PDCD-DAT – A global database of pyroclastic density current deposit field data

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Abstract:

Pyroclastic density currents represent one of the deadliest hazards posed by active volcanoes. Analysis of their deposits provides valuable insights into their internal dynamics and informs numerical simulations of pyroclastic density currents which underpin many volcanic hazard assessments. We present PDCD-DAT, a global database of pyroclastic density current deposit characteristics compiled from peer-reviewed literature. The database includes both quantitative datasets (e.g., grain size, density, bedform dimensions, thickness) and qualitative descriptors (e.g., sedimentary structures, lithofacies). PDCD-DAT includes data from 85 source publications, covering 97 eruptions or eruptive phases, and 214 individual depositional units from 55 globally distributed volcanoes. Eruptions recorded in the database range from VEI 1-8. We highlight examples of potential applications of the database, which include i) comparison of single deposit case studies to global datasets, ii) informing input parameters and conditions for numerical and analogue models of pyroclastic density currents, iii) validation of numerical and analogue models against a wide variety of natural case study deposit architectures, and iv) estimating hazard impact metrics of pyroclastic density currents from past eruptions. We show that the database represents a useful tool for improving our ability to model pyroclastic density currents, predict their associated hazards and understand the relationships between the internal dynamics of pyroclastic density currents and the properties of their deposits. PDCD-DAT is integrated with the FlowDat Mass Flow Database, which provides a sustainable platform for the database. We aim for PDCD-DAT to be expanded in the future through addition of pyroclastic density current deposit datasets from new field studies conducted by the volcanology research community.

Key words: Pyroclastic density current, deposit, database, grain size data, sedimentary structures, volcanic hazard, volcano

Introduction

Pyroclastic density currents (PDCs) are mixtures of ash, gas and rocks that form during explosive volcanic eruptions, or via lava dome collapse following rainfall or gravitational failure of perched loose material. PDCs pose one of the greatest volcanic hazards to populations near active volcanic centres and are directly responsible for over 90,000 deaths since 1600 AD (Auker et al. 2013). The internal dynamics of PDCs cannot be directly observed and much of our understanding of their complex physics is inferred from analysis of the deposits they leave behind. For example, the sedimentary structures within PDC deposits (e.g., cross-stratification, grading) and changes in maximum clast/grain size and deposit thickness with distance from source are used to infer properties of the parent current, e.g., high or low particle concentration, turbulent or granular flow (e.g., Branney and Kokelaar 2002; Sulpizio et al. 2007; Brand et al. 2016; Palladino and Giordano 2019; Giordano et al. 2024). The interpretation of PDC dynamics from their deposits is important for reconstructing eruption processes at individual volcanoes and informing hazard assessments. Complementary insights into PDC internal dynamics can be obtained from numerical models and analogue experiments, which simulate PDCs at varying scales and degrees of complexity. However, our ability to use numerical and analogue models to test relationships between deposit properties and the currents and/or processes that formed them is limited by a lack of compiled quantitative datasets for different PDC deposit architectures to inform and validate against. Here, we address this limitation and present a first global compilation of PDC deposit characteristics.

Data obtained from PDC deposits, such as grain size distributions (GSDs) and particle shape and density, are key input parameters in numerical simulations of PDCs (e.g., Gueugneau et al. 2020; Esposti Ongaro et al. 2020; Calabrò et al. 2022), which are becoming increasingly important for hazard assessment at active volcanoes (e.g., Charbonnier et al. 2020; Esposti Ongaro et al. 2020; Gueugneau et al. 2024; Aravena et al. 2024). For example, the product of particle sphericity (a shape parameter) and Sauter mean diameter (calculated from the grain size distribution) can be used to estimate the permeability of complex volcanic mixtures, which controls the formation and diffusion of elevated gas pressure in multiphase models (Breard et al. 2019). Particle density influences particle settling velocity and therefore represents an important parameter for modelling sedimentation from PDC's (e.g. Dellino et al. 2008; Kelfoun 2017; Jones et al. 2023).

Deposit data can also be used to inform input parameters in benchmarking studies which compare the outputs of different PDC models against a solution (field-based, analytical, etc) and assess their strengths and weaknesses. Ogburn and Calder (2017) used multiple physical and empirical models to simulate PDCs from Soufrière Hills Volcano (Montserrat, Lesser Antilles) and compared how well the different models reproduced characteristics of the natural PDC deposits (a field-based solution) such as runout and inundated area. Properties of the natural deposits, such as H/L (Ratio of height descended (H) to PDC runout (L)), volume, and planimetric area, were used to calculate model input parameters.

Field observations from natural PDC deposits (e.g., thickness, grain size and deposit temperature during emplacement) can be compared with model outputs to validate the extent to which numerical and analogue models are able to realistically simulate natural PDCs (Charbonnier and Gertisser 2012; Charbonnier et al. 2013; Lube et al. 2015; Kelfoun et al. 2017; Brosch and Lube 2020). For example, Smith et al. (2020) show that bedforms produced in their analogue experiments simulating dense, granular flows have similar morphology and stoss side angles to bedforms in the Pozzolane Rosse ignimbrite deposits of Colli Albani volcano. Kelfoun et al. (2017) showed that their numerical simulations of PDCs were able to quite accurately reproduce key characteristics of PDC deposits from the 2010 eruption of Merapi volcano, including thickness and volume.

Studies of PDC deposits can also improve our ability to forecast the hazards associated with PDCs. The hazard potential of PDCs can be evaluated based on parameters such as the dynamic pressure, which is used to estimate whether PDCs will damage buildings (Zuccaro et al. 2008), and particle volumetric concentration, which influences whether humans caught in a PDC can survive (Baxter et al. 2017; Dellino et al. 2021a). Recent models allow these hazard impact metrics to be estimated for dilute PDCs from past eruptions based on deposit properties such as grain size, bedform dimensions and particle shape (Dioguardi and Mele 2018; Dellino et al. 2021b). The estimated values for hazard impact metrics are assumed to be representative of the PDC at the location of the sampled outcrop (Dioguardi and Mele 2018; Dellino et al. 2021b) and represent time averages.

However, our ability to compare and collate comprehensive field datasets for integration with numerical, analogue and hazard models is currently limited, because i) many studies of PDC deposits focus on a single eruption or sometimes an individual depositional unit; (ii) there is no standardised approach for documenting deposit characteristics and (iii) there is no publicly available database of PDC deposit characteristics. Rather, many studies that attempt to use field data to inform or compare with either numerical or analogue models rely on single case studies (e.g. Charbonnier and Gertisser 2012; Salvatici et al. 2016; Kelfoun et al. 2017; Smith et al. 2020).

In this contribution, we present a global database of PDC deposit characteristics (PDCD-DAT), incorporating quantitative data (e.g., grain size, density, bedform dimensions) and qualitative descriptions of deposit appearance (e.g., sedimentary structures, lithofacies). PDCD-DAT is integrated with the FlowDat Volcanic Mass Flow Database (Ogburn, 2012, 2025). Integration with FlowDat provides a long-term sustainable platform for our database, which will allow for it to be expanded in the future and enables users to explore relationships between PDC deposit characteristics and the bulk PDC characteristics (e.g., volume, area) and mobility metrics (e.g., runout length, H/L) already recorded in FlowDat.

PDCD-DAT can be used for a variety of applications, including i) comparison of single deposit case studies to global datasets, ii) informing numerical and analogue model input parameters, iii) validation of numerical and analogue models against a wide variety of natural deposits, iv) estimating hazard impact metrics of PDCs from past eruptions to inform hazard assessments, v) identifying discrepancies between data required by modellers and the data most commonly collected and reported in PDC field studies. Therefore, the database represents a tool for improving our understanding of the dynamics of PDCs and our ability to model their complex physics and predict their associated hazards. We intend for PDCD-DAT to be expanded and improved in the future through incorporation of additional existing studies and members of the volcanological research community submitting newly collected quantitative datasets.

Construction and content

To determine the deposit properties to be recorded in the database, we compiled an initial list of quantitative measurements (e.g., grain size, componentry, bedform dimensions) and qualitative descriptors (e.g., sedimentary structures, lithofacies codes) commonly used in the literature to document PDC deposits. Further properties were added to the database throughout the compilation process, to capture the wide variety of data types reported in field studies of PDC deposits.

The FlowDat database (Ogburn, 2012, 2025) was used as a starting point to identify target PDC deposits and sources of PDC deposit data. We focused on eruptions in FlowDat for which quantitative data were already recorded for one or more of the following bulk PDC properties or mobility metrics: total flow bulk volume, total flow planimetric area, runout and H/L. This approach was chosen to enable users of the database to explore the relationships between PDC deposit properties and other PDC properties/mobility metrics. We searched the literature for studies on PDC deposits associated with these eruptions and relevant peer-reviewed studies containing at least one form of quantitative data were incorporated into the database. FlowDat also contains data on eruption VEI, magma composition and geographic location. Care was taken to ensure that deposit data for a global distribution of volcanoes, and eruptions spanning a wide range of magnitudes and magma compositions, were incorporated into the database.

We sourced additional data from the authorship teams' publications, as well as studies known to the authorship team containing high-quality quantitative datasets and example datasets for the least frequently reported properties, e.g., grain shape, Sauter mean diameter. Incorporating such example datasets ensures that additional datasets reporting these properties can be easily added into the database in the future, without modifying the data import template. Data from publications suggested by the wider PDC research community were also incorporated, following discussions at the 2nd National Science Foundation community workshop 'Benchmarking of PDC models and other avenues' held in August 2024. PDCD-DAT does not include datasets from submarine or welded PDC deposits, which are often described using different metrics to non-welded subaerial deposits (Quane and Russell, 2005).

The database currently includes data from 85 source publications, covering 97 eruptions or discrete phases within long-lived eruptions, and 214 individual depositional units. Seventy-two of the eruptions/eruption phases recorded in PDCD-DAT have associated data on PDC mobility metrics, VEI and magma composition in FlowDat. Eruptions recorded in the database vary in magnitude from VEI 1-8 and have magma bulk compositions ranging from basaltic andesite to rhyolite, and trachybasalt to trachyte and phonolite. The database includes deposits from 55 volcanoes distributed across 6 continents (Additional File 4).

We acknowledge that PDCD-DAT does not represent a complete record of published PDC deposit data and that our database compilation strategy introduces some limitations. For example, PDC deposits have been more extensively studied for volcanoes in some regions (e.g., Europe, North America) than others (e.g., Indonesia), hence PDCD-DAT contains data from multiple references for some volcanoes (e.g., Vesuvius), but none for other volcanoes which are known to produce frequent PDCs (but which are documented in FlowDat, e.g., Sinabung, Semeru). The lack of PDC deposit studies on volcanoes located in tropical/highly vegetated regions such as Indonesia is likely a product of poor exposure and high potential for erosion of PDC deposits in these regions (e.g., Carn, 1999).

Some PDC deposit properties (e.g., grain shape parameters) have far fewer entries than other properties that are more commonly reported (e.g., grain size). Although we have included at least one example dataset for all deposit properties recorded in the database, it is possible that our compilation strategy has overlooked some studies reporting the less well represented properties.

Eruptions of VEI 3-6 make up ~80 % of eruptions/eruption phases recorded in the database; PDCs from very low and high magnitude eruptions are less well represented. This is likely a reflection of the lower preservation potential of smaller volume deposits associated with lower VEI eruptions (e.g. Cowlyn et al. 2020), or simply that small, frequent PDCs are less often studied, and the less frequent occurrence of very high magnitude eruptions. At ocean island volcanoes, even high magnitude eruptions may be poorly preserved due to deposition into the surrounding ocean (e.g. Porecca et al. 2018). We hope that future expansion of the database will address some of these limitations, especially the low number of entries for certain deposit properties such as grain shape.

In PDCD-DAT, quantitative data is usually reported for individual samples/sampling locations or lithofacies, while qualitative observations may be reported for specific sampling locations or more generally for depositional units (or lithofacies). While PDCD-DAT is integrated into the relational SQL FlowDat database, we also provide a flat-file, spreadsheet version of the data (Additional File 1). This flat file is organised into nine categories – Metadata, Grain size, Grain Characteristics, Componentry, Sedimentary Structures, Bedforms, Thickness, GSD breakdown and Temperature. Each category is represented by a table containing a series of columns which record relevant PDC deposit properties. Each row in the tables represents an individual data entry (e.g., grain size measurements for a given sample, sedimentary structure(s) within a unit, bedform dimensions at a given distance from vent). The PDC deposit properties recorded in each category are briefly described below – the full list of properties and their definitions are provided in Additional File 2.

Metadata

The Metadata table records details of source publications and metadata associated with the data recorded in other tables, including the volcano and eruption date, vent and sampling location co-ordinates, the "PDC type" (e.g., concentrated, surge) as determined by the study authors, and the names of depositional units, sampling locations, sample names/identifiers and lithofacies codes. This table also includes event and unit IDs used to associate data across the tables and with FlowDat PDCs (see "Event and Unit ID explainer" tab in Additional File 2).

Grain size

The Grain Size table records raw grain size distributions (in phi units), the most frequently reported statistical parameters used to describe grain size (median diameter, sorting coefficient, F1 weight percentages) and maximum juvenile (pumice or scoria) and lithic clast sizes. The methods/equations used by source publication authors to calculate statistical parameters and determine maximum clast sizes, and the grain size range analysed for each sample, are reported to allow users to assess comparability of different datasets. Users are encouraged to refer to source publications for further details of the methods used to measure grain size. Raw GSD data is reported in 1 phi intervals to maintain consistency. If source publications reported data in half phi intervals, the data has been grouped into 1 phi bins accordingly. The notes column records additional relevant details, including whether more precise half phi interval data is available in the source publication, and grain sizes which were observed/measured but excluded from reported GSDs by authors e.g. “blocks > -6 phi”.

GSD Breakdown

The GSD Breakdown table contains example datasets for less frequently reported measures of grain size. These include statistical parameters (median diameter, sorting coefficient) for individual components (juveniles, lithics) and statistics for grain sub-populations obtained via deconvolution of polymodal grain size distributions.

Grain Characteristics

The Grain Characteristics table records measurements of individual grain/clast characteristics including (bulk) density and shape parameters (e.g., aspect ratio, Fourier Shape Analysis morphological coefficients) and the equations used to calculate these values.

Componentry

The components of PDC deposit samples are often specific to a particular volcano (e.g., ripped up fragments of the substrate lithology). To facilitate comparison between deposits from different locations, the Componentry table records the proportions of the general component categories “juveniles”, “lithics” and “crystals”. For the vast majority of samples documented in the database, components were explicitly assigned to one of these three categories in the source publication. We note that the definitions of “juvenile” and “lithic” may vary between studies and the reported values simply reflect the interpretation of the source publication authors. The Componentry table also records the grain size range analysed for componentry, in phi units, and whether the values were reported as wt % or proportions, to allow users to assess comparability of datasets.

Sedimentary structures

The Sedimentary Structures table contains columns titled with general terms used to describe structures in PDC deposits, e.g., massive, inverse grading, cross-stratification. In many source publications, sedimentary structures were described for depositional units as a whole, rather than individual sampling locations. In this scenario, all sample data entries from a given unit were assigned the relevant sedimentary structure. The "Notes" column is used to provide additional details of sedimentary structure distribution within a depositional unit, e.g., "lower half of unit inverse graded, upper half normally graded". Quantitative data associated with sedimentary structures, such as thicknesses of strata and angles of cross-stratification are also recorded.

Bedforms

The Bedforms table records quantitative measurements of bedform dimensions and features, e.g., length/wavelength, stoss and lee angle, plus relevant contextual information such as the underlying depositional slope angle, where reported. In Additional File 2, we provide typical definitions for bedform measurements. For example, "wavelength" is typically used to refer to the distance between the crests or troughs of two adjacent/periodic bedforms, whereas length is typically used to refer to the distance between the base of the stoss and lee sides of a single bedform. We recommend that users check the definitions for bedform measurements used in source publications (if provided by their authors), which may differ slightly from the typical definitions listed in Additional File 2, when comparing bedform datasets.

Thickness

The Thickness table records depositional unit thicknesses as either measured values or a range. Contextual information, including whether the top and base of a unit was exposed and the underlying topography at locations where thickness was measured (e.g., valley confined vs overbank), is also recorded where available.

Temperature

The Temperature table records estimated emplacement temperatures for PDC deposits and the methods used to calculate them.

Strategy for reporting of data

The names of depositional units, sub-units, and sample codes/lithofacies codes in the database exactly match the source publications wherever possible, to allow users to further investigate specific datasets or samples with ease. In some cases, we assigned a sample name (e.g., ML1 for a measurement of maximum lithic size at a given distance) to provide a unique identifier for a given data entry. The “PDC type” column reflects the terminology used by source publication authors to describe the type of current which formed the deposit (e.g. “block-and-ash flow”, “surge”, etc). The terminology used in the database to record sedimentary structures matches the majority of source publications, though the exact choice of wording describing the same feature may differ between sources (e.g., “parallel” vs “planar” stratification).

Quantitative data (e.g. distances, thicknesses, grain size, componentry, etc) were recorded directly from published tables of values or the source publication text, wherever possible. For deposit thickness, only numerical values were recorded in the database – measurements listed in the format “centimetre-decimetre”, without explicit values, were excluded. For source publications where quantitative data was only presented in figures, we manually extracted the data using the free online tool WebPlotDigitizer (https://apps.automeris.io/wpd4/). The “data source” column(s) in each table denote whether the data was obtained from a table, figure, text, or “estimated from figure” if extracted using WebPlotDigitizer.

The most common type of data extracted from figures were GSDs. Manual calibration of plot axes and manual selection of data points, combined with the low resolution of some figures, led to small inaccuracies in extracted GSDs (totals above or below 100 %). Therefore, all GSDs extracted from figures were normalised so that the sum of all grain size fractions totalled 100 %. We assessed the reproducibility of GSD extractions from figures using WebPlotDigitizer by performing 10 GSD extractions on the same figure, containing a GSD composed of 9 grain size fractions (-5 to 4 phi). The totals (prior to normalisation) of extracted GSDs ranged from 100.2-101.8. The relative standard deviation (expressed as (2SD/mean) * 100) of the normalised values for each grain size fraction was < 4 %, which confirms the reproducibility of our method for GSD extraction. When compiling the database, we found that uncertainties on quantitative data from PDC deposits are rarely reported, hence we do not list them for most of the properties recorded in the database.

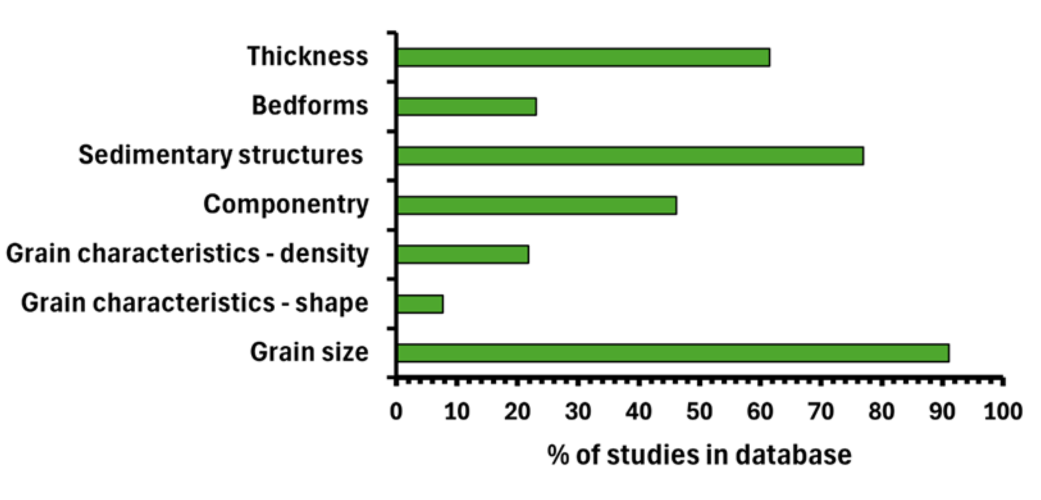

Figure 1: Percentage of studies in PDCD-DAT, excluding those included solely to record deposit emplacement temperatures, from which data corresponding to each category was extracted (n = 79). A further six studies were included in the Temperature category – no other data was obtained from these six studies.

Utility and discussion

Range of data recorded in PDCD-DAT

Figure 1 shows the percentage of studies in the database, excluding those included solely to record deposit emplacement temperatures, from which data corresponding to each category was extracted. Grain size represents the most frequently recorded data category (91% of studies), followed by sedimentary structures (77%). Density (22 %) and grain shape parameters

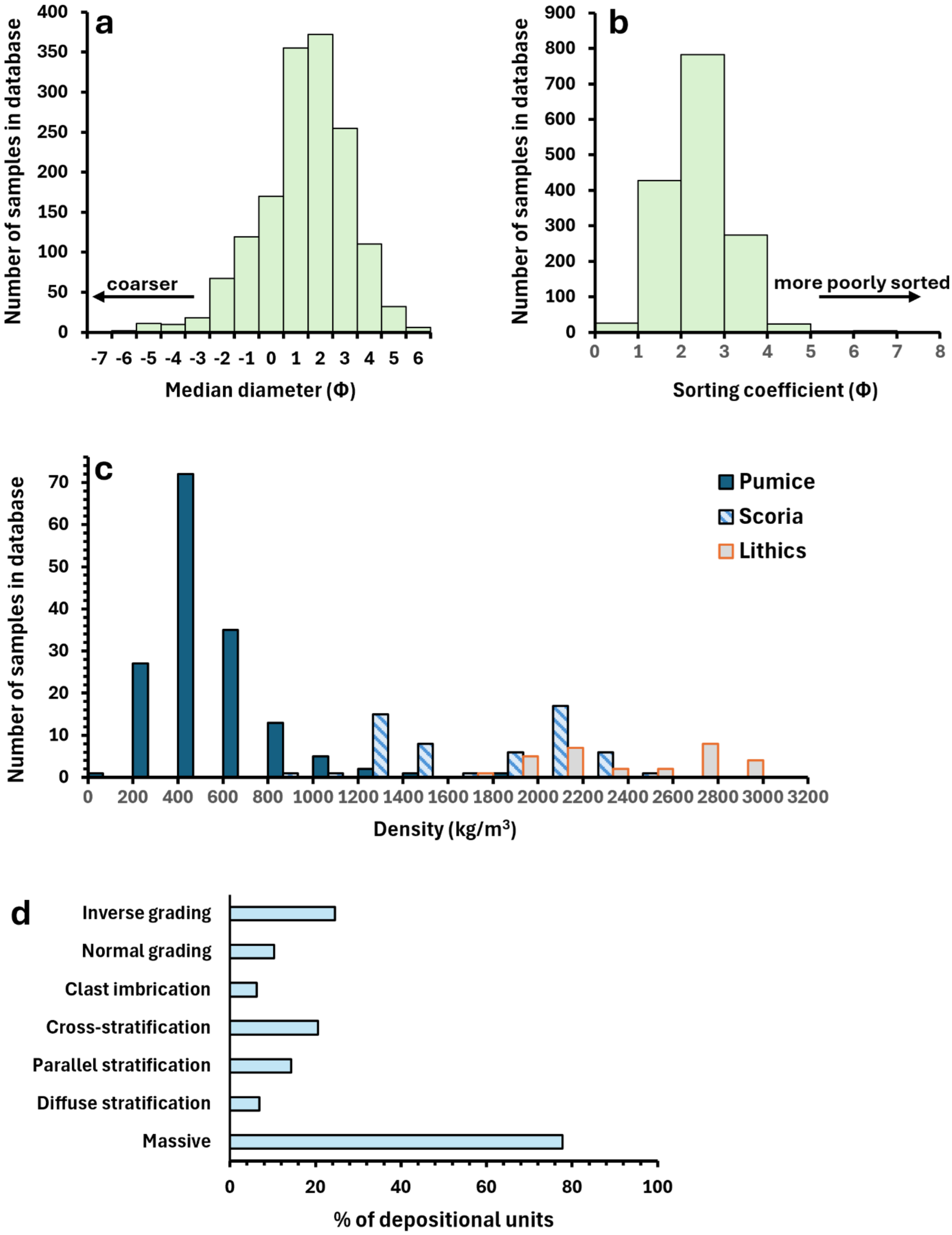

Figure 2: Distribution of **a)** median diameter, **b)** sorting coefficient and **c)** clast density values for all individual PDC deposit samples recorded in PDCD-DAT. Clast density values are taken from the "avg" column (Additional File 1) for pumice, scoria and lithic density. **d)** Percentage of depositional units recorded in PDCD-DAT displaying each type of sedimentary structure. Note that some units are associated with more than one sedimentary structure.

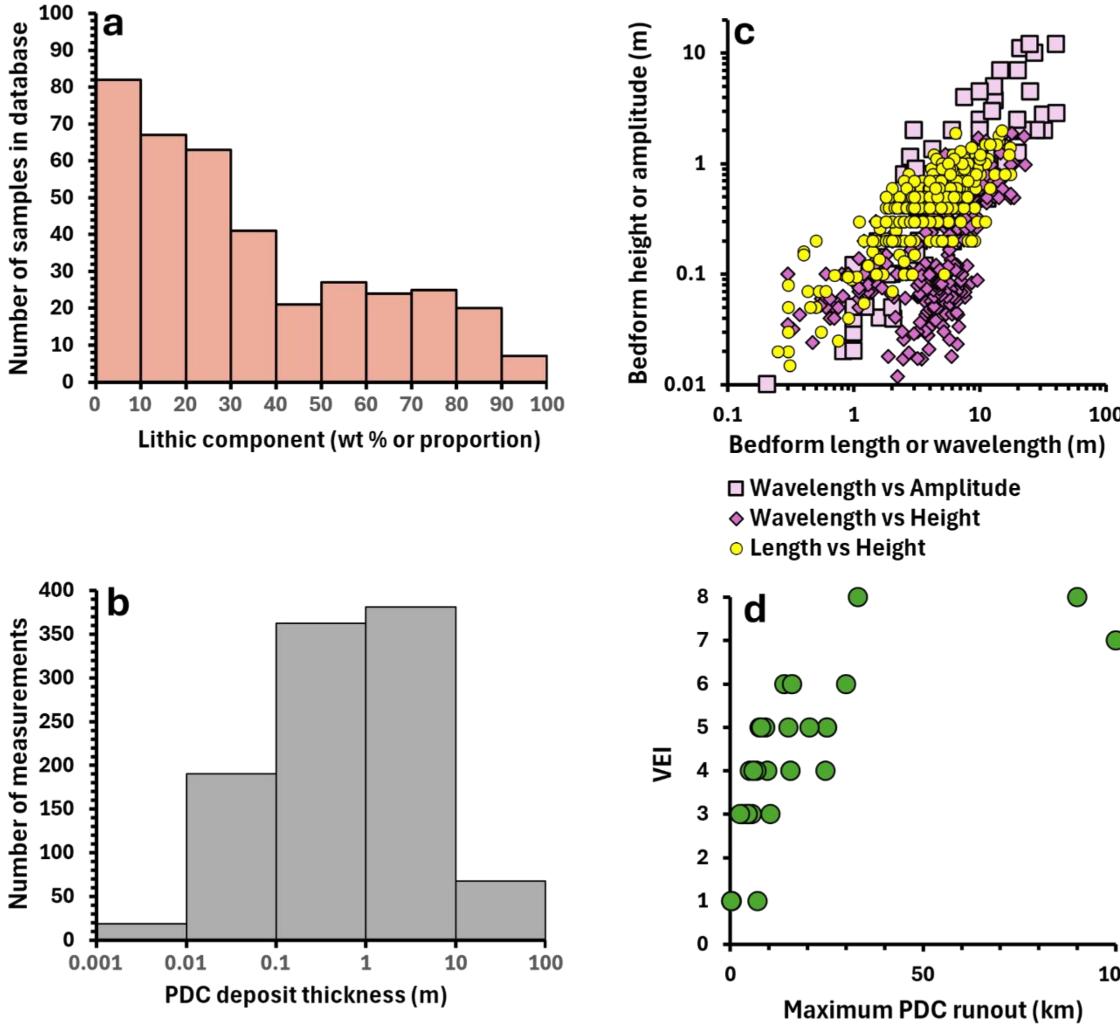

Figure 3: a) Distribution of percentage lithic component values for all individual PDC deposit samples recorded in PDCD-DAT. Note that percentage lithics is reported as both wt % and proportion depending on the source publication (Additional File 1). **b)** Distribution of PDC deposit thickness measurements (m) recorded in PDCD-DAT. **c)** Distribution of bedform measurements recorded in PDCD-DAT. Data is grouped by the different measurement combinations used to document bedforms – wavelength vs amplitude, wavelength vs height,

length vs height. **d)** VEI vs maximum runout values from the Flowdat database (Ogburn 2012, 2025) for all eruptions in PDCD-DAT which have associated data for these two metrics in Flowdat.

(8%) are the least frequently recorded data categories. Figures 2 and 3 illustrate the range and distribution of data recorded in PDCD-DAT. Individual samples of PDC deposits cover a wide grain size range, with median diameters between -7 and 6 phi and sorting coefficients between <1-8 (Figure 2, a,b). The majority of recorded PDC deposits (~78 % of depositional units) are either partly or entirely massive (Figure 2, d). Inverse grading is the most frequently reported sedimentary structure (recorded for 25 % of depositional units), followed by cross-stratification (21%) (Figure 2, d). The diverse componentry of PDC deposits is illustrated by the proportion of reported lithics, which varies from 0-100 % (Figure 3, a), though > 50 % of PDC deposit samples contain < 30 % lithics. PDC deposit thicknesses recorded in the database span four orders of magnitude, ranging from < 1 cm to 80 m (Figure 3, b). Bedform wavelengths and amplitudes vary from 0.2-40 m and 0.01-12 m respectively (Figure 3,c), whereas bedform lengths and heights span a slightly narrower range of 0.25-17.5 m and 0.01-2 m. Estimated PDC deposit emplacement temperatures recorded in the database range from 170-480 °C.

Applications of the database

In this section, we highlight some of the potential applications of PDCD-DAT using examples.

Informing, validating and benchmarking numerical and analogue models of PDCs

The database provides a valuable resource for reducing uncertainties associated with the choice of input parameters in some numerical and analogue models of PDCs. Grain size/GSDs, grain density and shape represent key input parameters in many numerical simulations of PDCs (e.g., Kelfoun et al. 2017; Gueugneau et al. 2020; Esposti Ongaro et al. 2020; Calabrò et al. 2022) and analogue experiments (e.g., Lube et al. 2015; Breard and Lube 2017; Smith et al. 2020). For example, Kelfoun et al. (2017) showed that their model outputs for total area covered by deposits and runout distance increased by ~20 % and 13 % respectively for a 50 % decrease in particle diameter used in the model simulation. The database can be used to select these parameters for individual eruptions to inform models aiming to reproduce PDCs formed during past events.

Comparison of modelling results with PDC deposit data provides a useful tool for validating numerical and analogue models of PDCs. Determining the extent to which models reproduce the features of natural PDC deposits may demonstrate how accurately these models simulate natural PDCs and depositional processes. Datasets such as thickness and grain size variations with distance from source are key deposit characteristics that can be compared with model outputs to evaluate the performance of numerical models (Charbonnier and Gertisser, 2012; Kelfoun et al. 2017; Gueugneau et al. 2020; Tadini et al. 2021). The integration of PDCD-DAT with FlowDat enables users to obtain additional data commonly used for numerical model validation, such as runout length and planimetric area (Widiwijayanti et al. 2009; Kelfoun et al. 2017; Gueugneau et al. 2020) and link this to the data for grain size, thickness, etc. PDCD-DAT enables numerical models to be calibrated against PDC deposits displaying a wide range of characteristics, from eruptions of different magnitudes (Figure 3d). Therefore, PDCD-DAT can support the modelling community to determine the best performing and most reliable models for assessing the hazards posed by PDCs with specific characteristics and/or during different magnitude eruptions.

Similarly, comparison of the sedimentary structures, grain size distributions and bedform appearance and dimensions in deposits formed in analogue experiments with natural PDC deposits can be used to confirm whether experiments can successfully replicate the transport and depositional processes of natural PDCs (Dellino et al. 2007; Lube et al. 2015; Brosch and Lube 2020: Smith et al. 2020). PDCD-DAT will enable analogue modellers to validate experiments which produce any of the common sedimentary structures/lithofacies reported in PDC deposits. Analogue experiments have the potential to provide new insights into the relationships between sedimentary structures/lithofacies/bedforms and the properties and internal processes of the currents which formed them, ultimately improving our ability to interpret natural PDC deposits.

Datasets for specific eruptions could also be used to select input parameters for benchmarking exercises which compare the outputs of different numerical models against a defined solution e.g. a natural deposit (e.g., Ogburn and Calder, 2017). Such benchmarking exercises can be used to evaluate the strengths and weaknesses of different models (e.g., how accurately do the models simulate natural PDC inundation, computational cost/time) to determine the scenarios in which they are best applied, e.g. as part of a procedure for rapid syn-eruption prediction of PDC inundation in a crisis.

Linking qualitative and quantitative PDC deposit data

Lithofacies and sedimentary structures exhibited by deposits (e.g., massive lapilli-tuff, cross-stratified tuff) are often used to infer conditions at the substrate-parent current interface, for example the common association of cross-stratified deposits with dilute and/or turbulent currents (e.g., Branney and Kokelaar, 2002; Giordano et al. 2024). Our database offers an opportunity to interrogate whether these qualitative descriptors can be associated with certain values or ranges in quantitative deposit properties, such as grain size, for deposits from a large number of eruptions.

A complete analysis of the database contents is beyond the objectives of this publication, but as an example of this application, we compare the grain size statistical parameters (median diameter and sorting coefficient) of PDC deposits displaying massive vs parallel/planar stratified and cross-stratified sedimentary structures in Figure 4a.

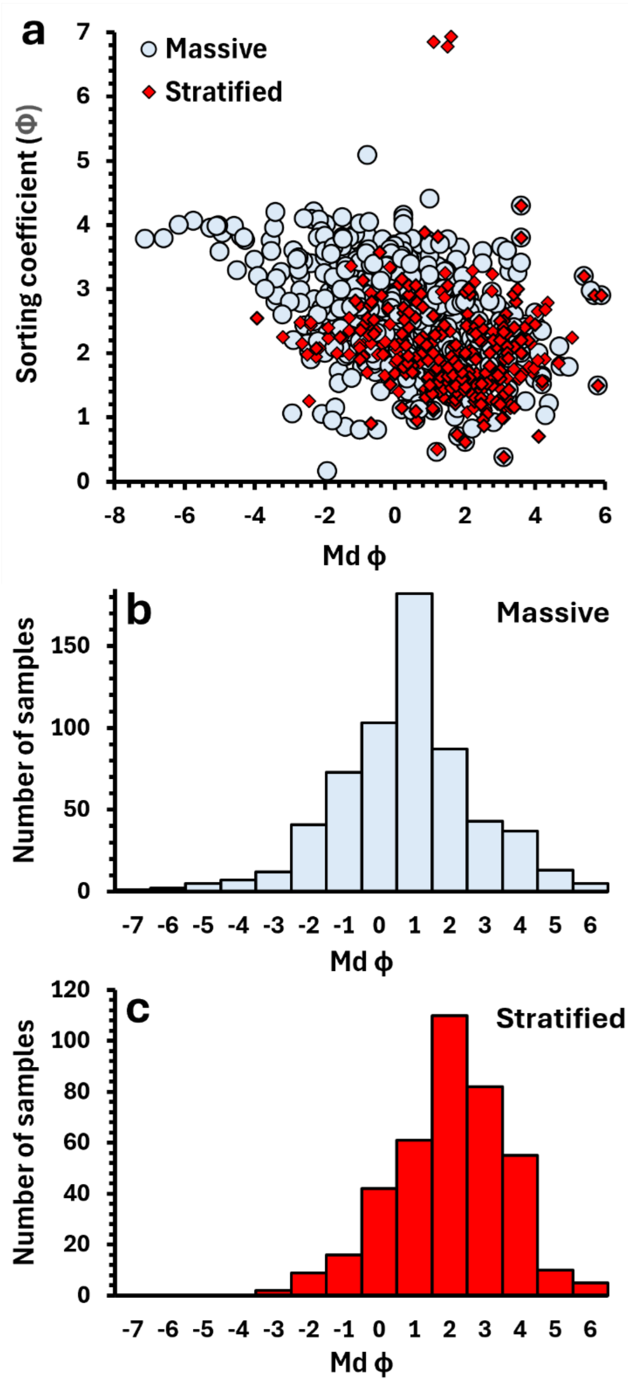

Figure 4: a) Median diameter (Md ϕ) vs sorting coefficient (phi units) for all PDC deposit samples in the database associated with massive (n = 611 individual samples), and parallel or cross-stratified (n = 392) sedimentary structures. **b)** Distribution of massive deposit median diameters. **c)** Distribution of stratified deposit median diameters. Note that the median

diameter and sorting coefficient values shown were calculated by source publication authors using multiple different equations and/or software (e.g. Inman 1952; Folk and Ward 1957; GRADISTAT (Blott and Pye 2001)). The corresponding grain size distributions are composed of varying grain size ranges and may have been measured in full or half phi units.

All data points reflect the values reported by source publication authors (as opposed to being calculated in this study). The reported median grain size and sorting of massive and stratified deposits show significant overlap, though massive deposits extend to larger median grain sizes and show a greater range in sorting compared with most stratified deposits (Figure 4). We note that not all data plotted is directly comparable due to the different equations employed by source publication authors to calculate statistical parameters and differences in the grain size ranges measured to obtain the corresponding GSDs (see the "grain size" tab, Additional File 1). Despite this limitation, the general trend shown could provide a guideline for the most representative median grain size(s) (or grain size distributions) to use in analogue experiments aiming to simulate PDCs which form either massive or stratified deposits.

Source publication authors often infer that a PDC deposit was formed by a parent current with specific characteristics (recorded in the "PDC type" column of the Metadata tab, Additional File 1). The database captures a varied terminology that has evolved as our understanding of PDCs evolves (for a recent review, see Lube et al., 2020). Broadly, currents described in publications in the database are categorised according to end-member definitions referring to the particle concentration of the current, that can be grouped as "concentrated" (including "granular") or "dilute" (including "surge"). The term "block-and-ash flow (BAF)" is used for concentrated currents that formed deposits composed of mostly juvenile blocks in an ash matrix (Brown and Andrews 2015; Giordano et al. 2024). The term "lateral blast" (or blast surge) is commonly used in studies of the 1980 Mt. St. Helens eruption (e.g. Fisher, 1990) to describe a PDC formed during a laterally directed explosion. The term “pyroclastic flow” is also commonly used, and it is unclear whether this is a general term or should be interpreted to mean concentrated current (e.g., different to “surge”). Some studies simply use the term “PDC” and do not use further terminology implying the characteristics of the parent current.

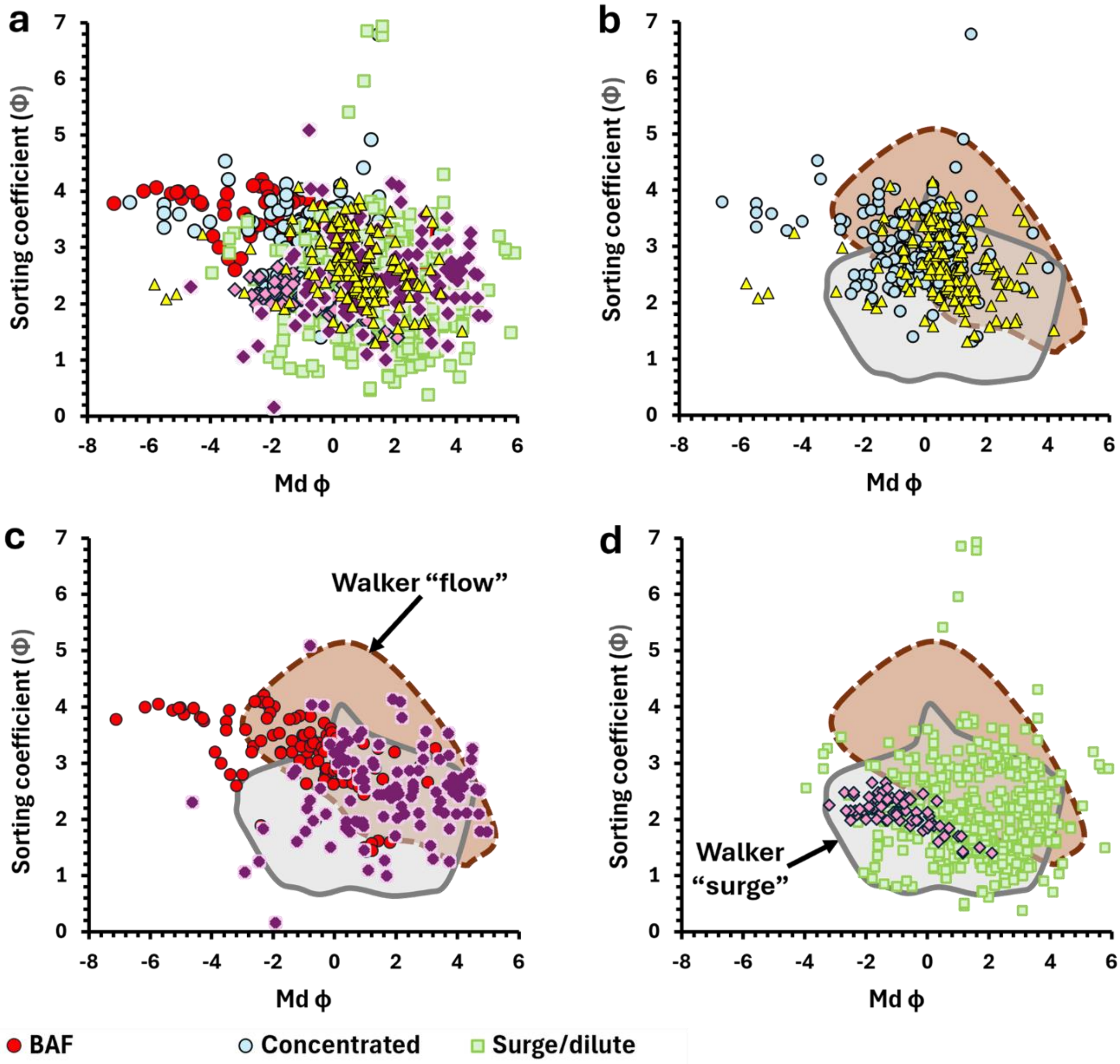

Figure 5: a) All data for median diameter (Md ϕ) vs sorting coefficient (phi units) in PDCD-DAT for deposits associated with a named “type” of pyroclastic current - “BAF” (n = 121 individual samples), “surge”/“dilute current” (n = 440), “concentrated current” (n = 180), “lateral blast” (n = 73), “pyroclastic flow” (n = 269), “PDC” (n = 112). **b), c), d)** The PDCD-DAT data for different named “types” of pyroclastic current are compared with the “pyroclastic surge” and “pyroclastic flow” fields of Walker (1983). Note that the median diameter and sorting

coefficient values shown were calculated by source publication authors using multiple different equations and/or software (e.g. Inman 1952; Folk and Ward 1957; GRADISTAT (Blott and Pye 2001)). The corresponding grain size distributions are composed of varying grain size ranges and may have been measured in full or half phi units.

We show median diameter vs sorting coefficient for PDC deposits inferred to have formed from different types of parent current in Figure 5, following the plots of Walker (1971, 1983) initially used to distinguish "pyroclastic flow" and "pyroclastic surge" deposits. The PDCD-Dat datasets for "pyroclastic flow" and "surge/dilute" extend beyond the equivalent fields defined by Walker (1971, 1983) and show a greater degree of overlap in grain size and sorting compared with the Walker (1971, 1983) "flow" and "surge" fields. Overall, Figure 5 demonstrates that the qualitative terminology used by source publication authors which implies parent current characteristics may not be reflected by clear differences in the reported quantitative properties of their deposits such as sorting and grain size. We note that these grain size statistical parameters may not accurately represent polymodal GSDs, such as those of many BAF deposits, and are not always directly comparable due to differences in the methods used to obtain GSDs and calculate statistical parameters (Additional File 1). Therefore, despite their common use, "Walker"-type plots may not represent a reliable tool for comparing PDC deposits or inferring parent current characteristics.

Comparing individual volcanoes and eruptions

PDCD-DAT offers a powerful tool for comparing PDC deposits based on a wide range of criteria, to identify similarities and differences between deposits from different volcanoes, eruptions, or "types" of parent current. Subsequent investigations into the factors controlling common trends in PDC deposit characteristics, and unique trends observed at individual volcanoes, have potential to yield improved understanding of fundamental aspects of PDC behaviour.

As an example of this application, in Figure 6 we compare trends of maximum juvenile and lithic clast size vs distance from source/vent for deposits from four eruptions. Maximum clast sizes decrease with distance from source in deposits inferred to have formed from dilute currents (Mt St Helens, Campi Flegrei). Deposits from two eruptions from the Vulsini volcanic district, Italy, show contrasting trends of decreasing lithic and increasing juvenile clast size with distance (Figure 6 c,d), which are interpreted to reflect deposition from concentrated currents (Palladino and Giordano 2019; Palladino and Pettini 2020). Future experimental and modelling studies could aim to reproduce these trends for dilute and concentrated currents to quantify the physical characteristics of the parent currents that produce them (e.g. flow density) and

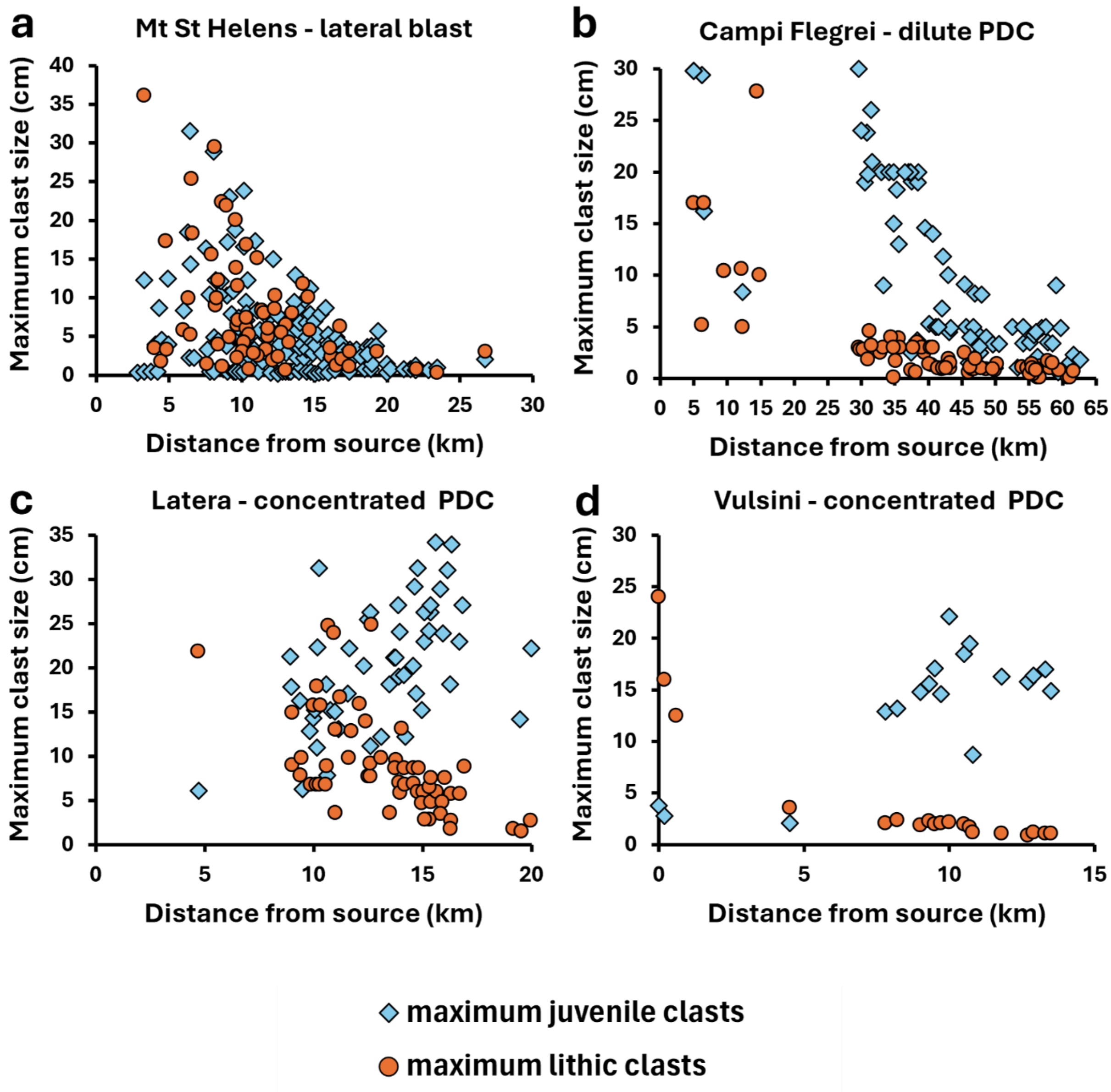

Figure 6: Maximum juvenile and lithic clast size vs distance from source/vent for deposits from four eruptions. **a)** Mt St Helens - data from the 18th May 1980 eruption (Fisher 1990). **b)** Campi Flegrei – data from the 39 ka Campanian Ignimbrite eruption (Silleni et al. 2024). **c)** Latera – data from the Arlena di Castro flow unit, erupted from the Latera Volcanic Complex, Vulsini, at 0.23 Ma (Palladino and Giordano 2019). **d)** Vulsini – data from the Orvieto-Bagnoregio ignimbrite, erupted from Vulsini at 333 ka (Palladino and Pettini 2020).

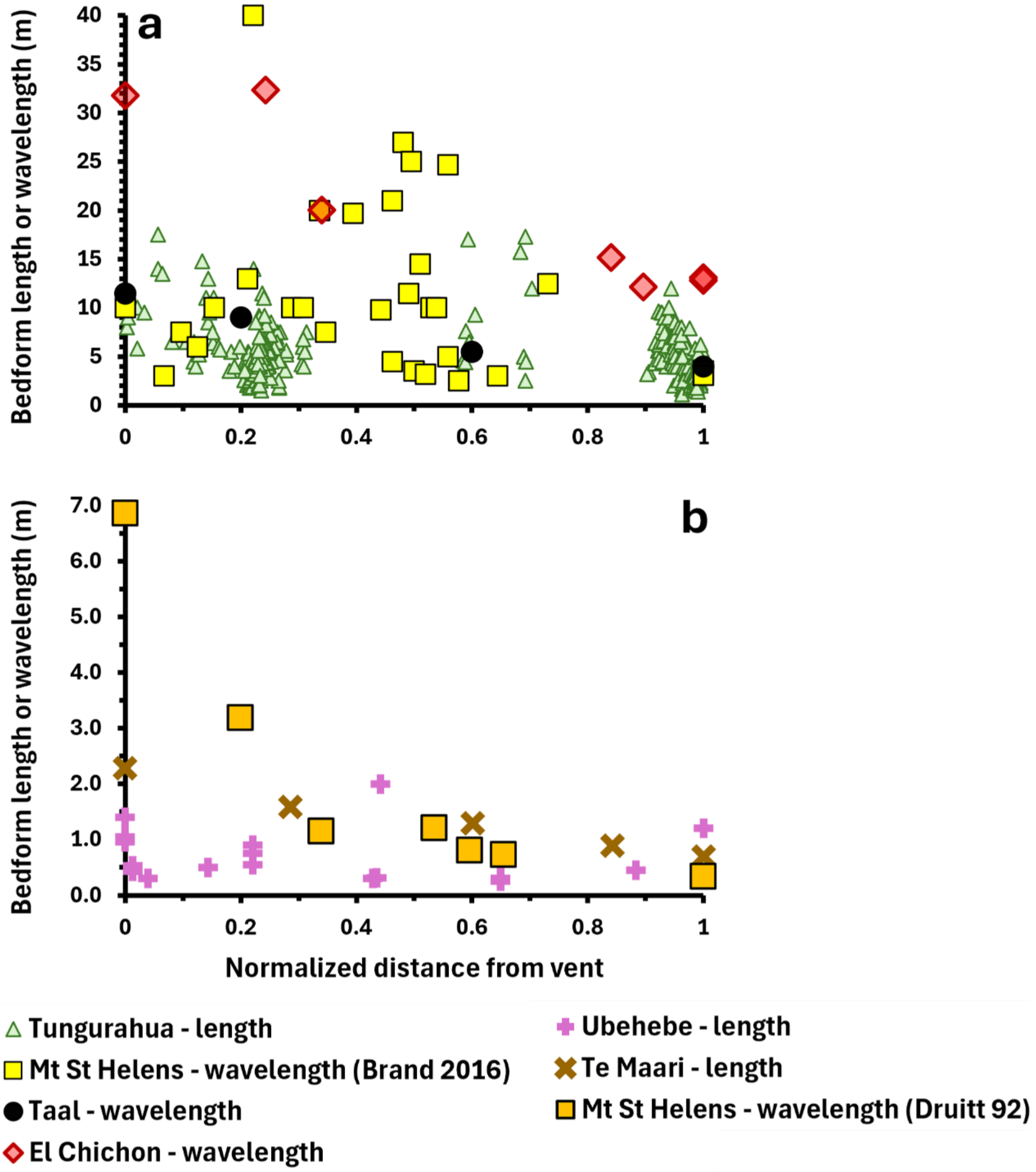

Figure 7: a), b) Trends of bedform length or wavelength vs distance from vent for PDC deposits from six different volcanoes. Wavelength refers to the distance between crests or troughs of

periodic bedforms. Length refers to distance between base of stoss and lee side of a single bedform. Tungurahua – data from the August 2006 eruption (Douillet et al. 2013). Mt St Helens, USA – data from the 18th May 1980 eruption (Druitt 1992; Brand et al. 2016). Taal, Phillipines – data from the 1965 eruption (Waters and Fisher, 1971). El Chichon, Mexico – data from the 4th April 1982 eruption (Sigurdsson et al. 1987). Upper Te Maari Crater, Tongariro, New Zealand – data from the 6th August 2012 eruption (Breard et al. 2015). Ubehebe craters, USA – data from deposits formed ~2.1 ka (Valentine et al., 2022). Normalised distance from vent = (sampling location distance – most proximal sampling location distance)/(most distal sampling location distance-most proximal sampling location distance).

associated ranges in hazard impact metrics (e.g. dynamic pressure) (Palladino and Giordano 2019).

Figure 7 shows that the length and wavelength of bedforms in PDC deposits from Taal, El Chichon, Mt St Helens, Te Maari and Ubehebe volcanoes generally decreases with distance from vent. The controls on this trend are poorly constrained, though it has been suggested that particle concentration, current velocity and current thickness may play a role (Brand et al. 2016). There is some evidence that bedform morphologies and scales can be quantifiably related to current characteristics (e.g. Dellino et al., 2020; Smith et al., 2020, Dellino et al., 2021b). The presence of this trend in the deposits of five different volcanoes implies that the factors controlling bedform length/wavelength may reflect processes common to many PDCs and is an important avenue for future exploration.

Estimating the hazard potential of past PDCs

The hazard potential of PDCs can be estimated by calculating hazard impact metrics, such as average dynamic pressure during the passage of the current at a given location (i.e., particle volume concentration and velocity) and the flow temperature near the substrate. These metrics can be estimated for past eruptions from deposit characteristics recorded in the database, including bedform wavelength and median diameter (grain size), for example using the equations provided by Dellino et al. (2021b). More advanced models, such as "PYFLOW 2.0", can be used to calculate hazard impact metrics from stratified deposits inferred to have formed from dilute currents, using thickness, grain size, density and shape input data (Mele et al. 2015; Dioguardi and Mele 2018). The database can be used to obtain these parameters where available and identify stratified deposits for which additional data could be obtained to facilitate these calculations. Metrics such as flow front velocity can be inferred from the size (e.g. maximum juvenile or lithic) and density of blocks reported from PDC deposits (Roche 2015; Roche et al. 2016).

Identifying gaps in data collection required for PDC modelling

Although we acknowledge that PDCD-DAT does not reflect a complete record of existing literature on PDC deposits, nor a random sample, it can be used to provide a guide to how frequently different types of PDC deposit data are reported.

Grain size, density and shape represent the main input parameters for numerical models of PDCs which can be derived directly from deposits (e.g., Dellino et al. 2008; Kelfoun et al. 2017; Esposti Ongaro et al. 2020; Calabrò et al. 2022). The low frequency of density and particularly shape measurements in PDCD-DAT (Figure 1, Additional File 1) suggests that it may not always be possible for modellers to obtain accurate constraints on these parameters from existing field data. Particle shape data, for example, sphericity and circularity, are required for calculation of the drag coefficient parameter used in many numerical models of PDCs (e.g. Dellino et al. 2008; Kelfoun et al. 2017; Dioguardi and Mele 2018; Gueugneau et al. 2020), which may otherwise be estimated by a trial and error approach which explores a range of possible values (Kelfoun et al. 2017; Gueugneau et al. 2020). Therefore, more frequent reporting of particle shape datasets in future field studies of PDC deposits will increase the amount of accurate particle shape data available to modellers.

Limitations of existing PDC datasets

PDCD-Dat can be used for a variety of applications, but users face some limitations due to the lack of standardised approaches to reporting PDC deposit (meta) data. For example, GSDs are determined using a variety of methods (e.g. dry and wet sieving, laser diffraction) and the range of grain sizes measured to obtain individual sample GSDs varies between studies (see “grain size” tab in Additional File 1). The equations used to calculate grain size statistical parameters such as mean diameter and sorting coefficient also differ between studies. Componentry data is inconsistently reported, as either wt % or proportion, and the criteria used for categorizing different components (e.g. juvenile, lithic) is not always clearly defined. Quantitative measurements of bedforms also vary in format, with some authors documenting wavelength/amplitude and others length/height (Figure 3c). These inconsistencies restrict the number of PDC deposits from different studies/volcanoes/eruptions that can be directly compared for some data categories.

Where studies report datasets such as GSDs and thickness only in figures, it was not always possible to accurately obtain these data for inclusion in the database; for example, if GSD histogram figures or thickness isopach maps were of insufficient resolution for digital extraction. Hence, published PDC deposit data for some volcanoes/eruptions is not always easily obtained for re-use by the wider scientific community. In constructing the database, we observed that few studies report uncertainties for quantitative data and grain size statistical parameters obtained from PDC deposits. Therefore, it is currently difficult to incorporate uncertainty on field/laboratory constrained parameters into numerical simulations of PDCs.

Conclusions and future developments

The PDCD-DAT database records both quantitative measurements from and qualitative descriptions of PDC deposits, representing 214 individual depositional units formed during 97 eruptions at 55 volcanoes distributed globally.

The database provides a valuable resource for improving numerical and analogue modelling of PDCs. Users can extract data from deposits with specific characteristics and/or from specific volcanoes and/or from eruptions of different magnitudes, to obtain well-constrained model input parameters and compare with model outputs for validation. Ultimately, the development of new and improved models has the potential to drive advances in understanding of the links between PDC dynamics and resulting deposits, as well as our ability to forecast and mitigate against the hazards posed by PDCs.

Some eruptions in PDCD-Dat have corresponding data on eruption source parameters in the IVESPA database (Aubry et al. 2021), which are used as inputs for numerical models of explosive eruption columns. Therefore, data from PDCD-Dat could be combined with IVESPA datasets to facilitate numerical modelling of past explosive eruptions involving both tephra fallout and PDC forming phases.

Some datasets for individual volcanoes can be used to estimate hazard impact metrics of PDCs from previous eruptions, providing valuable information for hazard assessment purposes. The database also enables users to compare deposits from different volcanoes and/or eruptions using many different criteria, to identify common trends and individual volcanoes/events where PDCs produced deposits with distinctive properties. Further investigation of the factors controlling common trends in PDC deposit characteristics may yield new insights into fundamental aspects of PDC behaviour and the interpretation of their deposits.

The integration of PDCD-Dat with FlowDat provides a sustainable platform for the database. A FlowDat website is currently under construction and PDCD-Dat will be hosted on a dedicated section of this website. The PDCD-Dat webpage will provide a user interface for searching and filtering the database and downloading selected data.

We envisage that PDCD-DAT will be expanded in the future, through addition of other existing published datasets and datasets from new field studies. We strongly encourage authors of future PDC field studies to submit their datasets for incorporation into the database. We provide a “data import template” for authors to submit their datasets in Additional File 3, which can be e-mailed to the corresponding author. This template will also be made available on the PDCD-Dat webpage once established. Future submissions of new, high-quality datasets will increase both the quantity and quality of the data available in PDCD-DAT, adding to its value as a resource for the scientific community studying PDCs.

List of abbreviations

PDC - Pyroclastic density current

GSD - Grain size distribution

BAF - Block and Ash flow

H/L – Ratio of height descended (H) to PDC runout (L).

Declarations

Availability of data and materials

The datasets supporting the conclusions of this article are included within the article and its additional files.

Competing interests

The authors declare no competing interests.

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Authors' contributions

JB compiled the database, made the analyses and wrote the first draft of the manuscript. SO advised on database construction. All authors input into discussions of the design of the database and contributed to the final draft of the manuscript. RW conceptualised the project and acquired the funding.

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Additional files

Additional File 1.xlsx

PDCD-DAT Flat File database – A spreadsheet containing the complete PDCD-DAT database.

Additional File 2.xlsx

PDC deposit properties definitions – A spreadsheet listing definitions for each PDC deposit property recorded in the database. Each property corresponds to a column in the database spreadsheet (Additional File 1).

Additional File 3.xlsx

Data import template – A blank spreadsheet with column headers corresponding to the PDC deposit properties recorded in the database. Researchers can download the spreadsheet and populate it with their field datasets, which can then be e-mailed to the corresponding author for inclusion in the database.

Additional File 4.pdf

Map - A figure showing a world map of the volcanoes featured in PDCD-Dat.