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VolcAshDB open services for visualization and Machine Learning–driven classification of volcanic ash particles

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Abstract

Volcanic ash particles contain critical pieces of information about their origin and the processes driving the eruptive activity. However, the classification of particles into different types (juvenile, lithic, free crystal, altered material) is not standardized and varies from observer to observer. As a result, datasets produced by different research groups are often difficult or not possible to compare, which limits intercomparison and thus generalization between eruptive episodes within and between volcanoes. To address this, we previously developed the Volcanic Ash DataBase (VolcAshDB), an open repository of ash-particle data accessible through a web platform (`volcashdb.ipgp.fr`), and used it to build machine-learning classifiers for more objective and reproducible classification. In this contribution, we present three new web services for particle visualization and semi-automatic classification of multi-focused binocular particle images. We show how users can browse and download different datasets of particles using advanced filters, generate visual summaries, and compare particle populations across volcanoes and eruptive styles. We also provide a service for semi-automatic ash particle classification that requires small prior user knowledge based on a Vision Transformer trained on the VolcAshDB dataset in January 2024. The service includes (i) optional image processing to help users process images before upload, (ii) a pre-classification check that evaluates whether uploaded images are similar to the training set using an Out-of-Distribution method, and (iii) an automatic classification into the main particle types using probabilities. We evaluated the classifier with 600 new multi-focused binocular particle images from five volcanoes. The model yielded an average macro F1-score of 0.86. The pre-classification check adds a reliability layer by identifying uploads that fall outside the range covered by the training images, helping users interpret model predictions. Together with the relatively good performance on new data, the classification service should be useful for componentry studies. As VolcAshDB grows to include additional samples and imaging setups, we expect performance to further improve, supporting a more robust and generalizable classifier for global comparisons of ash componentry and, ultimately, near real-time petrologic monitoring of volcanic eruptions.

Keywords: Volcanic ash; Database; Classification; Machine Learning; Web service; Open-source.

1 Introduction

An ever-increasing amount of data in volcanological research plays a vital role in improving our ability to anticipate volcanic activity and reduce risk. For instance, the greater completeness of the eruptive records helps establishing magnitude-frequency relationships to model return periods aiding assessment of the risk [Condit and Connor 1996; Ho 2008; Deligne et al. 2010]. Time-series monitoring of various data types are used to interpret pre- and syn-eruptive processes that may warn of a transition into a more explosive phase, e.g. scalation of seismicity prior to the 2010 Merapi, Indonesia [Jousset et al. 2013], inflation-deflation patterns preceding intensified explosive events in Sakurajima volcano, Japan [Ishii and Iguchi 2024], or geochemical changes in precursory activity at Mt Taranaki, New Zealand [Green et al. 2013].

To obtain and be able to properly use such a wealth of high-quality data, researchers often use procedures that are tailored to the specific volcanoes or eruptions at hand. This specificity allows the capture of subtle variations of a given event, but hinders the generality and integration of datasets across volcanoes or research teams, limiting the ability to derive global statistical insights (e.g. identification of volcano analogues [Tierz et al. 2019; Burgos et al. 2023]). Therefore, there is a need for data interoperability that has become more pressing with advances in data storage and the emergence of Machine Learning (ML) techniques capable of processing large datasets and extracting new insights [Carniel and Guzmán 2025].

ML-driven research has been recently shown to be very fruitful for analysis of seismic data analysis from different volcanoes and eruptions [Ardid et al. 2025]. At the same time, ML models may fail when applied beyond the conditions represented in their training data. This limitation has been documented in volcano-seismic monitoring: classifiers trained on a closed set of event types can confidently misclassify previously unseen signals. A common solution is to add an Out-of-Distribution (OOD) check to flag inputs that fall outside the training domain [Espinosa-Curilem et al. 2025] indicating when model outputs are likely to be reliable and when they should be interpreted with more caution.

The need for standardization and processing has motivated the development of shared infrastructure and services with the views of mitigation of volcano hazards [Trasatti et al. 2021]. At the European level for instance, the Volcano Observations Thematic Core Service, part of the European Plate Observing System (EPOS), coordinates researchers and volcano observatories to implement a framework for providing access to multiple data, software and services [Puglisi et al. 2022; Spampinato et al. 2024]. At the global level, WOVOdat hosts a database of volcanic unrest. It compiles a wide variety of data (seismic, deformation, hydrological, thermal, amongst others) in a standardized structure from approximately 1500 different monitoring stations and provides users with services for data

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search and statistical tools [Newhall et al. 2017; Costa et al. 2019; Widiwijayanti et al. 2024; Nang et al. 2025].

In practice, many volcanological data types are still not standardized [Trasatti et al. 2021; Andrews et al. 2022], and this is the case in the classification of volcanic ash particles. Ash refers to solid material ejected during explosive eruptions (tephra) with a diameter smaller than 2 mm. Ash is commonly generated through four main mechanisms: (i) phreatic explosions, driven by overpressurisation and expansion of shallow groundwater into steam, without direct involvement of magma; (ii) hydrothermal explosions, driven by overpressure from deeper, magmatic fluids interacting with the hydrothermal system; (iii) phreatomagmatic explosions, where rising magma interacts with external water triggering fragmentation; and (iv) magmatic explosions, where magma ascending to the surface fragments due to the rapid exsolution of dissolved gases. The particles produced by each of these mechanisms can have distinctive optical, physical and chemical properties, making particle classification a valuable tool for inferring eruptive processes. For instance, fragments of newly erupted magma, the so-called juvenile particles, indicate that magma is near the surface, with implications for hazard assessment. Other particle types, such as hydrothermally altered or lithic fragments, can point to the involvement of the hydrothermal system or the excavation of pre-existing rock.

Petrologists have classified particles into different types (juvenile, lithic, altered material and free-crystal) and other subtypes (e.g. by shape, crystallinity, or color) mainly based on examination of distinctive features of whole and cross-sectioned particles in the Scanning Electron Microscope (SEM) [Dellino and La Volpe 1996; D'Oriano et al. 2011; Cioni et al. 2014; Pardo et al. 2014; Liu et al. 2015; Alvarado et al. 2016; Pompilio et al. 2017; Dürig et al. 2018; Polacci et al. 2019; Liu et al. 2020; Pardo et al. 2020], as well as under the optical microscope [Andronico et al. 2009; Miwa et al. 2009; D'Oriano et al. 2014; Gaunt et al. 2016; Benet et al. 2021; Gaunt et al. 2024; Cascante et al. 2025]. Other studies have relied on measurements of the refractive indices [Watanabe et al. 1999] and luminance [Miwa et al. 2015], the chemical analysis by electron microprobe [Pardo et al. 2014] and mass spectrometry [Rowe et al. 2008]. Despite its valuable insights, the classification of particles into types (a task known as componentry analysis) has remained underutilized because classification can be difficult, subjective and time-intensive, and criteria may vary depending on the volcano, eruption, and the observer [Pardo et al. 2014; Alvarado et al. 2016].

To alleviate this situation the Volcanic Ash DataBase (VolcAshDB) was developed [Benet et al. 2024a; 2025] with the main aims of: (i) providing a quick and intuitive access to a large number of classified ash particle images from a range of eruptive styles and volcanoes (`volcashdb.ipgp.fr`); and (ii) using its contents to train ML models to classify ash particles in a reproducible and systematic manner. In this contribution, we present three new services that allow for visualization and classification of volcanic ash particles. These include (i) the Catalogue, which allows visualization and download of the dataset with advanced filters, (ii) the Plots, comprising summary plots of the contents and comparing data distributions between volcanoes, and (iii) the Classify, which allows users to classify their own images of particles including a pre-classification similarity check to flag images that fall outside the range covered by the training set. We show that preliminary results of the classifier with new, unseen data show decent performance and thus should be useful to complement expert, observer-based classification. The classifier has been trained on multi-focused binocular images, and thus classification of cross-sectioned backscattered SEM images is not within the scope of this work. We first describe the database structure and platform architecture, followed by the three services, the evaluation of the classifier with new samples under varying image acquisition conditions, and at the end we discuss its potential applicability for componentry analysis, current limitations and future directions. All services, research products and software are free and open source.

2 Methods and materials

2.1 VolcAshDB structure

VolcAshDB is structured as a centralized repository of ash particle data. It currently contains data from 11,808 particles and each particle is associated with a multi-focused binocular image, 33 physical characteristics related to the shape, texture, and color, and a classification label that contains information about the type of particle (juvenile, lithic, altered material or free-crystal) and its metadata. The dataset as of April 2026 is available in Figshare* and its acquisition and coverage is described in Benet et al. [2025].

The database uses `MongoDB`, a NoSQL database, to organize data into flexible, schema-less collections. These collections store and manage various data types, including the Volcanoes and Eruptions collections (Figure 1) which record basic information such as the vent location, eruption date, main rock compositions, and are sourced from Smithsonian's "Volcanoes of the World" database [Venzke 2025]. The Ash-Forming Events (AFEs) collection records information about the ash-forming event such as the date and its volcanic context (e.g. eruptive style). The Samples collection contains information about sampling details such as the location and collection technique, and laboratory procedures such as cleaning and sieving. The Particles collection contains a unique identifier for each particle, the particle main type (juvenile, lithic, altered material or free-crystal) given by the user, an image, metadata such as the image acquisition conditions, and 33 measured features related to the particles' shape, texture and color. These features were selected based on their sensitivity to particle properties that can be distinctive between ash particle types and their established use in the literature [Dellino and La Volpe 1996; Leibrandt and Le Pennec 2015; Liu et al. 2015; Dürig et al. 2018]. For the definition and calculation of the features the reader is referred to Supplementary Material 1. In brief, shape features capture fine-scale perimeter roughness (e.g. Rectangularity), overall form (e.g. Elongation, Aspect Ratio), and particle-scale cavities (e.g. Compactness); textural features were derived from the Gray Level Co-occurrence Matrix (GLCM) [Hall-Beyer 2017] to quantify surface complex-

*https://figshare.com/collections/_/7644656

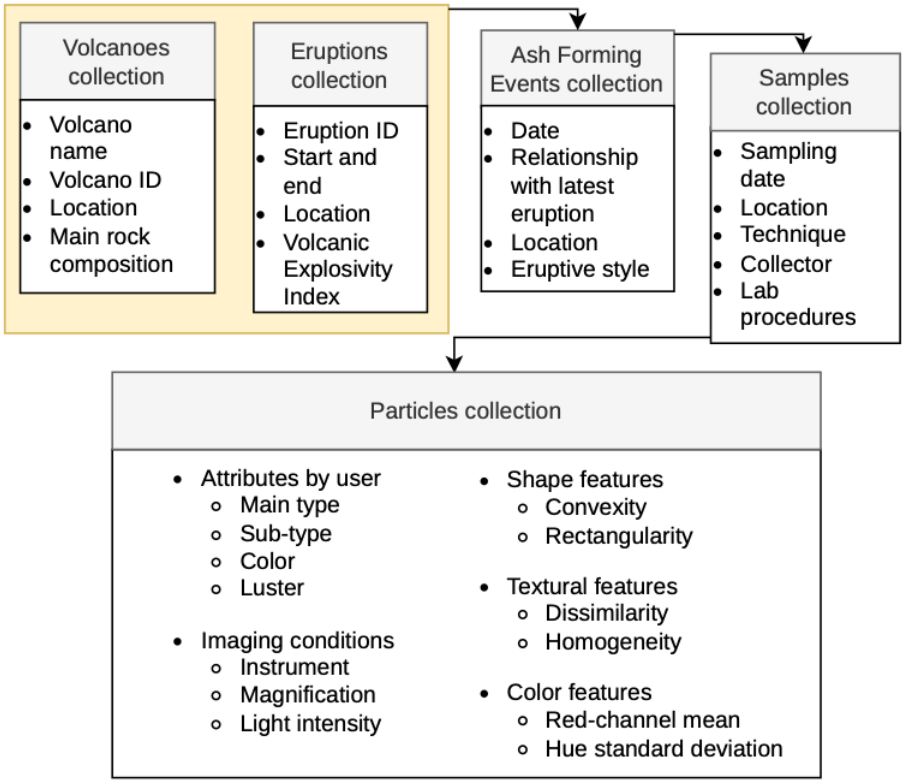

Figure 1: Schematic of the database hierarchical structure based on five MongoDB collections. Lists within bullet points are not exhaustive. Volcanoes and Eruptions collections in beige were adopted from Smithsonian's "Volcanoes of the World" database [Venzke 2025]. The other collections are those in VolcAshDB.

ity (e.g. Dissimilarity) and smoothness (e.g. Correlation); and color features consist of the mean, mode, and standard deviation of pixel values across RGB and HSV color spaces, sensitive to dominant hue, color intensity, and brightness.

2.2 VolcAshDB platform, web, and services

2.2.1 *Web-platform architecture and software*

We developed a web-based platform to make the dataset and services open-access and easy to navigate. The platform is built using the MERN stack (`MongoDB`, `Express.js`, `React.js`, and `Node.js`) and runs on a virtual machine hosted by the Shared Virtualisation Service at the Institut de Physique du Globe de Paris (IPGP). It has two main components: (i) a backend that stores and manages the data, and (ii) a frontend that provides responsive interface for the services (Figure 2). The backend uses `Node.js` and `Express.js` for server-side functions, while `MongoDB` manages the data across the different collections. The frontend is developed in `React.js` and supports interactive exploration of the dataset and access to the classification service. Communication between the client and server is handled through a `RESTful` API. Below, we describe the three main services in VolcAshDB platform: Catalogue, Plots, and Classify.

2.2.2 *Catalogue service*

The Catalogue* allows users to effectively query, navigate, and download the particle images in a user-friendly manner. For querying, we developed a system of tags with dropdown menus that allow filtering by volcano, eruptive activity type, grain-size fraction, particle type and shape (Figure 3). We added a search bar where users can type an element of interest to retrieve the images (e.g. by volcano name). All the metadata and features compiled for each particle can be accessed on screen by double-clicking the particle image. Users can download the selected images and an excel spreadsheet with the particle features as a ZIP file after user verification. Verification is performed through an email confirmation step, where users receive an email with an activation link.

2.2.3 *Plots service*

This service† provides visual summaries of the data which allows for user interaction. We divided the Plots into "Natural Data", for samples erupted by volcanoes, or "Experimental Data" for samples experimentally generated in the lab by crushing pyroclastic material into ash-sized grains [see D'Oriano et al. 2013; Benet et al. 2025] (Figure 4). Pie charts show the proportions of number of particles per volcano (Figure 4A), per particle type (Figure 4B), and per activity type (Figure 4C). Ternary diagrams show the proportion of particle types normalized without free crystals per sample and according to eruptive activity type (Figure 4D). We also use Principal Component Analysis of the features (Figure 4E) to display differences between different particle types [Benet et al. 2024b]. Another available visualization is the histograms which show the distribution of values of a given feature and volcano (Figure 4F). Further insights from all plots can be obtained by hovering with the mouse over any marker. Data from the derived plot outputs, such as PCA coordinates, are not directly exportable but underlying particle features' data

*`volcashdb.ipgp.fr/catalogue`

†`volcashdb.ipgp.fr/analytic`

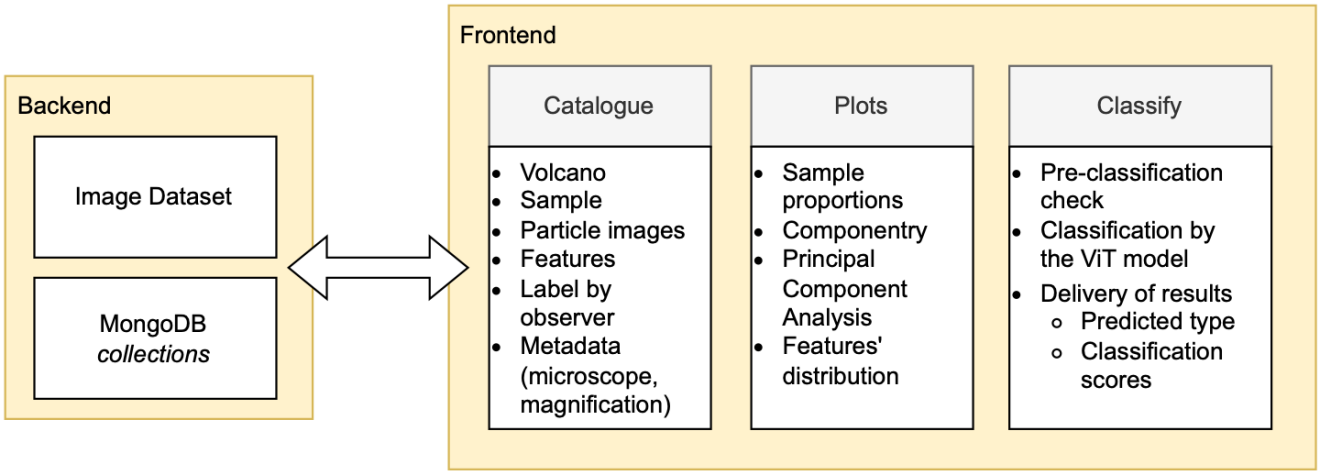

Figure 2: Dataflow and general architecture of VolcAshDB web-platform. The backend is the server-side part that users do not access directly; it handles data storage, authentication, and the requests sent by the frontend. The frontend is the user-facing part of the website (the pages and interactive elements displayed in the browser). Details of the `MongoDB` collections shown in Figure 1.

and metadata can be downloaded for independent analysis and visualization via the Catalogue service.

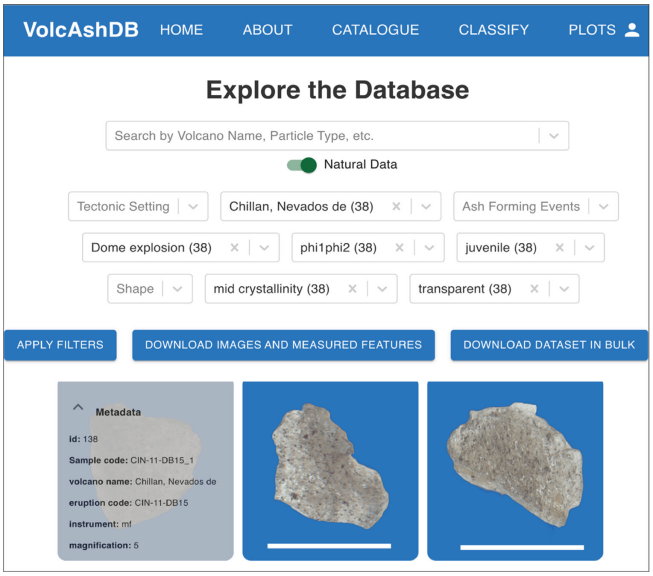

Figure 3: Screenshots of the Catalogue page in VolcAshDB web site. The white bars at the bottom of the particle images correspond to a 0.5 mm bar for scale.

2.2.4 *Classify service*

The Classify service* allows users to upload their own binocular microscope images of individual ash particles and receive as output a particle type classification (altered material, free-crystal, juvenile, or lithic), a confidence score indicating how certain the model is in its prediction, a similarity check flagging whether the uploaded image is sufficiently similar to the training images, and the 33 shape, texture and color features described under the Particles collection. No specialized knowledge of machine learning is required to use the service. Uploaded images are not stored or retained after classification, and are not used for any other purpose. The underlying ash-particle classifier is a `Vision Transformer` (`ViT`) model trained on VolcAshDB image data as of January 2024. The `ViT` operates directly on particle images and outputs class-wise probabilities. The `ViT` was fine-tuned on approximately 10,000 augmented multi-focused binocular particle images across the four particle types and achieved a macro F1-score of 0.93 on the test set. Full details of model development, training, and evaluation are provided in Benet et al. [2024a]. The service comprises three steps: (1) optional image processing to prepare user images for upload, (2) a pre-classification check that evaluates how similar the uploaded particle images are to the training images used to build the `ViT`, and (3) classification by the `ViT`, with results delivered to the user by email.

▹ **Step 1: Preparation of input image data** The classification service accepts images of individual ash particles. To maximize the model performance, we recommend a set of preprocessing tasks and provide an online tool in the interface of the Classify service. These procedures aim to reproduce the same image type that was used to train the `ViT` model.

First, we recommend acquiring images with a binocular microscope system that produces multi-focused images (i.e. images that are sharp across the full particle surface), such as the Leica LMT260 XY or the Keyence VHX-7000. If such systems are not available, multiple standard binocular images can be combined into a single multi-focused image using pretrained deep learning models such as `SESF-Fuse` [Ma et al. 2020] or `VAEEDOF` [Piano et al. 2025]. We also recommend imaging particles against a light or white background, as the training images were acquired on a white background with transparent tape; darker backgrounds will alter the apparent colour and brightness of the particles and may decrease classification performance.

*`volcashdb.ipgp.fr/classify`

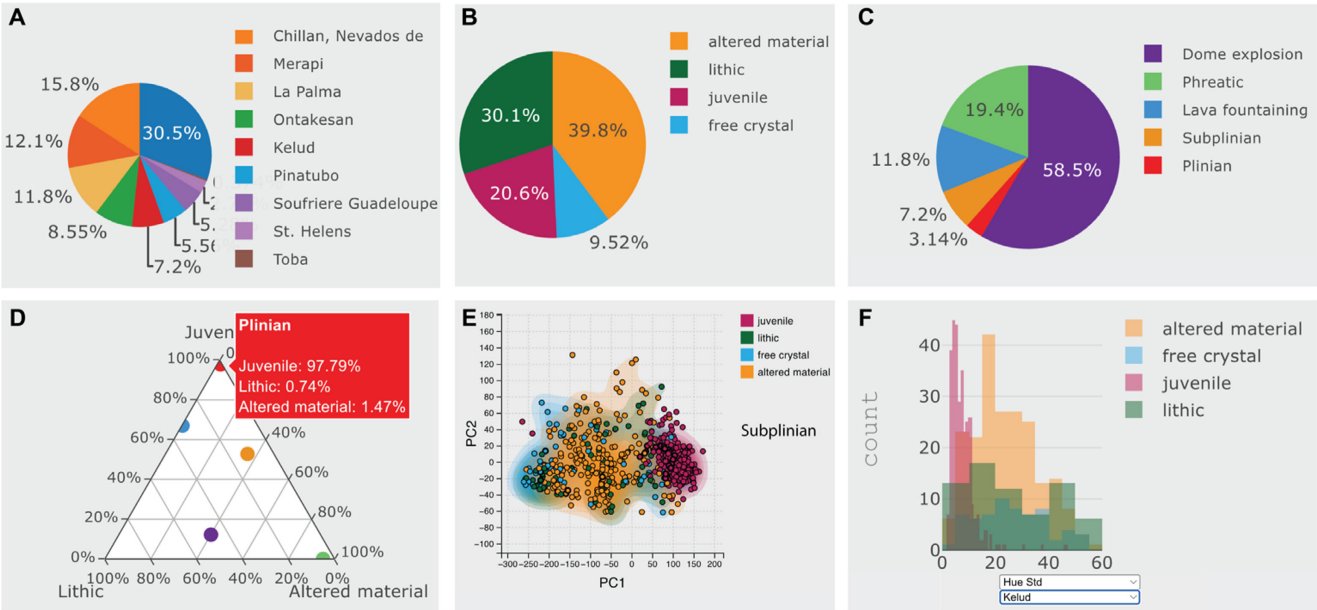

Figure 4: Screenshots of six representative panel plots from the Plots service page in VolcAshDB web site, including piecharts [A]–[C], a ternary diagram [D], a scatter plot of the two principal components (PC1 and PC2) obtained from Principal Component Analysis of the particle features from Subplinian eruptive style [E], and a histogram that allows users to select the particle feature and volcano to be displayed [F].

Second, if an image contains multiple particles, it should be segmented into individual particle images prior to upload. This can be done in our Classify page by uploading the image (up to 2.5 GB) and cropping each particle by drawing bounding boxes in the interface (Figure 5A). Alternatively, the user could independently implement automatic segmentation prior to upload using simple thresholding when particles have a clear contrast with the background [Wang 2008] or using a deep learning segmentation model such as `Fast-SAM` [Zhao et al. 2023]

Last, images should be provided with the background removed so that the classifier focuses on particle features rather than the imaging setup. This step is done automatically if using the tool from the Classify page (Figure 5B), where background removal is performed using the rembg Python library. The library provides a deep learning-based tool trained on a large dataset of foreground-background image pairs which performs robustly on ash particles even when contrast between the particle and background is low. Other alternatives for background removal include the built-in macOS workflow (right-click an image → Quick Actions → Remove Background), a free online service (), or licensed software including Adobe Express Remove Background © or Adobe Photoshop © [Comida et al. 2022]. Finally, the individual particle images should be placed in a single folder and compressed as a ZIP file prior to upload.

▹ **Step 2: Pre-classification check** Before running the ash classifier, we recommend a pre-classification check to assess whether the new ash-particle images to be classified are similar to those used to train the `ViT`. Users may upload either a small set of representative images (for example, covering the different particle types) or a larger batch, provided the total upload is <1 GB. This pre-classification check follows a standard Out-of-Distribution (OOD) approach [Kuan and Mueller 2022], which we use here as a practical quality-control step. Each uploaded particle image is first processed by the `ViT`, and we compute the values produced at the penultimate layer, which summarize the image content just before the model assigns a class. We then compare these summaries with those from the training images to estimate how closely the upload matches the data used to build the classifier. These image summaries can also be visualized after dimensionality reduction (e.g. UMAP [McInnes et al. 2020]), which helps inspect the embedding space and identify clusters of uploaded particles that fall outside the region occupied by the training set. Based on this comparison, a closeness colour is given according to where each uploaded image falls relative to the training reference range (Figure 5C): Green if the image lies within the central range of the training distribution (between the 0th and 97.7th percentiles), Amber if it lies near the edge of the training distribution (97.7th–99th percentiles), and Red if it falls beyond the 99th percentile. A high proportion of Green images indicates that the upload is well aligned with the training conditions and the predicted classes are expected to be more reliable. In contrast, a high proportion of Red images suggests that the upload differs from the training images (due to image acquisition conditions, background, or particle characteristics), and the classification results should be treated with caution. As a best practice, we encourage users to report the proportion of Green, Amber, and Red images alongside their classification results when publishing data derived from this service, as this provides an important indicator of how well the uploaded dataset matches the training data.

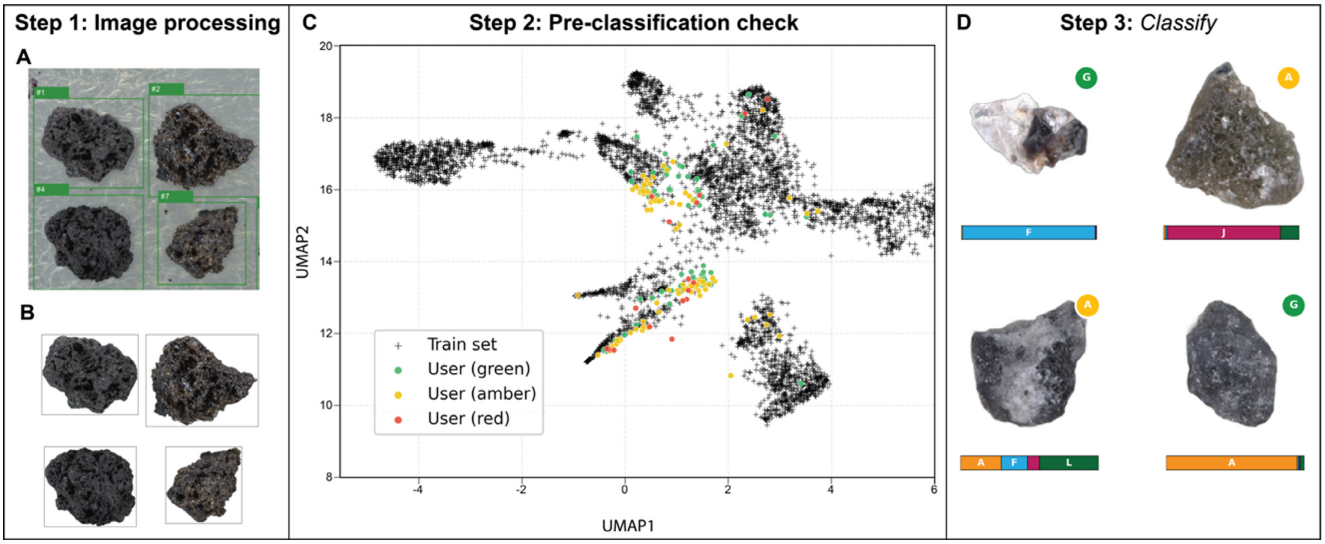

Figure 5: Workflow involved in the Classify service with screenshots of the outputted results. Image processing consists of [A] delineating bounding boxes and [B] image background removal. [C] Uniform Manifold Approximation and Projection (UMAP) representation of the ViT embedding space used for the pre-classification check of the sample B-MAR. Uploaded images are plotted relative to the training-set distribution and colored by closeness: Green for images within the 5th–97th percentiles, Amber for those between the 97th and 99th percentiles, and Red for those beyond the 99th percentile. [D] The results from ash particle classification include the particle type and class-wise probabilities predicted by the model shown as horizontal stack bar where orange is for altered material (A), light blue for free-crystal (F), magenta for juvenile (J), and dark green for lithic (L). Note that each particle image, at the top-right corner, contains the given closeness color by the Out-of-Distribution analysis with a G for Green, A for Amber, and R for Red.

▹ **Step 3: Automatic model classification** After sign-up and verification in the web platform, users can upload either a single image or a ZIP file containing multiple images (up to 1 GB). Once the upload is complete, processing starts automatically and, when finished, users receive an email containing a ZIP file with the outputs (see Supplementary Material 2 for an example folder of the ZIP file). The ZIP file includes: (i) a folder named "ood_analysis" with the results from Out-of-Distribution results including the closeness colors, a summary of the outputted values, and visualization of the results for each particle image; (ii) a folder named "results" with the ViT predictions "results.csv" file and a reference file containing all particles in the VolcAshDB dataset ("volcashdb_particles.csv"), structured in the same way as results.csv to facilitate comparison; (iii) a folder named "visualizations" with a summary of the model predictions for each particle image, and a legend of the symbols and colors used; and (iv) a README file describing the content of each output file.

The "results.csv" file contains (i) the 33 particle features describing shape, texture, and color defined in Benet et al. [2024b], (ii) the particle type together with the class-wise probability predicted by the model [Benet et al. 2024a], and (iii) the DOI of the publication describing the model (included because we plan to host multiple models in the future). The class-wise probabilities range from 0 to 1 and indicate how strongly the model supports each class or type of particle for a given image, with values closer to 1 corresponding to higher model confidence. These probabilities are intended as a practical indicator to help users interpret results, particularly for images flagged by the pre-classification check or cases where probabilities are similar across multiple classes, which may reflect ambiguity in particle classification (see Benet et al. [2024a] for more details and explanation).

3 Evaluating ViT's performance with new samples and different image acquisition conditions

3.1 Data acquisition

To evaluate ViT's performance with new data that were not included in the training set of the model, we used 600 particles across five different volcanoes following the procedure in Benet et al. [2024b]. For each particle, we obtained one multi-focused image and we classified it into one of the four main types (juvenile, lithic, altered material or free-crystal), regardless of the observer's level of confidence in the assignment. We first cleaned the samples with several cycles of ultrasound baths of 15 s, dried overnight and sieved into grain-size fractions 0–1ϕ (i.e. from 2 to 1 mm particle diameter), 1–2ϕ (1–0.5 mm), and 2–3ϕ (0.5–0.25 mm). Then, we laid the particles of the coarsest grain-size fraction to a transparent double-sticky tape glued on a glass slide and re-arranged the particles as a grid with the help of a needle. The glass slide was then scanned with a Keyence VHX-7000 optical microscope and software system at IPGP with a magnifying lens of ×100 and light intensity value of 130. Particle images were segmented using the FastSAM model [Zhao et al. 2023], and we obtained an average resolution per image of about 780 × 780 pixels with the particle occupying on average 160,000 pixels (30 % of the particle image). The particle was classified

based on diagnostic observations of particle features [Benet et al. 2024a]: Juvenile particles are generally glossy, smooth-surfaced, sharp-edged with a fresh aspect. Lithic particles are dark, dull, with subrounded edges. Altered material exhibits white, yellow, or red coatings, can have a granular texture, and often exhibits signs of alteration such as dissolution surfaces. Free crystals can be recognised for their optical characteristics like the crystal habit, cleavage, or twinning.

3.2 Sample descriptions

We evaluated `ViT`'s performance using a range of samples, some included in the training set and others not (Table 1). By training set, we mean the image data from samples used in the model that learned the patterns for classification in Benet et al. [2024a]. Here we used the following samples: (1) Ash particles from the sub-Plinian phase of February 2014 Kelud volcano (Indonesia; KE-DB3) and the lava fountaining of Tajogaite eruption (Canary Islands; CV-DB1), October 2021 that were included in the training set but which were imaged with a different microscope system; (2) samples from Nevados de Chillán volcano (Chile; NC-DB14), January 2018, and La Soufrière de Guadeloupe (Antilles; SG-DB3), August 1977, both of which are samples not covered in the training set, although the volcanoes and eruption were; and (3) Marapi (Indonesia; B-MAR), December 2023, which is a volcano not covered in the training set.

3.3 Simulating different image acquisition conditions

We acquired images and simulated gradual changes in a range of image conditions to assess the effect on the `ViT`'s model performance. First, we increased the blur of the images to simulate a loss in image resolution. For this, we passed a Gaussian kernel from the `scikit-image` library at increasing values of blurring intensity which is measured in sigmas (σ). Second, we used the Gaussian kernel to incrementally blur most of the particle image while keeping a region in good focus as a proxy for single-focus images. Third, we varied the image brightness by using the `Pillow`'s function `ImageEnhance`.Brightness, where an enhancement factor of 0 makes the image black, 1 is the original, and values above increases brightness. Lastly, we evaluated `ViT`'s performance across varying thicknesses of the margin (i.e. the border between the particle and the image edges), measured in steps. Each step is defined as an integer (n) multiple of one-fifth of the particle diameter (D): step = $n{\cdot}D/6$. A set of ten images for each parameter are shown in Figure S1 in Supplementary Material 3.

3.4 Model evaluation

The `ViT`'s predictions were categorized into: True Positives (TP), where the prediction correctly matches the particle type given by the user, True Negative (TN), where the prediction correctly identifies the absence of a particle type; False Positive (FP), where the prediction wrongly identifies the presence of a particle type, and False Negatives (FN), where the prediction wrongly identifies the absence of a particle type. We evaluated the model's performance at two levels: (i) the performance per particle type using the per-class F1-scores, and (ii) the overall performance using the macro F1-score, defined as the unweighted average of the per-class F1-score. The F1-score is the harmonic mean of precision and recall:

$$\text{F1-score} = 2 \cdot \frac{\text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}}, \tag{1}$$

where

$$\text{Precision} = \frac{\text{TP}}{\text{TP} + \text{FP}}; \quad (2) \qquad \text{Recall} = \frac{\text{TP}}{\text{TP} + \text{FN}}. \quad (3)$$

We calculated the overall performance per sample using the macro F1-score which results from averaging the F1-score per each particle type, as opposed to the weighted F1-score, which also takes into account the number of particles that have been predicted per type. The macro F1-score is recommended for imbalanced datasets when FN and FP are equally important [Grandini et al. 2020]. The macro F1-score ranges from 0 to 1, where 1 indicates perfect classification across all particle types and 0 indicates complete failure. A random classifier assigning particles equally across four classes would yield a macro F1-score of approximately 0.25. Thus, scores substantially above this value reflect meaningful learned discrimination between particle types. However, what constitutes acceptable or optimal performance depends on the intended use. For applications such as pre-labelling large datasets to assist expert validation, an overall macro F1-score above 0.8 may be sufficient, whereas for monitoring applications where the presence of juvenile particles must be reliably detected users should require F1-scores for juvenile particles above 0.9 or higher, and should inspect the per-class scores rather than relying on the macro average alone.

4 Results and discussion

4.1 `ViT`'s performance under varying imaging conditions

For this analysis we used the 600 new particle images and investigated the effect of low-resolution images of the entire particle or part of it, changes in brightness, and the thickness of the image margin (Figure 6). We also blurred our original particle images (average pixel resolution of ~780 × 780).

4.1.1 *Effect of blur*

We found that for blurring, the `ViT` performance peaks between 0–1σ and remains at an overall performance >0.9 macro F1-score until 4σ (Figure 6A). For a Gaussian blur >4σ, the classification performance decreases at a higher rate, particularly the lithic particle type reaching an F1-score of 0.75 at 10 . Considering that our images at 4σ yield lower but relatively high F1-score, we recommend the use of images with a resolution of at least 500 × 500 pixels.

4.1.2 *Effect of single versus multi-focused images*

To evaluate the effect of using single-focus images, we increasingly blurred the original images using the Gaussian blur as in the previous section but leaving a part of it in good focus (Figure 6B). The starting blur is at 10σ yielding 0.91 of macro F1-score. This suggests that the model is able to identify discriminant information from single-focus-like images with res-

Table 1: Details of samples used for ViT's evaluation and their variable coverage within the training set.

Sample details				Coverage in the training set		
Code	Volcano	Eruption date	Grainsize	Volcano	Sample	Microscope
KE-DB3	Kelud	14/2/14	1–2ϕ	Seen[1]	Seen	Unseen[2]
CV-DB1	Cumbre Vieja	19/10/21	0–1ϕ	Seen	Seen	Unseen
NC-DB14	Nevados de Chillán	23/1/18	0–1ϕ	Seen	Unseen	Unseen
SG-DB3	Soufrière de Guadeloupe	23/8/76	0–1ϕ	Seen	Unseen	Unseen
B-MAR	Marapi	4/12/23	1–2ϕ	Unseen	Unseen	Unseen

[1] "Seen" means that particles from this volcano were used in the training set of the Benet et al. [2024a] model. [2] "Unseen" means that the images were acquired with a different microscope from that of the training set images.

olution 750 × 750 pixels. Increasing blur between 10–50σ yields a progressive drop of F1-score by more than 0.1. The free crystals are particularly misclassified likely because their planar surfaces and bright reflections, which are discriminant, were partially erased when blurring. It is worthwhile to note that the classification of juvenile particles remains quite consistent (>0.90 F1-score).

4.1.3 *Effect of rescaling pixel intensity*

We also investigated the effect of rescaling the image pixel values to lower (darker) or higher (brighter) values using a brightness factor. Our images were acquired at a light intensity of 130 in the Keyence VHX-7000, which is represented as a brightness factor of 1 in these simulations (Figure 6C). The ViT yields relatively high macro F1-score (>0.90) within a narrow range of ±0.1. When the variation in brightness factor is higher than ±0.2, the F1-score drops significantly by more than 0.1 at 0.6 (dark) and 1.3 (bright) of brightness factor. This suggests that the ViT can handle well some variations in light intensity, provided that particles are imaged against a light or transparent background consistent with the training data.

4.1.4 *Effect of particle margin thickness*

We evaluated how margin thickness affects ViT performance. The margin is the border that separates the particle contour and the image boundaries. We parameterized the margin thicknesses in steps, where each step is an integer (n) multiple of one-sixth of the particle diameter (D) (step = $n{\cdot}D/6$). With margin = 0, ViT performs best (macro F1-score = 0.94). At a margin of 1 step, the macro F1-score drops abruptly by up to 0.3. For margins >1 step, performance gradually recovers toward its original F1-score value. This performance behavior is puzzling as we would expect performance to decrease as margin thickness increases. One plausible explanation is that a small margin (margin step value of 1) introduces just enough background to disrupt the spatial attention patterns learned by the ViT during training, while thicker margins may allow the model to effectively re-learn to ignore the surrounding area. Therefore, we recommend removing the margin by cropping the image as a practical precaution.

Table 2: Results of pre-classification check across the new samples and a subset of the ViT's test set [Benet et al. 2024a]. Results are reported by number of particles and in percentages in brackets.

Code	# particles	Green[1]	Amber[2]	Red[3]
Test set*	100	97 (87 %)	3 (3 %)	0 (0 %)
KE-DB3	131	26 (20 %)	71 (54 %)	34 (26 %)
CV-DB1	62	4 (6 %)	42 (68 %)	16 (26 %)
NC-DB14	49	5 (10 %)	29 (59 %)	15 (31 %)
SG-DB3	99	2 (2 %)	42 (42 %)	55 (56 %)
B-MAR	259	80 (31 %)	129 (50 %)	50 (19 %)

*25 randomly sampled particles for each particle type from the test set in Benet et al. [2024a]. [1]Green if it belongs to the training set distribution between 5th–97th percentiles. [2]Amber between 97th–99th percentiles. [3]Red beyond the 99th percentile.

4.2 Testing the pre-classification check with new samples

We applied the pre-classification Out-of-Distribution (OOD) check to the 600 particles from five different samples with variable overlap with the ViT training set (see Section 3.2 and Table 1 for details) to evaluate how closely these new images match the training set. In addition, we analysed a subset of 100 particles from the ViT test set [Benet et al. 2024a] which shares the same samples and imaging conditions as the training data, and used it as a reference where most particles are expected to fall within the training distribution. We found that 97 % of the test-set particles were flagged as Green (between the 5th and 97th percentiles of the training set distribution), with only 3 % flagged as Amber (Table 2).

The new samples show a higher proportion ranging between 42 % and 68 % of Amber particles and between 19 % and 56 % of Red particles (Table 2) consistent with the fact that one or more key factors (volcano, sample, and/or microscope) are not represented in the training set (Table 1). In particular, particles from the sample from La Soufrière de Guadeloupe, 1976 (SG-DB3) are almost entirely Red and Amber with 56 % and 42 % respectively. Visualization of the SG-DB3 distribution shows that it forms a cluster out of the training distribution through the UMAP (Figure 7). However, as shown

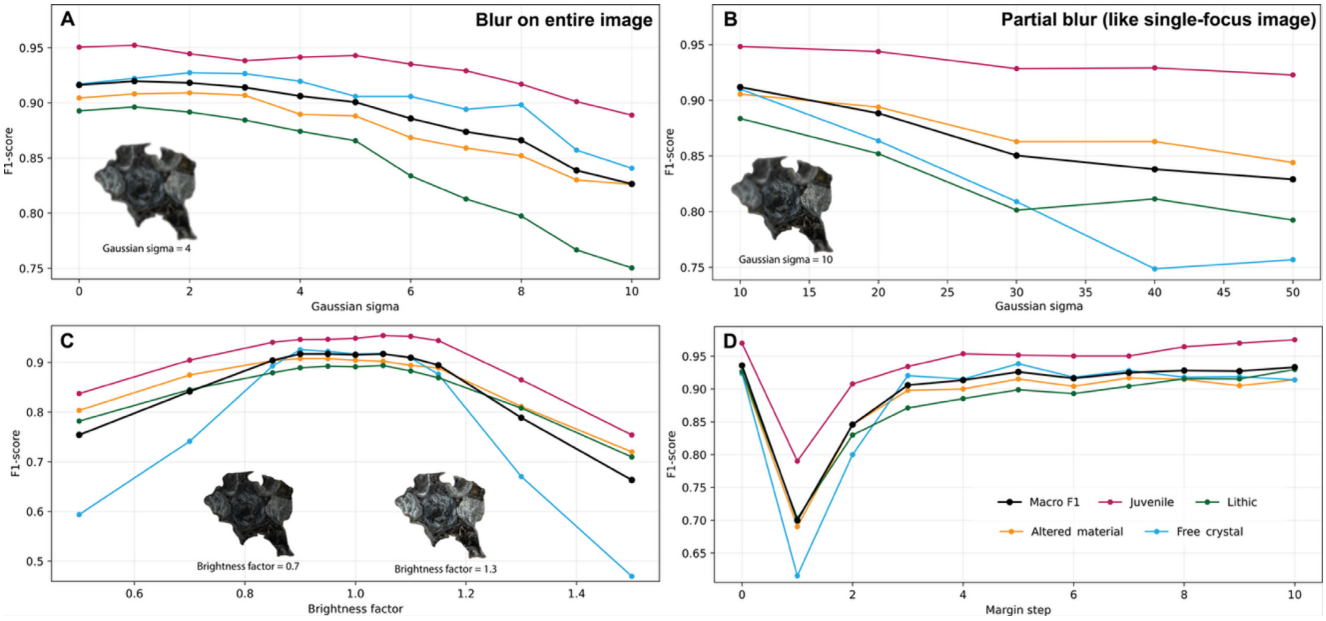

Figure 6: Plots with the F1-score values obtained showing the effect of image variations: [A] Gaussian blur applied to the entire image (proxy for reduced resolution), [B] partial Gaussian blur (proxy for single-focus imaging), [C] brightness scaling, and [D] image-margin thickness (expressed in steps).

in the next section, all SG-DB3 particles are correctly classified by the model as altered material, indicating that the pre-classification check captures difference from the training domain rather than expected failure of the classifier. By contrast, particles from Marapi, 2023 (B-MAR) are mostly classified as Green (31 %) and Amber (50 %), while the remaining 19 % are flagged as Red. This Red fraction includes a group of particles that is systematically misclassified (Figure 7), suggesting that in this case the pre-classification check successfully highlights the part of the dataset that is least represented in the training set and most prone to error.

4.3 Testing ViT performance with new samples

The results of the model of the five new samples yield a macro F1-score of 0.86 (Table 3) with juvenile particles showing the highest per-class F1-score (0.89) and lithics the lowest (0.76). Despite the high proportion of images flagged as Red in several samples, classification performance remains generally robust, but errors occur more frequently for particles that deviate most from the training domain.

The particles from Kelud, 2014 (KE-DB3) are from the same sample and volcano as those included in the training set, but they were imaged with a different microscope setup. The macro F1-score is 0.85 (Table 3), which is lower than the original test-set performance (macro F1-score of 0.91 [Benet et al. 2024a]) indicating that the use of a different microscope and image software can affect performance even if both sets of images are multi-focused and acquired following the same procedure. For example, there is a cluster of juvenile particles that are predicted by the ViT as altered material (Figure 8A). While the juvenile, true positives have a well-defined vesicularity (Figure 8A: I), the false positives have vesicles partially blur (Figure 8A: II).

The particles from Cumbre Vieja, 2021 (CV-DB1) volcano also come from the same sample as the training set, but were also imaged with a different microscope setup. The macro F1-score is 0.83, which is lower than the 0.91 reported for the original test set [Benet et al. 2024a]. The sample consists of two particle types, i.e. lithics (mostly recycled juveniles) and juvenile particles (Figure 8B). The model generally classifies well dull particles with signs of recrystallization (Figure 8B: III) but can misclassify as juvenile particles with metallic reflections (Figure 8B: IV) typical of recycling [D'Oriano et al. 2014]. This could be due to the different interaction of the reflections with the light condenser of the Keyence VHX-7000 microscope and how the software handles them with respect to the original imaging setup.

Samples from Nevados de Chillán volcano were included in the training set, but here we analyzed a sample (NC-DB14) from a different eruption date (January 2018) although from the same eruptive cycle. The macro F1-score is 0.81, which is slightly lower than 0.85 reported for the original test set, suggesting that the model generalizes reasonably well to new material from the same eruptive cycle. We did not find a systematic misclassification of a cluster of particles, and it can be difficult to decide whether a mismatch in particle types between the ViT and the observer are classification mistakes by the model, or the other way around. For instance, the ViT model classifies as juvenile, vesicular and glossy particles (Figure 8C: V) as well as those with adhered orange material on the surface (Figure 8C: VI). The latter was classified as altered material by the observer because its coatings were interpreted to originate from interaction with the hydrothermal system. However, these coatings could also result from sublimation in the volcanic plume, maintaining its juvenile origin [Spadaro et al. 2002], which makes the distinction ambiguous.

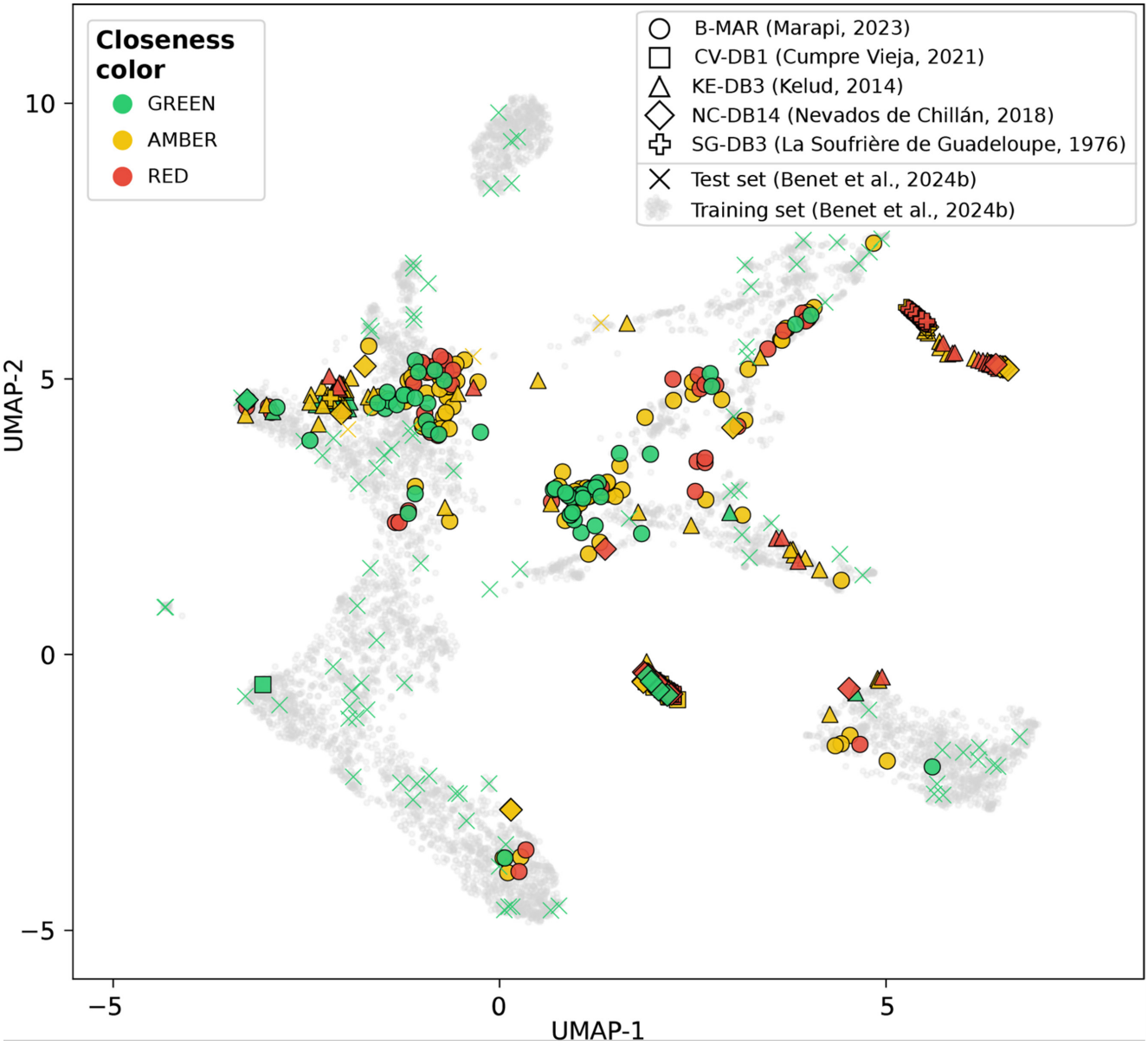

Figure 7: UMAP projection of the `ViT` embedding space used for the pre-classification check. Grey dots represent the training images, whereas symbols correspond to particles from the reference test set and the five new samples. Each particle is colored according to its closeness to the training distribution: Green if it falls within the 5th–97th percentile range, Amber between the 97th and 99th percentiles, and Red beyond the 99th percentile. The plot allows visual inspection of how new datasets overlap with, or diverge from, the training-set distribution, including the presence of clusters that lie partly or entirely outside the main training domain.

Almost 100 particles from a new sample from La Soufrière de Guadeloupe (SG-DB3) volcano were correctly classified as altered material (Figure 8D). The particles are completely (Figure 8D: VII) or partially (Figure 8D: VIII) covered by white to yellow coatings and the model yields probabilities >0.95 of belonging to altered material. The correct classification of these particles, which appears relatively straightforward, adds value to the capabilities of the model, especially in the context of the eruption of La Soufrière de Guadeloupe 1975–1977, where erroneous classification of ash particles led to disputed interpretations of the processes driving the activity [Feuillard et al. 1983].

Finally, we also acquired data from 259 particles from the December 2023 Marapi volcano eruption, which was not included in the training set of the `ViT`. Classification by the model of these particles is relatively robust with a macro F1-score of 0.81 (Figure 8E). The `ViT` model correctly identifies most of the glossy, vesicular juvenile particles (Figure 8E: IX), but almost 20 % are misclassified as free crystals. Examination of the particle images reveals that some of these false positives consist of glassy, transparent particles with bright reflections, and the model assigns them to the free-crystal type with high confidence (e.g. probability of free-crystal = 0.99; Figure 8E: X). A likely explanation is that juvenile particles with the com-

Table 3: Number of particles analysed, per sample componentry and per-class F1-score across the five studied samples (see Table 1 for more details). For componentry, counts per particle type are shown with associated errors in parentheses, computed as the margin of error at the particle level [Benet et al. 2024a].

Code	# particles	Componentry				F1-score				
		A[1]	F[2]	J[3]	L[4]	Macro	A	F	J	L
KE-DB3	131	62 (±11)	19 (±8)	46 (±11)	4 (±4)	0.85	0.91	0.86	0.88	0.73
CV-DB1	62	0	0	47 (±7)	15 (±7)	0.83	0.00	0.00	0.91	0.75
NC-DB14	49	6 (±4)	5 (±4)	14 (±6)	24 (±7)	0.81	0.60	0.83	0.93	0.87
SG-DB3	99	99	0	0	0	1.00	1.00	0.00	0.00	0.00
B-MAR	259	104 (±15)	48 (±12)	66 (±14)	41 (±12)	0.81	0.88	0.82	0.83	0.70
					Average:	0.86	0.85	0.84	0.89	0.76

[1]A is altered material particle type. [2]F is free-crystal particle type. [3]J is juvenile particle type. [4]L is lithic particle type.

bined transparency and reflections were not included in the training set, and that the model associates them with plagioclase crystals, which were present in the training set.

5 Conclusions and future work

The web-based classification service we developed can be readily used to classify ash particles images into altered material, free-crystal, juvenile or lithic types. Our `ViT` model provides a classification score that can support robust and systematic componentry analysis for understanding the processes that lead to the eruption, and distinguishing phreatic, phreatomagmatic and magmatic events [Heiken 1974; Heiken and Wohletz 1985; Cioni et al. 1992; Pardo et al. 2014; Alvarado et al. 2016]. The componentry analysis provided by the model can also inform about the role of ash transport at different distances of the crater in impacting the componentry [Eychenne et al. 2013], and where detailed time-series of ash samples are available, to combine it with other observables for monitoring [Gaunt et al. 2016; Liu et al. 2020; Benet et al. 2021; Martin-Del Pozzo and Nieto-Torres 2024]. The classifier can generalize relatively well to new samples (Table 3), with residual errors likely reflecting natural sources of uncertainty such as variations in image acquisition conditions, or occlusion of diagnostic features from random particle orientation on the glass slide. However, the `ViT` can systematically misclassify particles with distinctive, previously unseen features, as exemplified with transparent glass shards from Marapi that we report (Figure 5E). To this end, we also provide the pre-classification check for users to quantify the proportion of such "unseen" particles and get an intuition of the model's reliability. For optimal performance, we recommend using multi-focused images or, if unavailable, the highest possible resolution (>500 × 500 per particle image), and we provide a tool for cropping images and remove background.

The `ViT`'s training dataset was acquired using a standardized imaging protocol designed to capture subtle variations in particle shape, texture, and color across particle types. This controlled approach produced a consistent dataset that helps reveal how particle-type distributions vary across eruptive styles. However, the same level of standardization also limits its generalizability, because the model sees a narrow range of microscope setups and acquisition conditions during training. Improving generalizability therefore requires expanding the dataset to include images acquired with different microscopes, settings, and preparation conditions, and then retraining a more robust classifier. VolcAshDB already hosts the current dataset, and the services presented in this work provide a practical entry point for adding new data and benchmarking performance. Ultimately, a systematic and reproducible particle classification will support consistent componentry, which is critical for volcano monitoring, and will allow for global-scale comparisons to identify broader relationships and similarities across datasets.

Author Contributions

Damià Benet led the development, acquired and processed the data, and wrote the original manuscript of the project, which was supervised and revised by Fidel Costa. Kévin Migadel and Damià Benet led the development of front-end and the back-end of the new web-platform services. The final version of the manuscript has been read, reviewed and approved by all co-authors.

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Data Availability

Ash-particle data of both images and features is available through our Catalogue service (`volcashdb.ipgp.fr/catalogue`) and as an open repository in Figshare (`https://figshare.com/collections/_/7644656`). The source code

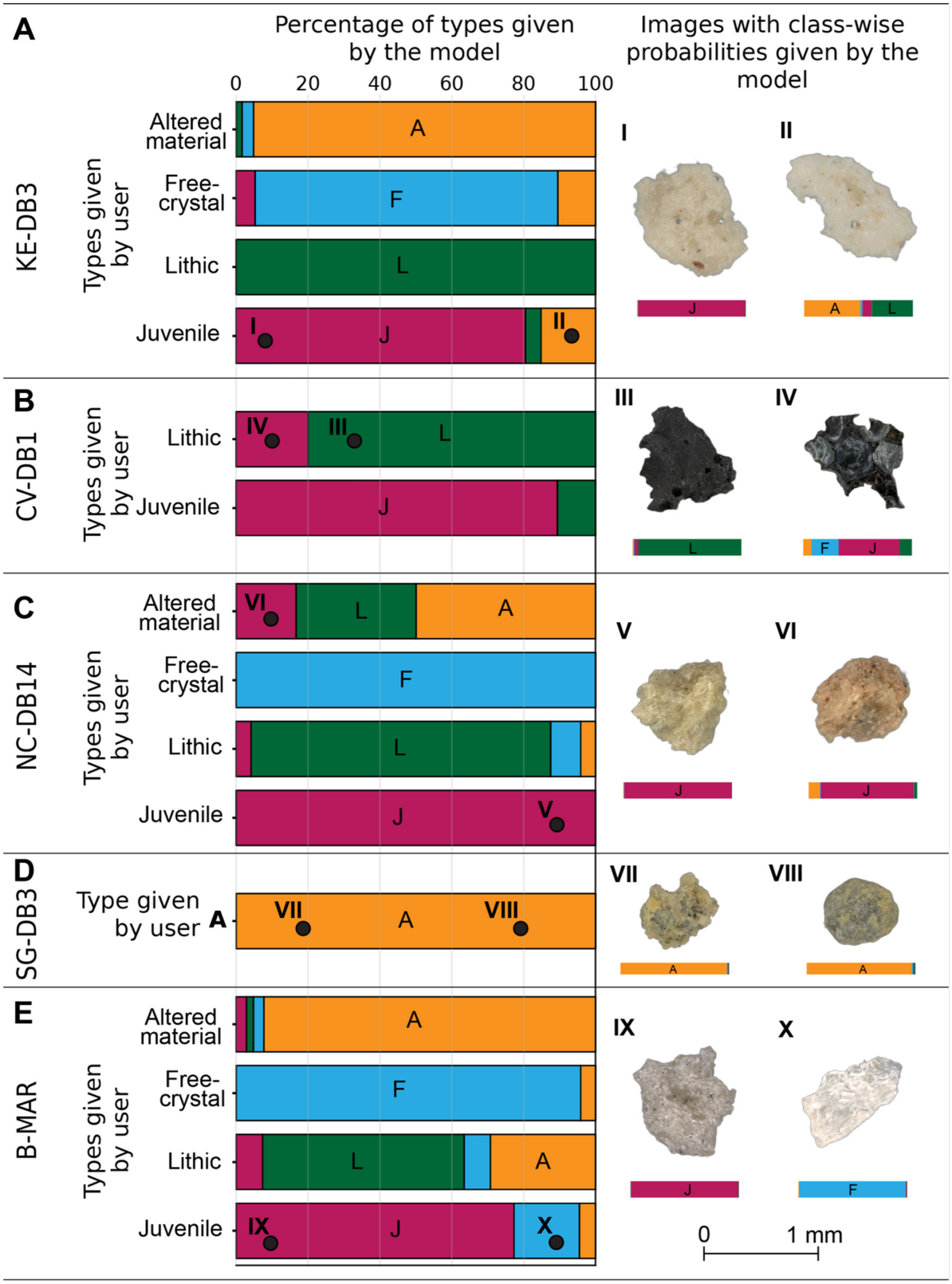

Figure 8: Bar charts showing the percentage of predicted types respect to the assigned label. If all predictions were of the same type as the observed, each bar would be single-coloured as follows: orange for altered material (A), light blue for free-crystal (F), magenta for juvenile (J), and dark green for lithic (L). For each sample (A, B, C, D, and E) we show two representative images. The particle type where each image belongs is mapped with a dot and associated with Roman numerals from I to X. Below each representative image, the horizontal bar shows the class-wise probabilities outputted by the model, using the same colour scheme as the bar charts.

of VolcAshDB web-platform is available in the GitHub repository: https://github.com/dbenet-ntu/VolcAshDB-web_Apr2026.

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