VolcAshDB – A global database of volcanic ash particles

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Abstract *(Maximum 170 words recommended)*
Volcanic ash is made of particles smaller than 2 mm and is produced during volcanic eruptions. Studying the properties of volcanic ash is key for a range of applications, including volcano monitoring. However, given the large variety of textures, colors, and shapes of particles from different eruptions and volcanoes it is challenging to classify them in a reproducible and systematic manner. Here, we present an open access web-based platform that displays the contents of a database of volcanic ash particles, VolcAshDB (https://volcashdb.ipgp.fr/). Particle data includes optical microscope images, physical characteristics of the shape, texture and color, and a classification label with the particle type (free-crystal, altered material, juvenile or lithic). It currently hosts data of 12,044 particles from 53 samples across 13 volcanoes that can be visualized and downloaded in a user-friendly manner. The database has already been used to develop particle classifiers with Machine Learning. We plan to continue it to grow and encourage the volcano community to contribute towards standardizing volcanic ash classification.

Background & Summary
Volcanic ash is made of particles smaller than 2 mm in diameter and is produced during explosive eruptions. The study of its chemical composition and physical properties is important for a range of applications, from understanding the impact of volcanic plumes to the Earth's climate[1] or air traffic[2], through human health impacts[3] as well as to monitoring the beginning and end of an eruption, and transition among eruptive styles[4–7]. In particular for monitoring purposes, using volcanic ash requires the proper identification and characterization of its particles into different components (free crystals, altered material, lithic, and juvenile). However, it is commonly difficult to unequivocally associate the features observed under the optical and scanning electron microscopes to a given particle type[8]. Moreover, the criteria for classification and measurement of particle characteristics are not standardized, and thus, the volcanic ash particle data are hard to compare between different eruptions and volcanoes.

To alleviate this situation, Benet et al.[9] created the Volcanic Ash DataBase (VolcAshDB) which aims at compiling the physical and visual characteristics of ash particles from a range of eruptions and volcanoes using a standardized methodology. As of now, data of 12,044 ash particles from 25 eruptions across 13 volcanoes (Figure 1A) have been collected. The dataset was used to develop Machine Learning (ML)-based models that are able to automatically classify volcanic ash particles into different categories[10]and thus opens opportunities for comparative studies between eruptions and for time-series analysis that could be used during volcanic crises. Here, we present the database design, web interface (https://volcashdb.ipgp.fr), and resources to download, navigate and visualize the database contents. Our plan is to continue to grow the database to increase its robustness and representativity of the wide ranges of volcanic ash, and to encourage the volcano community to contribute to VolcAshDB to advance towards standardising volcanic ash particle classification.

Methods
Procedure for image acquisition of ash particles. Samples were first ultrasonically cleaned, dried and sieved using four meshes of 0ϕ (1 mm), 1ϕ (0.5 mm), 2ϕ (0.25 mm), and 3ϕ (0.125 mm) pore-size dimensions. Using the coarsest available grain-size per sample, particles were arranged on adhesive-coated glass slides for scanning on a binocular scanning stage. Several scans at different focal depths were obtained and "fused" into a 2D-array with a good particle focus. The resulting scans were segmented and color normalized to generate individual, high-resolution (~1,800 pixels/mm in average) particle images that are the main data type of the dataset (see more details in Benet et al.[9]). The images were obtained using a Leica binocular microscope equipped with an LMT260 XY Scanning Stage and a LAS X imaging software at Nanyang Technological University, Singapore (Benet et al.[9]), and a binocular scanning stage, Keyence VHX-7000, coupled with its Keyence machine system and software at Institut de Physique du Globe de Paris (IPGP).

Extraction of features from images of particles. Particle images were quantitatively analyzed to extract 33 measurements of particle properties (Figure 1B), hereafter called features. These characterize the particle shape, texture, and color (see Figure 1C for three examples; and Benet et al.[9] for their definition and calculation). Shape features were obtained from the particle contour and have been extensively used to characterize perimeter-based irregularities, particle-scale cavities, and/or overall external morphology[11–13]. Textural features were quantified from the distribution of grayscale pixel intensity values on the particle surface. Features such as the dissimilarity or correlation are calculated from the Gray Level Co-occurrence Matrix (GLCM[14]), to distinguish for example between high textural complexity and uniform smoothness. Color features were extracted as the mean, mode and standard deviation of the distribution of each channel in both the Red-Green-Blue (RGB) and Hue-Saturation-Value (HSV) color spaces. These features are sensitive to chromaticity, indicative of dominant color hues, intensity, and brightness. The procedure for feature extraction was automated through a Python script available in a public GitHub repository (https://github.com/dbenet-max/volcashdb_classification) and run in the High-Performance Computing center S-CAPAD at IPGP.

Procedure for image classification. Ash particles were classified from visual inspection of the images into free-crystal, altered material, juvenile and lithic types (Figure 1C) following the criteria described in[9]. The main approach involves recognizing diagnostic features for each type. In short: Free crystals are identified by their well-faceted shapes, sometimes exhibiting twinning and cleavage, and color. Altered material appears in colors ranging from white to yellowish, with a granular texture and a variety of hydrothermal secondary minerals, sometimes showing devitrification textures and secondary minerals. Lithic particles are characterized by their dark, dull appearance, and non-vesicular density with incipient alteration and rounded edges. The classification of some of the particles sometimes included Scanning Electron Microscope (SEM) analysis to examine for etch pits or alteration signs. Juvenile particles are distinguished by their gloss, smooth-skinned surface and lack of alteration. SEM analyses are sometimes necessary to ascertain the lack of alteration signs [6,15,16].

Database design. The database is structured using MongoDB, a NoSQL database that organizes data into flexible, schema-less *collections*. These *collections* store and manage various types of volcanic data (Table 1). They include the *Volcanoes* and *Eruptions collections* (Figure 2) 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[17]. 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 technique, and lab procedures such as cleaning and sieving. The *Particles collection* contains a unique identifier for each particle with its associated image, metadata such as the imaging conditions, and the 33 measured *features*.

Architecture and Technologies of VolcAshDB web-based platform. The platform consists of two main parts, a data input of images from which the features are extracted, and a data output that allows for search, visualization, analysis and downloading of the data (Figure 3). The platform is built using the MERN stack, which includes MongoDB, Express.js, React.js, and Node.js. The backend uses Node.js and Express.js for server-side functions, while MongoDB stores and manages the data. The frontend is built with React.js, providing a responsive interface for easy interaction and visualization. Communication between the client and server is handled through a RESTful API. The platform runs on a Linux server managed by Proxmox VE, with deployment managed by PM2 for process control.

Data Records

Access. VolcAshDB contents are publicly accessible for image and feature visualization and plotting through the VolcAshDB interface at https://volcashdb.ipgp.fr/catalogue, and for download after logging in. To sign up, users must provide an email for verification. The data are licensed under CC-BY-4.0 and can be cited using the DOI https://doi.org/10.18715/ipgp.2024.lx32oxw9.

Data coverage. As of September 2024, VolcAshDB contains the 33 *features* and classified image data from 12,044 volcanic ash particles from 53 samples across 13 different volcanoes (Table 2). The collection comprises basaltic to rhyolitic magmas, and a range of activity types, including phreatic eruptions, lava dome explosions, basaltic lava fountaining, and Plinian to Sub-plinian eruptions. The database also includes experimental samples that provide insights into the effect of alteration of the particles under a range of specific conditions of temperature and oxygen fugacity[18]. Some of our samples have also been used to better understand volcanic processes during activity, such as for Nevados de Chillán eruptive period, 2016-2018[19], or are currently being investigated to obtain critical insights into the eruption progression at Marapi, 2023–2024 (Nurfiani et al., *in prep*).

Technical Validation

Effect of image resolution and focus on measured features. To evaluate how the features extracted from the particle images are affected by poor resolution or focus, we modeled how the feature values change by varying the two parameters on our particle images. For this we used four particle images with different shape, texture and color. The resolution unit we use to model is defined by the number of pixels (pxls) comprised in the area (a) of the particle per image (pxls/a). We found that feature values only begin to shift when resolution falls below 3.5x104 pxls/a, whereas our average image resolution is 1.41x106 pxls/a, confirming that our resolution is more than sufficient (Figure 4A). To evaluate the effect of focus, we applied a Gaussian blur to the images (measured in sigmas). We found that feature values remain stable until the blur reaches 0.2 sigma, beyond which convexity starts to change and some instances become truncated (Figure 4B). This shows that extracted features in our database are not influenced by poor focus.

Usage Notes

Catalogue, Image Browsing and Data Download. Users can access the page "Catalogue" at https://volcashdb.ipgp.fr/catalogue to browse images. The catalogue contains two subsets of data, those of natural samples and those of experimental samples. Users can swap between them by ticking the "Natural Data" button. Advanced image searching can be done by using a set of filters displayed as tags with dropdown menus (Figure 5). Filters include options for volcano, eruptive activity type, grain-size fraction, particle type and shape. To download the filtered images, particle features and metadata, users must first sign up by providing an email address, country, and institute. Upon email verification, users will be able to click on "Apply Filters" and "Download Images and Measured Features". A zip file is automatically created which can be downloaded with the filtered particle images and an excel spreadsheet. The spreadsheet contains the particle features and metadata (imaging conditions, volcano, date of emission, etc.) and each row represents a particle of the dataset.

Data analysis and Plots. Users can access https://volcashdb.ipgp.fr/analytic to visualize and interact with various plots that illustrate the contents of the database in various manners (Figure 6). Plots are provided for natural or experimental samples, and users can swap between them by ticking the "Natural Data" button. Pie charts show the proportions of number of particles per volcano, per particle type and per activity type, and users can select or unselect specific subgroups. Juvenile–Altered material–Lithic ternary diagrams show the proportion of particle types normalized without free crystals per sample and according to eruptive activity type. We also analyze by Principal Component Analysis the features as reported in Benet et al.[9] and show the data transformed into the Principal Components 1 and 2. The plot is accompanied with a dropdown menu that allows users to select among eruptive activity types. The "Subplinian", for instance, shows a distinctive cluster of juvenile particles in violet color. Histograms show the distribution of values of a given feature and two dropdown menus allow choosing which feature and by which volcano. Further insights from all plots can be obtained by hovering with the mouse over any marker.

Code Availability

The Python program for feature extraction and for Principal Component Analysis are available at https://github.com/dbenet-ntu/Volcash-Project. The code for the web-based platform is available at https://github.com/dbenet-ntu/VolcAshDB-web_Sept2024. The Python code was developed using its version 3.9. Data wrangling and analysis was done using Numpy v.1.21.6, Pandas v. 1.3.5, image processing using Scikit-image v.0.19.2 and opencv v.3.4.2, and plotting by matplotlib v.3.5.1 and seaborn v.0.11.2.

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Author contributions

Benet led the development, acquired and processed the data, and wrote the original manuscript of the project, which was supervised and revised by Costa. Migadel and Benet led the development of front-end and the back-end of the web-platform. Lee, D'Oriano, Pompilio, Nurfiani and Rifai provided some samples. The final version of the manuscript has been read, reviewed and approved by all co-authors.

Competing interests

The authors declare no competing interests.

Figures

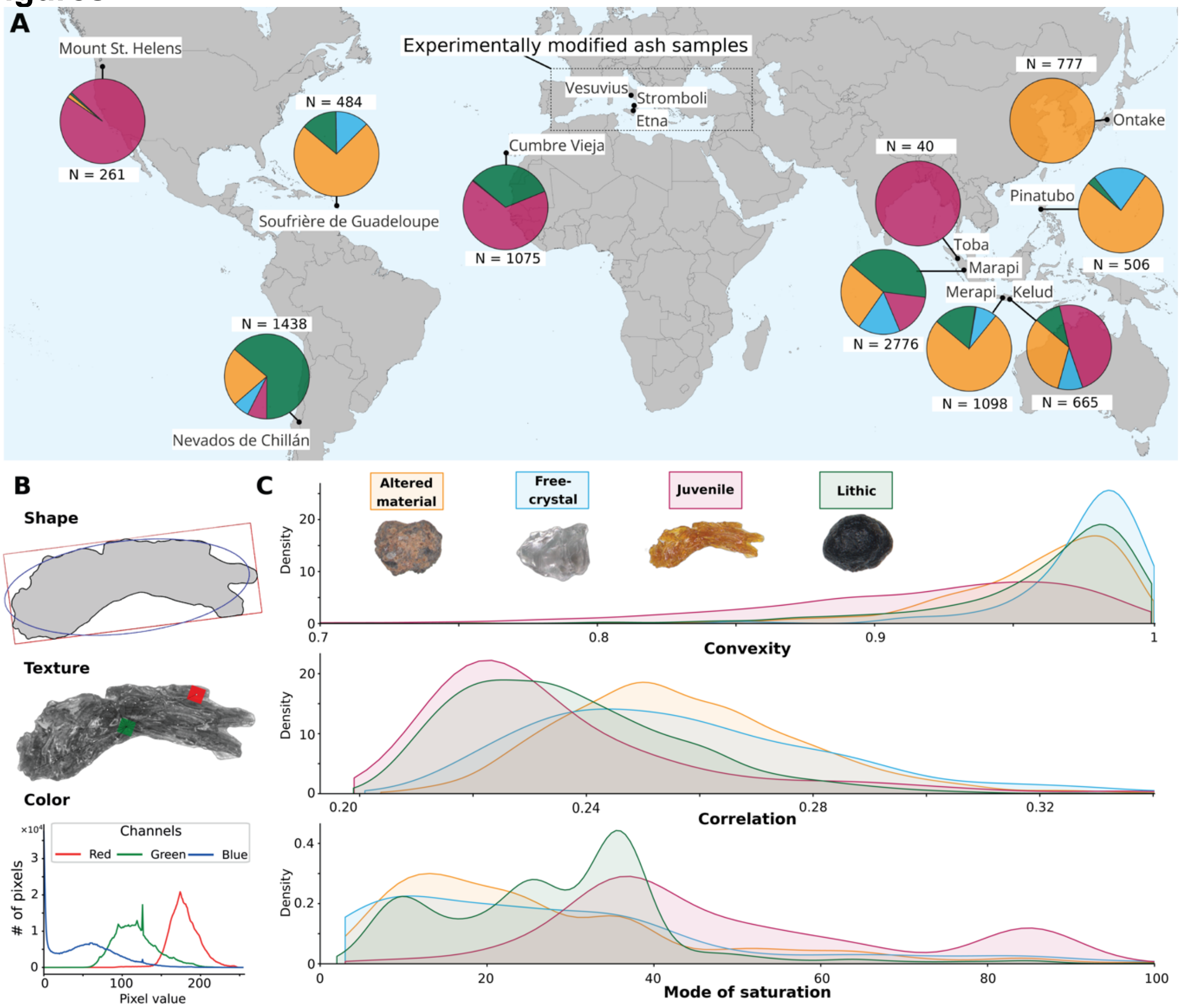

Figure 1

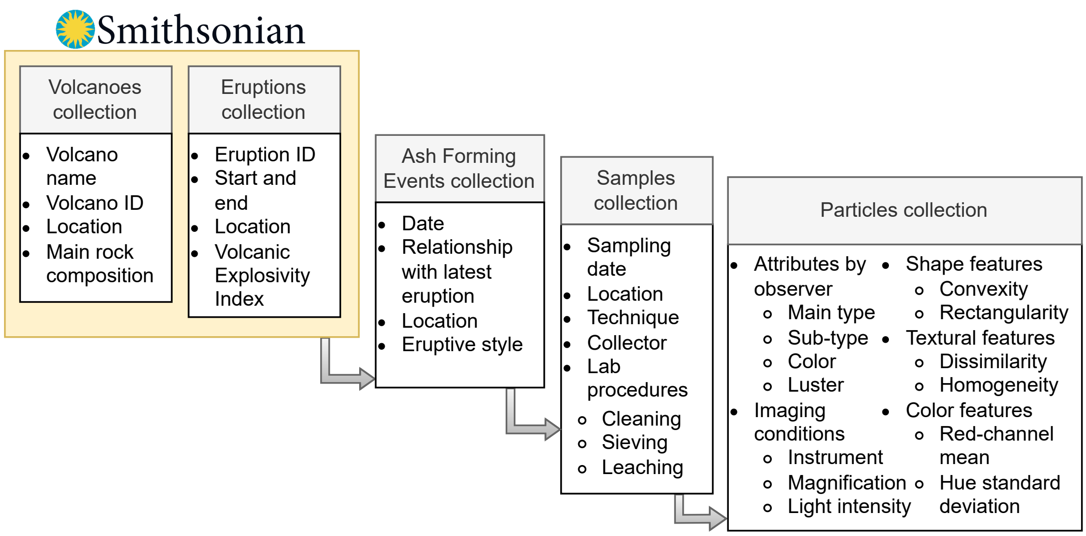

Figure 2

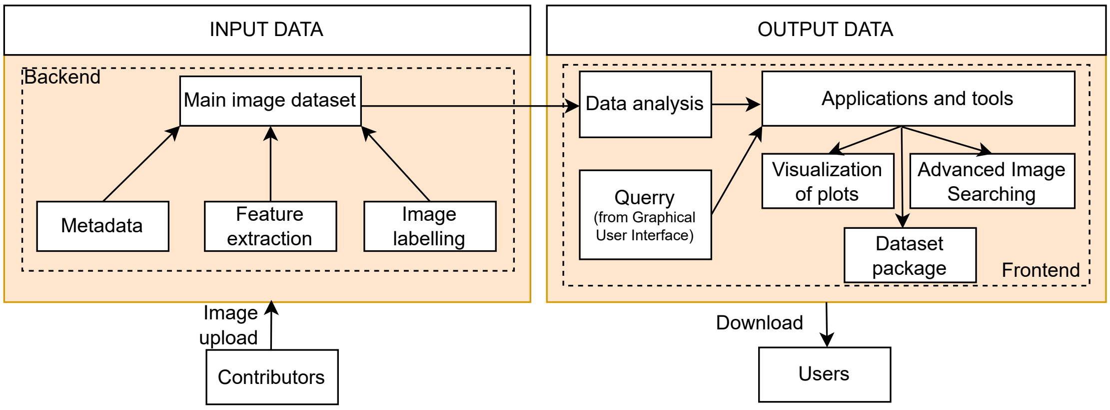

Figure 3

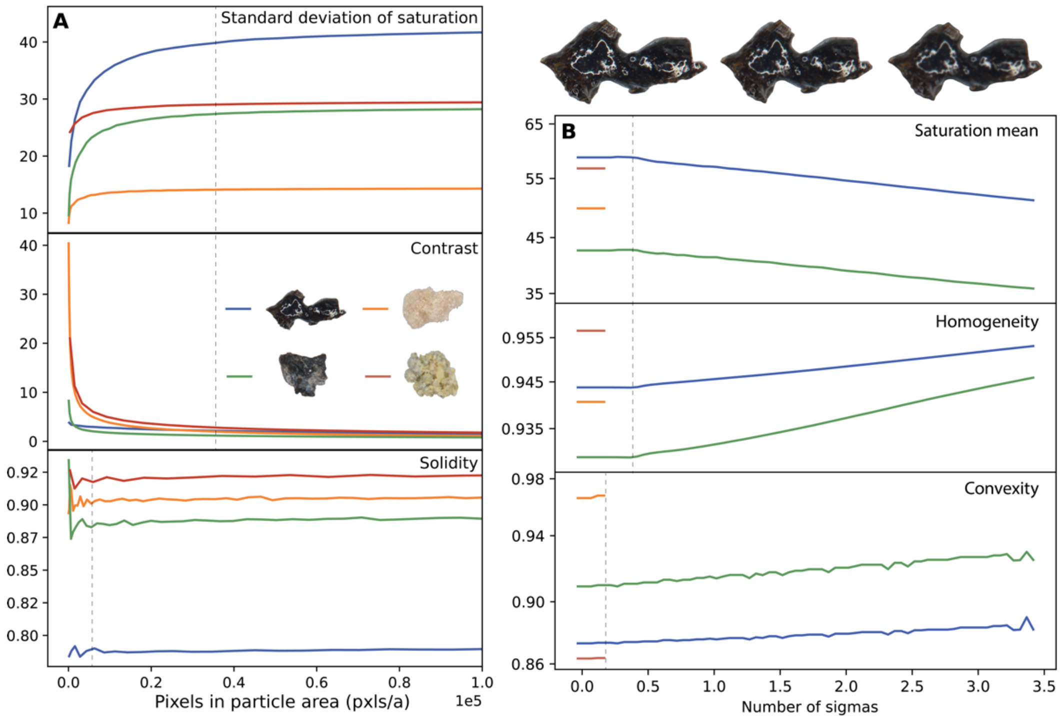

Figure 4

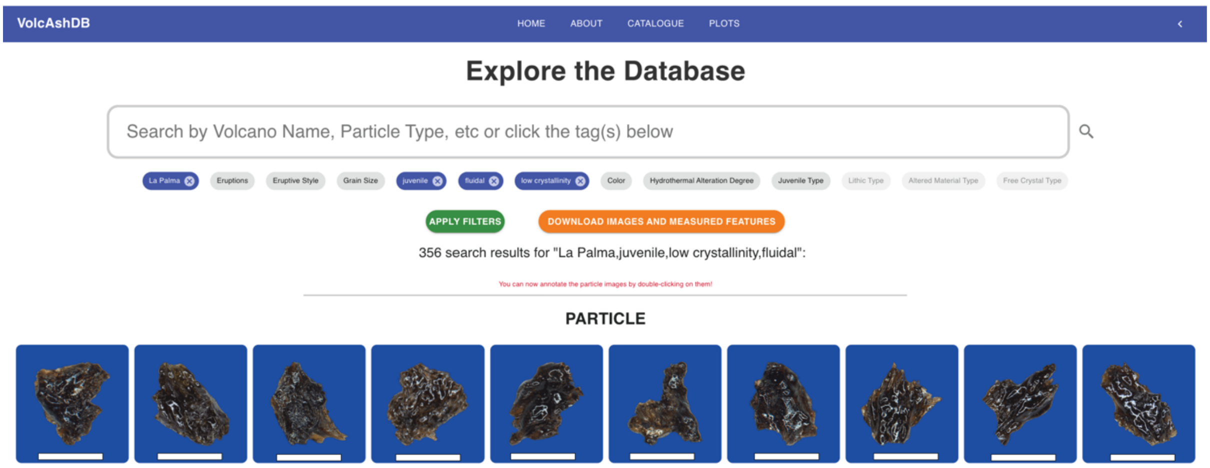

Figure 5

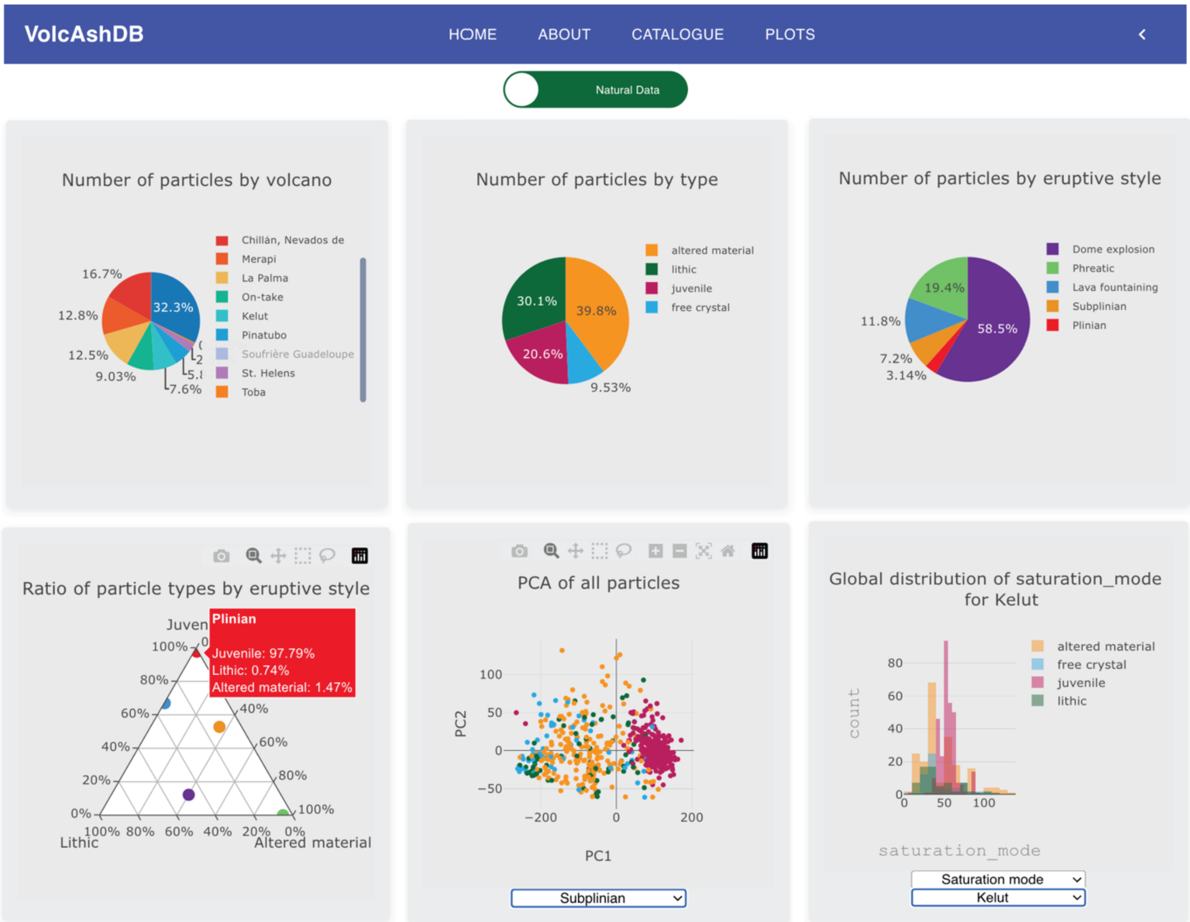

Figure 6

Figure Legends

Figure 1: Summary of the main contents and data types found in VolcAshDB. (A) World map[20] with the location of volcanoes for which we have collected data, and pie charts showing the average proportion of the particle main types (orange color is altered material, blue is free-crystal, violet is juvenile and green is lithic) of samples by volcano. (B) Examples of the properties we have measured for each ash particle, including the contour for shape, the grayscale homogeneity of the surface for texture, and the color-channels histogram distributions for color. (C) Plots showing the varied distributions of three particle features (convexity, correlation, mode of saturation) across the four main types (color-coded as above). "Density", in the y-axis, is the probability density function calculated by the Kernel Density Estimate plot, which can take values above 1.

Figure 2. Schematic of the database hierarchical design based on five MongoDB *collections*. Lists within bullet points are not exhaustive. *Volcanoes* and *Eruptions collections* were adopted from Smithsonian's "Volcanoes of the World" database (Global Volcanism Program, 2024).

Figure 3. Dataflow, main tasks and general architecture of the web-based platform.

Figure 4. Plots with the modelled feature values to estimate the influence of image focus and resolution. (A) The values of the features standard deviation of saturation, contrast, solidity are modelled by decreasing pixel resolution, and (B) the values of saturation mean, homogeneity, convexity are modelled at varying blur for four representative particle images with grain-size between 1–2 mm. Colors of the curves in (A) and (B) correspond to the different particles shown inside the

"Contrast" panel. The effect of the Gaussian blur to the original image (top-left image) is shown at 5 (top-center) and 10 (top-right) sigmas. Dashed lines indicate the values of resolution or focus beyond which feature values start to shift.

Figure 5. Screenshot of the "Catalogue" page in VolcAshDB web site. The screenshot includes the following filters: "Volcano Name" as "La Palma", "Main Type" as "juvenile", "Shape" as "fluidal" and "Crystallinity" as "low". The white bars show the scale for 1 mm under the microscope.

Figure 6. Screenshots of six representative plots from the "Plots" page in VolcAshDB web site.

Tables

Table 1: List of fields and definitions of the collections that make VolcAshDB.

Field	Type	Optionality	Description
Volcanoes collection (source Smithsonian database)			
_id	ObjectId	O[1]	Document identifier
volc_name	String	M[2]	Volcano name
volc_num	Int(32)	M	Volcano identifier
volc_slat	String	M	Volcano location (latitude)
volc_slon	String	M	Volcano location (longitude)
volc_status	String	O	Status of the volcano
volc_type	String	O	Type of volcano
Eruptions collection (source Smithsonian database)			
_id	ObjectId	O	Document identifier
volc_num	Int(32)	M	Volcano identifier
volc_name	String	M	Volcano name
ed_stime	Date	M	Eruption start date
ed_etime	Date	M	Eruption end date
Ash-Forming Events collection			
_id	ObjectId	O	Document identifier
afe_code	String	M	Ash forming event identifier
volc_num	Int(32)	M	Volcano identifier
afe_date	Date	M	Ash forming event date
eruptive_style	String	M	Description of eruption style
afe_lat	String	M	Ash forming event location (latitude)
afe_lon	String	M	Ash forming event location (longitude)
plume_col	String	O	Plume color
max_plume_height	Int(32)	O	Maximum recorded plume height
fumarolic_activity	String	O	Observed fumarolic activity intensity
Samples collection			
_id	ObjectId	O	Document identifier
sample_stime	Date	M	Sampling date
sample_lat	String	M	Sampling coordinate latitude
sample_lon	String	M	Sampling coordinate longitude

sample_nat	Boolean	M	Sample is natural or experimental
sample_techn	String	O	Technique (e.g. ashmeter)
sample_surf	String	O	Sampling surface (e.g. roof)
sample_collector	String	O	Collector/s name
ultrasound	Boolean	O	Ultrasonicated
gsLow	String	M	Lower value of grain-size fraction
gsUp	String	M	Upper value of grain-size fraction
Particles collection			
_id	ObjectId	O	Document identifier
imgURL	String	M	Filename of the particle's image
main_type	Object	M	Main type of the particle
sub_type	String	O	Sub type of the particle
color	String	O	Color of the particle
luster	String	O	Luster of the particle
shape	String	O	Shape of the particle
crystallinity	String	O	Crystallinity of the particle
alter_degree	String	O	Degree of alteration of the particle
weathering_sign	String	O	Presence of weathering signs
instrument	String	O	Instrument for particle image
magnification	Int(32)	O	Magnification of particle image
multi_focus	Boolean	O	Use of multi-focus for particle image
convexity[3]	Double	M	Convexity of the particle (shape)
contrast[3]	Double	M	Contrast of the particle (texture)
hue_mean[3]	Double	M	Mean value of hue histogram (color)

1: "O" stands for "Optional"
2: "M" stands for "Mandatory"
3: Only one feature for each category of shape, texture and color is listed as example. See Benet et al [9] for more details.

Table 2: Characteristics of the volcanoes represented in our database and number of particles that have been analyzed and archived.

Volcano	Magma composition	Volcano type	Reference	# particle images
Cumbre Vieja	Trachybasalt / Tephrite Basanite	Cinder cone	[21]	1075
Kelud	Andesite / Basaltic Andesite	Stratovolcano	[22]	665
Merapi	Basaltic Andesite	Stratovolcano	[23]	1098
Soufrière de Guadeloupe	Basaltic andesite-Andesite	Stratovolcano	[24]	484
Nevados de Chillán	Basaltic-Andesite	Dome complex	[25]	1438
Ontake	Andesite	Stratovolcano	[26]	777
Pinatubo	Dacite	Caldera	[27]	506

Mount St. Helens	Dacite	Stratovolcano	[28]	261
Marapi	Andesite	Stratovolcano	[29]	2776
Toba	Dacite / Rhyolite	Caldera	[30]	40
Vesuvius (EXP)[1]	Tephriphonolite	Stratovolcano	[18]	806
Etna (EXP)	Trachybasalt / Tephrite Basanite	Stratovolcano	[18]	1374
Stromboli (EXP)	Basalt	Stratovolcano	[18]	645

1: (EXP) denotes that the sample has been experimentally obtained for example by crushing scoria into ash-sized grains [18].

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