 3, the main source of the winter 2022 eruption, and approximately the same eruption volume and/or eruption flux.

experience with VICTOR and about its influence on their sense of comfort proficiency with modeling, coding, and accessing data. Going forward, we plan to deploy more assessment instruments, inspired, for example, by those used to assess the Seismology Skill Building Workshop (SSBW) [Hubenthal and Brudzinski 2025].

6.2 Sustainability of VICTOR

Building and sustaining VICTOR requires ongoing investment. Core expenses include personnel (research software engineers, an education coordinator, a quality assurance team, and PIs), cloud-computing costs, hub management services provided by 2i2c, and participant support for workshops and training events. As the project matures, ensuring financial stability and long-term sustainability becomes increasingly important. To date, VICTOR has been supported by NSF and NASA, but future growth will likely require additional and more diverse sources of funding. In addition to federal agencies, philanthropic foundations and international organizations with interests in science, education, or disaster mitigation represent a promising avenue for support.

One potential pathway sometimes taken by public data repositories is introducing service tiers. Free accounts will always be available, though over time they may be allocated to less powerful (and less costly) machines. Users who require more resources could purchase “Pro” accounts, which would provide greater computational capacity, enhanced technical support, and additional features. Universities might subscribe at the course or department level, enabling broad educational access, while observatories could opt for Pro accounts with resources and support tailored to their volcanoes and regions. Private entities could also be offered fee-based access. Another option is a “bring your own” model, where teams with existing cloud allocations (e.g. through grants) apply them directly within VICTOR. We have built sustainability into VICTOR from the start. The platform relies heavily on open-source and decentralized tools—such as GitHub—that minimize ongoing maintenance costs while ensuring transparency and community ownership. Just as importantly, the VICTOR community

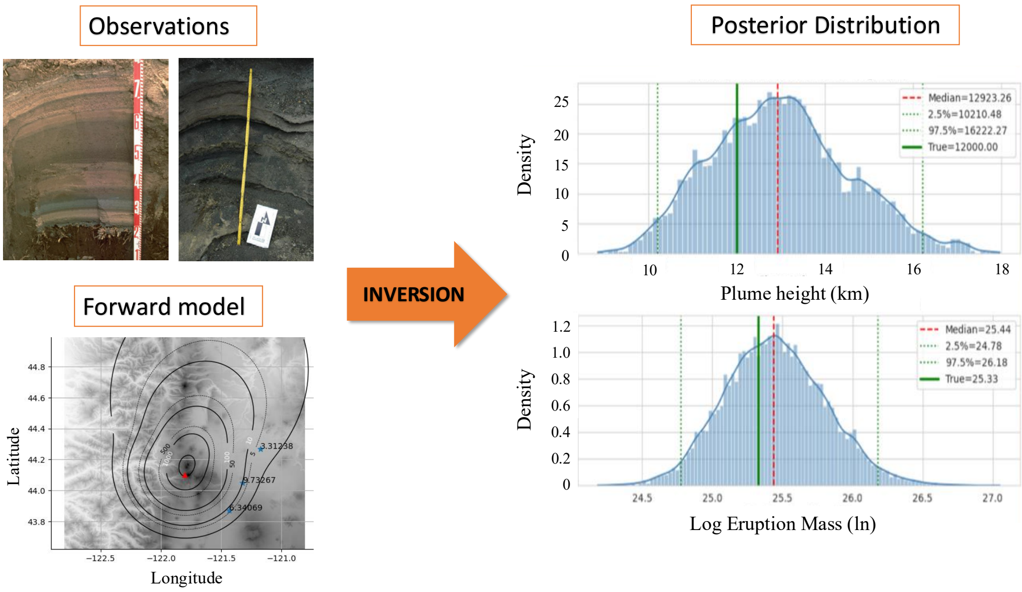

Figure 7: An example of an inversion workflow available on VICTOR, which takes observations of tephra deposits (top left), and uses the Tephra2 forward model (sample output on bottom left) through the Metropolis-Hastings inversion algorithm to estimate and give a posterior probability distribution of eruption parameters such as plume height (top right) and eruption mass (bottom right). Observations pictures are by Andy Lockhart (left) and Lis Gallant (right), Smithsonian Global Volcanism Program images 01683 and 12795.

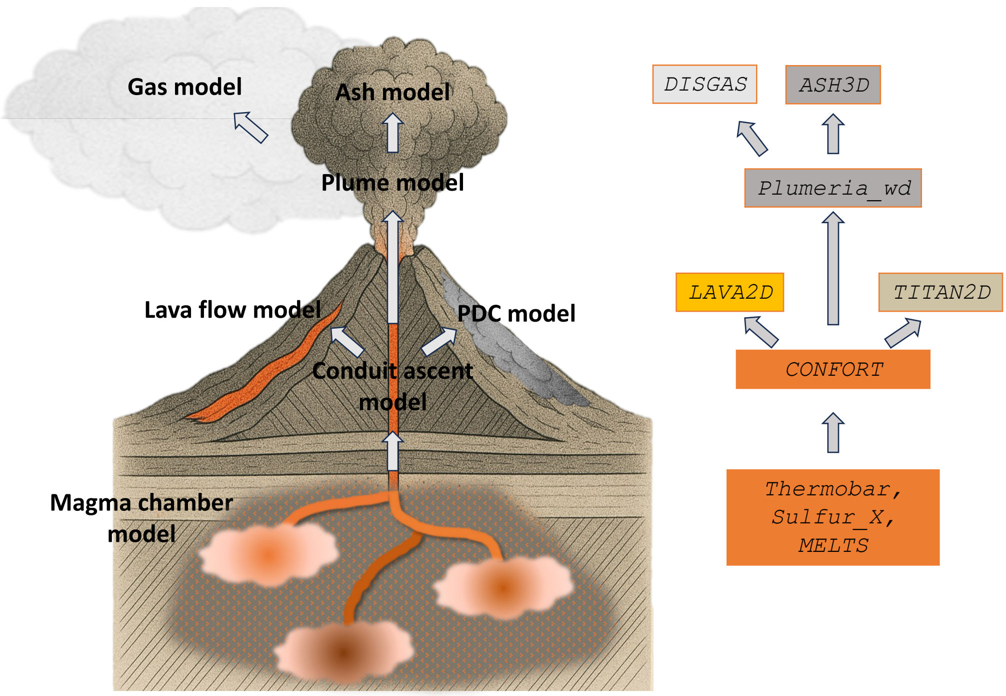

Figure 8: A vision for future workflows where models of individual processes in the magmatic and volcanic system could be coupled to each other thanks to all being available through VICTOR and their shared interfaces through Jupyter Notebooks.

is already contributing to its growth and upkeep. In the spirit of open-source projects, users are giving back by improving tools, sharing knowledge, and supporting one another, helping ensure that VICTOR remains a durable resource for research and education.

7 Conclusions

VICTOR represents a transformative step toward modernizing the computational landscape of volcanology. By integrating a diverse suite of modeling tools, data access pipelines, and educational resources into a unified, cloud-based platform, VICTOR lowers technical barriers and fosters open, re-

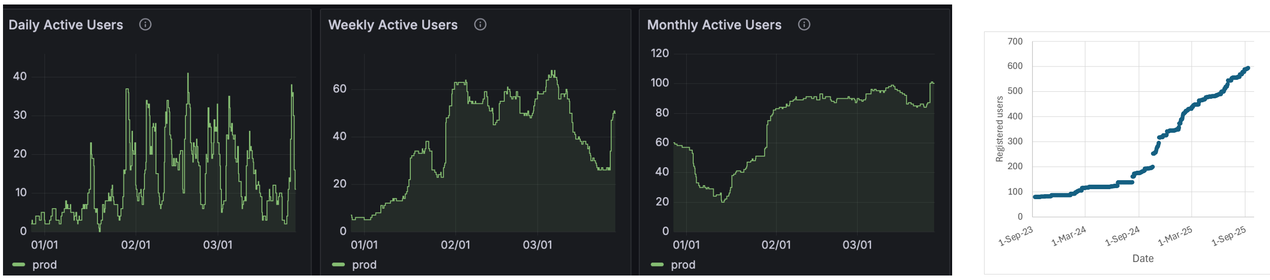

Figure 9: Plots showing the changes over time in the numbers of daily, weekly, and monthly active users on VICTOR year-to-date in 2025. The rightmost panel shows the number of registered users.

producible science. Its design emphasizes accessibility, interoperability, and user-driven development, enabling a wide range of users—from students to observatory scientists—to engage with state-of-the-art computational workflows.

The platform's active collaboration with the volcanology community, combined with its flexible infrastructure, ensures that it evolves in response to emerging research needs and technologies. Through workshops, courses, and modular teaching materials, VICTOR also cultivates computational literacy and supports the next generation of volcanologists.

Looking ahead, VICTOR is poised to enable increasingly sophisticated workflows, including model coupling, inversion, and integration with machine learning methods. As adoption grows, VICTOR aims to continue evolving to meet the future needs of volcano science, to serve not simply as a repository of tools, but as a catalyst for scientific innovation and a model for cyberinfrastructure development in other Earth science domains.

Author Contributions

Einat Lev: Project leadership, funding acquisition, software, writing—original draft, visualization; **Sam Krasnoff:** methodology, software, validation, data curation, writing—original draft, visualization, project administration; **Sylvain Charbonnier:** Funding acquisition, project leadership, writing—review & editing, project administration; **Charles Connor:** Funding acquisition, project leadership, writing—review & editing; **Abani Patra:** Funding acquisition, project leadership, writing—review & editing; **Amelia Mullins:** writing—review & editing, visualization.

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Data Availability

VICTOR resources are available on the platform's GitHub repository, located at github.com/volcanocyber, as well as within within the platform itself, which is accessible through directly through hub.victorproject.org, or through the project's main page: victorproject.org. Links to the primary developer repositories are provided when available. Model details and attributions are available at docs.victorproject.org. The VICTOR team works to maximize collaboration and open access within and across disciplines.

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References

Ahern, T. K. (2003). "The FDSN and IRIS Data Management System: Providing easy access to terabytes of information". *International Geophysics*. Volume 81. Elsevier, pages 1645–1655. DOI: 10.1016/s0074-6142(03)80298-x.

Ahrens, J., B. Geveci, and C. Law (2005). *ParaView: An End-User Tool for Large Data Visualization*. ISBN 978-0123875822. DOI: 10.1016/b978-012387582-2/50038-1.

Alaska Satellite Facility (2023). *ASF Search API - Python Package for Searching and Downloading SAR Data*. Version 3.3.0. DOI: 10.1017/9781108591942.002.

Antoshechkina, P. and P. Asimow (2016). *AlphaMELTS software manual.*

Aruoba, S. B. and J. Fernández-Villaverde (2014). *A comparison of programming languages in economics*. Technical report. Cambridge, MA: National Bureau of Economic Research. DOI: 10.3386/w20263.

Barker, M., N. P. C. Hong, D. S. Katz, A.-L. Lamprecht, C. Martinez-Ortiz, F. Psomopoulos, J. Harrow, M. G. Leyla Jael Castro, P. A. Martinez, and T. Honeyman (2022). "Introducing the FAIR Principles for research software." *Scientific Data* 9. DOI: 10.1038/s41597-022-01710-x.

Battaglia, M., P. F. Cervelli, and J. R. Murray (2013). "dMODELS: A MATLAB software package for modeling crustal deformation near active faults and volcanic centers". *Journal of Volcanology and Geothermal Research* 254, pages 1–4. DOI: 10.1016/j.jvolgeores.2012.12.018.

Biagioli, E. (2023). *BiElisa/IMEX_LavaFlow: IMEX_LavaFlow*. Version v1.0. DOI: 10.5281/zenodo.7900930.

Blair, K. (2023). "LaharZ". *GitHub*. [GitHub repository].

Bonadonna, C., C. B. Connor, B. Houghton, L. Connor, M. Byrne, A. Laing, and T. Hincks (2005). "Probabilistic modeling of tephra dispersal: Hazard assessment of a multiphase rhyolitic eruption at Tarawera, New Zealand". *Journal of Geophysical Research: Solid Earth* 110(B3). DOI: 10.1029/2003jb002896.

Brogi, F., S. Colucci, J. Matrone, C. P. Montagna, M. De'Michieli Vitturi, and P. Papale (2021). "MagmaFOAM-1.0: a modular framework for the simulation of magmatic systems". *Geoscientific Model Development Discussions* 2021, pages 1–34. DOI: 10.37473/fic/10.5194/gmd-2021-224.

Brown, J., R. Williams, S. Ogburn, B. Brand, E. Breard, S. J. Charbonnier, N. J. Dowey, J. Dufek, M. Jellinek, U. Kueppers, et al. (2025). "PDCD-DAT–A global database of pyroclastic density current deposit field data". *EarthArXiv*. DOI: 10.31223/x5rf13. [Preprint].

Campagnola, S., C. Romano, L. Mastin, and A. Vona (2016). "Confort 15 model of conduit dynamics: applications to Pantelleria Green Tuff and Etna 122 BC eruptions". *Contributions to Mineralogy and Petrology* 171, pages 1–25. DOI: 10.1007/s00410-016-1265-5.

Carniel, R. and S. R. Guzman (2021). "Machine learning in volcanology: A review". *Updates in Volcanology: Transdisciplinary Nature of Volcano Science*. Edited by K. Németh. IntechOpen Limited. Chapter 5. DOI: 10.5772/intechopen.94217.

Cassidy, M., M. Manga, K. Cashman, and O. Bachmann (2018). "Controls on explosive-effusive volcanic eruption styles". *Nature communications* 9(1), pages 1–16. DOI: 10.1038/s41467-018-05293-3.

Charbonnier, S. J., C. B. Connor, L. Connor, M. Sheridan, J. O. Hernández, and J. Richardson (2018). "Modeling the October 2005 lahars at Panabaj (Guatemala)". *Bulletin of Volcanology* 80(4). DOI: 10.1007/s00445-017-1169-x.

Chevrel, M. O., J. Labroquère, A. J. Harris, and S. K. Rowland (2018). "PyFLOWGO: An open-source platform for simulation of channelized lava thermo-rheological properties". *Computers & Geosciences* 111, pages 167–180. DOI: 10.1016/j.cageo.2017.11.009.

Cocco, M., K. Atakan, H. Pedersen, and E. Consortium (2016). "The European Plate Observing System (EPOS) Services for Solid Earth Science". *EGU General Assembly Conference Abstracts*. EGU General Assembly Conference Abstracts, EPSC2016-12931, EPSC2016–12931.

Connolly, J. (2005). "Computation of phase equilibria by linear programming: A tool for geodynamic modeling and its application to subduction zone decarbonation". *Earth and Planetary Science Letters* 236(1), pages 524–541. DOI: https://doi.org/10.1016/j.epsl.2005.04.033.

Connor, L. J. and C. B. Connor (2006). "Inversion is the key to dispersion: understanding eruption dynamics by inverting tephra fallout". *Statistics in Volcanology*. Edited by H. Mader, S. C. Coles, C. B. Connor, and L. J. Connor. Geological Society, London, pages 231–242. DOI: 10.1144/iavcei001.18.

Cordonnier, B., E. Lev, and F. Garel (2016). "Benchmarking lava-flow models". *Geological Society, London, Special Publications* 426(1), pages 425–445. DOI: 10.1144/sp426.7.

Costa, A., G. Macedonio, G. Chiodini, et al. (2005). "Numerical model of gas dispersion emitted from volcanic sources". *Annals of Geophysics*. DOI: 10.4401/ag-3236.

de' Michieli Vitturi, M. and S. Tarquini (2018). "MrLavaLoba: A new probabilistic model for the simulation of lava flows as a settling process". *Journal of Volcanology and Geothermal Research* 349, pages 323–334. DOI: https://doi.org/10.1016/j.jvolgeores.2017.11.016.

Deelman, E., K. Vahi, G. Juve, M. Rynge, S. Callaghan, P. J. Maechling, R. Mayani, W. Chen, R. F. Da Silva, M. Livny, et al. (2015). "Pegasus, a workflow management system for science automation". *Future Generation Computer Systems* 46, pages 17–35. DOI: 10.1016/j.future.2014.10.008.

Dietterich, H. R., E. Lev, J. Chen, J. A. Richardson, and K. V. Cashman (2017). "Benchmarking computational fluid dynamics models of lava flow simulation for hazard assessment, forecasting, and risk management". *Journal of Applied Volcanology* 6(9). DOI: 10.1186/s13617-017-0061-x.

Ding, S., T. Plank, P. J. Wallace, and D. J. Rasmussen (2023). "Sulfur_X: A Model of Sulfur Degassing During Magma Ascent". *Geochemistry, Geophysics, Geosystems* 24(4), e2022GC010552. DOI: 10.1029/2022gc010552.

Donoho, D. L., A. Maleki, I. U. Rahman, M. Shahram, and V. Stodden (2009). "Reproducible Research in Computational Harmonic Analysis". *Computing in Science Engineering* 11(1), pages 8–18. DOI: 10.1109/MCSE.2009.15.

Eaton, J. W. (1997). *GNU Octave: A high-level interactive language for numerical computations*. 3rd edition. Boston, MA: Free Software Foundation. 346 pages.

Fink, J., K. Cashman, and F. Sigmundsson (2023). "Looking backward and forward: volcanology in the years 2000, 2010, 2020, and beyond". *Bulletin of Volcanology* 85(2), page 13. DOI: 10.1007/s00445-022-01604-1.

Folch, A., A. Costa, and R. K. S. Hankin (2009a). "TWODEE-2: A shallow layer model for dense gas dispersion on complex topography". *Computers & Geosciences* 35(3), pages 667–674. DOI: https://doi.org/10.1016/j.cageo.2007.12.017.

Folch, A., A. Costa, and G. Macedonio (2009b). "FALL3D: A computational model for transport and deposition of volcanic ash". *Computers & Geosciences* 35(6), pages 1334–1342. DOI: 10.1016/j.cageo.2008.08.008.

Garin, F., S. J. Charbonnier, S. Krasnoff, E. Lev, C. Connor, and A. K. Patra (2024). "Best fit Assessment for numerical Models (BAM): A versatile Python-based tool to assess the performance of numerical models used in volcanology". *AGU Fall Meeting Abstracts*. Volume 2024. AGU Fall Meeting Abstracts, V32B-02, V32B–02.

Ghiorso, M. S., M. M. Hirschmann, P. W. Reiners, and V. C. Kress III (2002). "The pMELTS: A revision of MELTS for improved calculation of phase relations and major element partitioning related to partial melting of the mantle to 3

GPa". *Geochemistry, Geophysics, Geosystems* 3(5), pages 1–35. DOI: 10.1029/2001gc000217.

Global Volcanism Program (2025). "Volcanoes of the world". v.5.3.1. Edited by E. Venzke. DOI: 10.5479/si.GVP.VOTW5-2025.5.3. [Database].

Granger, B. E. and F. Pérez (2021). "Jupyter: Thinking and Storytelling With Code and Data". *Computing in Science & Engineering* 23(2), pages 7–14. DOI: 10.1109/MCSE.2021.3059263.

Harris, C. R., K. J. Millman, S. J. van der Walt, R. Gommers, P. Virtanen, D. Cournapeau, E. Wieser, J. Taylor, S. Berg, N. J. Smith, R. Kern, M. Picus, S. Hoyer, M. H. van Kerkwijk, M. Brett, A. Haldane, J. F. del Río, M. Wiebe, P. Peterson, P. Gérard-Marchant, K. Sheppard, T. Reddy, W. Weckesser, H. Abbasi, C. Gohlke, and T. E. Oliphant (2020). "Array programming with NumPy". *Nature* 585(7825), pages 357–362. DOI: 10.1038/s41586-020-2649-2.

Hubenthal, M. and M. Brudzinski (2025). "Undergraduate persistence in an open-access, online, scientific computing training is influenced by expectancy, value, and cost". *Journal of Geoscience Education* 73(3), pages 259–275. DOI: 10.1080/10899995.2024.2416365.

Hyman, D. M. R., H. R. Dietterich, and M. R. Patrick (2022). "Toward Next-Generation Lava Flow Forecasting: Development of a Fast, Physics-Based Lava Propagation Model". *Journal of Geophysical Research: Solid Earth* 127(10). DOI: 10.1029/2022jb024998.

Iverson, R. M., S. P. Schilling, and J. W. Vallance (1998). "Objective delineation of lahar-inundation hazard zones". *Geological Society of America Bulletin* 110(8), pages 972–984. DOI: 10.1130/0016-7606(1998)110%3C0972:ODOLIH%3E2.3.CO;2.

Jasak, H. (2009). "OpenFOAM: Open source CFD in research and industry". *International journal of naval architecture and ocean engineering* 1(2), pages 89–94. DOI: 10.2478/ijnaoe-2013-0011.

Jones-Ivey, R., A. Patra, and M. Bursik (2022). "Workflows for Construction of Spatio-Temporal Probabilistic Maps for Volcanic Hazard Assessment". *Frontiers in Earth Science* 9(744655). DOI: 10.3389/feart.2021.744655.

Jutzeler, M., R. J. Carey, Y. Dagasan, A. McNeill, and R. A. F. Cas (2024). "Machine-learning crystal size distribution for volcanic stratigraphy correlation". *Scientific Reports* 14(31793). DOI: 10.1038/s41598-024-82847-0.

Kelfoun, K. (2017). "A two-layer depth-averaged model for both the dilute and the concentrated parts of pyroclastic currents". *Journal of Geophysical Research: Solid Earth* 122(6), pages 4293–4311. DOI: 10.1002/2017jb014013.

Kelfoun, K. and S. V. Vargas (2016). "VolcFlow capabilities and potential development for the simulation of lava flows". *Geological Society, London, Special Publications* 426(1), pages 337–343. DOI: 10.1144/sp426.8.

Kluyver, T., B. Ragan-Kelley, F. Pérez, B. Granger, M. Bussonnier, J. Frederic, K. Kelley, J. Hamrick, J. Grout, S. Corlay, et al. (2016). "Jupyter Notebooks–a publishing format for reproducible computational workflows". *Positioning and power in academic publishing: Players, agents and agendas*. IOS press, pages 87–90. DOI: 10.3233/978-1-61499-649-1-87.

Larsen, G. and M. Guðmundsson (2025). *Catalogue of Icelandic Volcanoes*. Edited by B. Oladottir, G. Larsen, and M. T. Guðmundsson. IMO, UI and CPD-NCIP.

Lehnert, K. A., Y. Su, C. H. Langmuir, B. Sarbas, and U. Nohl (2000). "A global geochemical database structure for rocks". *Geochemistry, Geophysics, Geosystems* 1(5). DOI: 10.1029/1999gc000026.

Lehnert, K. A., D. Walker, and B. Sarbas (2007). "EarthChem: A geochemistry data network". *Goldschmidt Conference Abstracts 2007*. Volume 71. Cologne, Germany: Geochemical Society and the European Association of Geochemistry, A559. DOI: 10.1016/j.gca.2007.06.020.

Macedonio, G., A. Costa, and A. Longo (2005). "A computer model for volcanic ash fallout and assessment of subsequent hazard". *Computers & Geosciences* 31(7), pages 837–845. DOI: 10.1016/j.cageo.2005.01.013.

Martínez-Sepúlveda, M., J. Martí, and M. López-Saavedra (2024). "VOLCANBOX: A software platform for volcanic hazard assessment". *International Journal of Disaster Risk Reduction* 113(104817). DOI: 10.1016/j.ijdrr.2024.104817.

Mastin, L. G. (2014). "Testing the accuracy of a 1-D volcanic plume model in estimating mass eruption rate". *Journal of Geophysical Research: Atmospheres* 119(5), pages 2474–2495. DOI: 10.1002/2013jd020604.

McLennan, M. (2008). *Developing Tools for nanoHUB.org*. URL: https://nanohub.org/resources/3863.

Musu, A., V. Parodi, M. Toplak, A. Carfì, M. Á. López, F. Mastrogiovanni, J. Zhangzhou, D. Perugini, D. Belmonte, B. Zupan, et al. (2025). "Orange and Orange-Volcanoes: a New Open and Collaborative Platform to Perform Data-Driven Investigations and Machine Learning Analyses in Petrology and Volcanology". *EarthArXiv*. DOI: 10.31223/x5ft60.

National Academies of Sciences, Engineering, and Medicine (NASEM) (2017). *Volcanic Eruptions and Their Repose, Unrest, Precursors, and Timing*. DC: National Academies Press. 134 pages. ISBN: 0-309-45412-3. DOI: 10.17226/24650.

Ogburn, S. E. (2025). *FlowDat: Volcanic Mass Flow Database*. U.S. Geological Survey. DOI: 10.5066/P13CMDC2.

Palma, J. L., L. Courtland, S. Charbonnier, R. Tortini, and G. A. Valentine (2014). "Vhub: a knowledge management system to facilitate online collaborative volcano modeling and research". *Journal of Applied Volcanology* 3(2). DOI: 10.1186/2191-5040-3-2.

Papale, P. (2017). "Rational volcanic hazard forecasts and the use of volcanic alert levels". *Journal of Applied Volcanology* 6(1), pages 1–13. DOI: 10.1186/s13617-017-0064-7.

Patra, A. K., A. C. Bauer, C. Nichita, E. B. Pitman, M. F. Sheridan, M. Bursik, B. Rupp, A. Webber, A. Stinton, L. Namikawa, et al. (2005). "Parallel adaptive numerical simulation of dry avalanches over natural terrain". *Journal of Volcanology and Geothermal Research* 139(1-2), pages 1–21. DOI: 10.1016/j.jvolgeores.2004.06.014.

Peck, D. L., M. S. Hamilton, and H. R. Shaw (1977). "Numerical analysis of lava lake cooling models; Part II, Application to Alae lava lake, Hawaii". *American Journal of Science* 277(4), pages 415–437. DOI: 10.2475/ajs.277.4.415.

Petrelli, M., L. Caricchi, and D. Perugini (2020). "Machine learning thermo-barometry: Application to clinopyroxene-bearing magmas". *Journal of Geophysical Research: Solid Earth* 125(9), e2020JB020130. DOI: 10.1029/2020jb020130.

Poland, M. P. and K. R. Anderson (2020). "Partly cloudy with a chance of lava flows: Forecasting volcanic eruptions in the twenty-first century". *Journal of Geophysical Research: Solid Earth* 125(1), e2018JB016974. DOI: 10.1029/2018jb016974.

Riel, N., B. J. Kaus, E. Green, and N. Berlie (2022). "MAGEMin, an efficient Gibbs energy minimizer: application to igneous systems". *Geochemistry, Geophysics, Geosystems* 23(7), e2022GC010427. DOI: 10.1029/2022GC010427.

Schilling, S. P. (2014). "Laharz_py: GIS tools for automated mapping of lahar inundation hazard zones". *US Geological Survey Open-File Report* 2014-1073. DOI: 10.3133/ofr20141073.

Schwaiger, H. F., R. P. Denlinger, and L. G. Mastin (2012). "Ash3d: A finite-volume, conservative numerical model for ash transport and tephra deposition". *Journal of Geophysical Research: Solid Earth* 117(B4). DOI: 10.1029/2011jb008968.

Segall, P. (2013). "Volcano deformation and eruption forecasting". *Geological Society, London, Special Publications* 380(1), pages 85–106. DOI: 10.1144/sp380.4.

Selva, J., W. Marzocchi, P. Papale, and L. Sandri (2012). "Operational eruption forecasting at high-risk volcanoes: the case of Campi Flegrei, Naples". *Journal of Applied Volcanology* 1(1), pages 1–14. DOI: 10.1186/2191-5040-1-5.

Shi, S., W. H. Towbin, T. Plank, A. Barth, D. Rasmussen, Y. Moussallam, H. J. Lee, and W. Menke (2024). "PyIRoGlass: An open-source, Bayesian MCMC algorithm for fitting baselines to FTIR spectra of basaltic-andesitic glasses". *Volcanica* 7(2), pages 471–501. DOI: 10.30909/vol.07.02.471501.

Sparks, R. S. J. (2003). "Forecasting volcanic eruptions". *Earth and Planetary Science Letters* 210(1-2), pages 1–15. DOI: 10.1146/annurev.earth.14.1.267.

Stein, A. F., R. R. Draxler, G. D. Rolph, B. J. B. Stunder, M. D. Cohen, and F. Ngan (2015). "NOAA's HYSPLIT Atmospheric Transport and Dispersion Modeling System". *Bulletin of the American Meteorological Society* 96(12), pages 2059–2077. DOI: 10.1175/bams-d-14-00110.1.

The pandas development team (2020). *pandas-dev/pandas: Pandas*. Version latest. DOI: 10.5281/zenodo.3509134.

Thelen, W. A., R. S. Matoza, and A. J. Hotovec-Ellis (2022). "Trends in volcano seismology: 2010 to 2020 and beyond". *Bulletin of Volcanology* 84(26). DOI: 10.1007/s00445-022-01530-2.

Tierz, P. (2020). "Long-term probabilistic volcanic hazard assessment using open and non-open data: observations and current issues". *Frontiers in Earth Science* 8. DOI: 10.3389/feart.2020.00257.

Tierz, P., S. C. Loughlin, and E. S. Calder (2019). "VOLCANS: an objective, structured and reproducible method for identifying sets of analogue volcanoes". *Bulletin of Volcanology* 81(12), pages 1–22. DOI: 10.1007/s00445-019-1336-3.

Tonini, R., L. Sandri, D. Rouwet, C. Caudron, W. Marzocchi, and Suparjan (2016). "A new Bayesian Event Tree tool to track and quantify volcanic unrest and its application to Kawah Ijen volcano". *Geochemistry, Geophysics, Geosystems* 17(7), pages 2539–2555. DOI: https://doi.org/10.1002/2016GC006327.

Valentine, G. A. and K. H. Wohletz (1989). "Numerical models of Plinian eruption columns and pyroclastic flows". *Journal of Geophysical Research: Solid Earth* 94(B2), pages 1867–1887. DOI: 10.1029/jb094ib02p01867.

Vignaux, M. and G. J. Weir (1990). "A general model for Mt. Ruapehu lahars". *Bulletin of Volcanology* 52, pages 381–390. DOI: 10.1007/bf00302050.

Wieser, P., M. Petrelli, J. Lubbers, E. Wieser, S. Özaydin, A. Kent, and C. Till (2022a). "Thermobar: An open-source Python3 tool for thermobarometry and hygrometry". *Volcanica* 5(2), pages 349–384. DOI: 10.30909/vol.05.02.349384.

Wieser, P. E., K. Iacovino, S. Matthews, G. Moore, and C. Allison (2022b). "Vesical: 2. A critical approach to volatile solubility modeling using an open-source python3 engine". *Earth and Space Science* 9(2), e2021EA001932. DOI: 10.1029/2021ea001932.

Wilkinson, M. D., M. Dumontier, I. J. Aalbersberg, G. Appleton, M. Axton, A. Baak, N. Blomberg, J.-W. Boiten, L. B. da Silva Santos, P. E. Bourne, J. Bouwman, A. J. Brookes, T. Clark, M. Crosas, I. Dillo, O. Dumon, S. Edmunds, C. T. Evelo, R. Finkers, A. Gonzalez-Beltran, A. J. Gray, P. Groth, C. Goble, J. S. Grethe, J. Heringa, P. A. 't Hoen, R. Hooft, T. Kuhn, R. Kok, J. Kok, S. J. Lusher, M. E. Martone, A. Mons, A. L. Packer, B. Persson, P. Rocca-Serra, M. Roos, R. van Schaik, S.-A. Sansone, E. Schultes, T. Sengstag, T. Slater, G. Strawn, M. A. Swertz, M. Thompson, J. van der Lei, E. van Mulligen, J. Velterop, A. Waagmeester, P. Wittenburg, K. Wolstencroft, J. Zhao, and B. Mons (2016). "The FAIR Guiding Principles for scientific data management and stewardship". *Scientific Data* 3(1). DOI: 10.1038/sdata.2016.18.

Witsil, A. J. and J. B. Johnson (2020). "Volcano video data characterized and classified using computer vision and machine learning algorithms". *Geoscience Frontiers* 11(5), pages 1789–1803. DOI: 10.1016/j.gsf.2020.01.016.

Wohletz, K., T. McGetchin, M. Sandford, and E. Jones (1984). "Hydrodynamic aspects of caldera-forming eruptions: Numerical models". *Journal of Geophysical Research: Solid Earth* 89(B10), pages 8269–8285. DOI: 10.1029/jb089ib10p08269.

Yang, Q., E. B. Pitman, M. Bursik, and S. F. Jenkins (2021). "Tephra deposit inversion by coupling Tephra2 with the Metropolis-Hastings algorithm: algorithm introduction and demonstration with synthetic datasets". *Journal of Applied Volcanology* 10(1). DOI: 10.1186/s13617-020-00101-4.

APPENDIX A

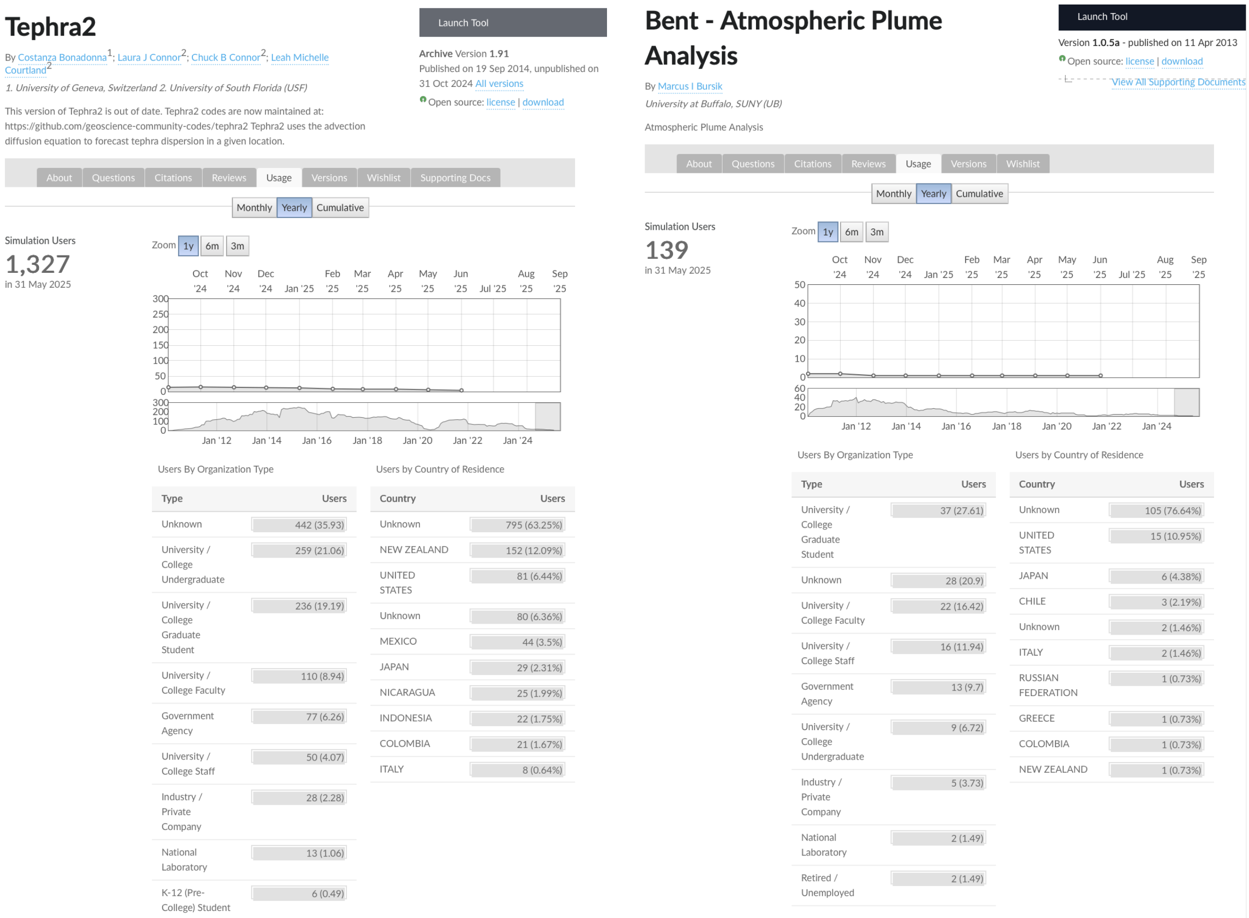

Figure A1: Screen captures from the VHub dashboard showing the usage statistics for two of the most popular tools on VHub, `Tephra2` (left) and `Bent` (right). Both plots show rise and then decline in use levels over time. User affiliation information show that most users were at universities, and government agencies (most likely volcano observatories) accounted for at least 6–10 % of users, or more, given the high percentage of users with an "unknown" affiliation.