EUROVOLC

European Network of Observatories and Research Infrastructure for Volcanology

Deliverable Report

D18.1 Report on the WP18 TA and VA activities during the project

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Summary

WP18 provided accesses to the Volcano Dynamics Computatioanl Center (VDCC) at INGV Pisa, which is entirely dedicated to the design, development and application of numerical codes describing the dynamics of volcanic systems, from their plumbing regions at km depth to into the atmosphere and over the Earth topography. Access has been in the form of Trans-National (TA) and Virtual (VA) accesses, constituting two separate Tasks within the WP. TAs were offered in the form of supervised visits to our premises in order to use the numerical models we develop on our computing resources to help solve a scientific question relevant for the user; the project were first screened for technical feasibility and then ranked by an external panel for scientific validity. VAs were offered as possibility to run some relatively fast and efficient models online from the VDCC webpage, without any screening.

Both TAs and VAs were successful: the VDCC hosted a total of 6 TA projects in two calls, and accesses to the VA were in the hundreds from all over the world.

Introduction

The objective under this WP is constituted by access provision to the numerical resources of the VDCC at INGV Pisa, in the form of TA (Task 18.1) and VA (Task 18.2), for a total offering of 9 numerical code. The installations provided for TA are in turn organized into:

• Installation VDCC.1: Transient Multi-Dimensional Transport Models (TDMod). This installation includes three HPC numerical codes (**GALES**, **PDAC**, **ASHEE**) to solve the magma and volcano dynamics from magma chamber level into the atmosphere. Individual access is provided for each code, as it will be specified in the related calls. All codes are documented in the INGV VMSG (Volcano Modelling and Simulation Gateway) http://vmsg.pi.ingv.it/index.php/en/software.

GALES: (GAlerkin Least Squares) HPC finite element C++ code for 1 to 3D simulations of compressible-to-incompressible multicomponent magma dynamics within underground reservoirs, dykes, and conduits with user-defined geometries. It includes space-time-dependent properties as a function of local physical and chemical conditions, non-ideal multi-component volatile saturation modelling (SOLWCAD), and user-defined non-Newtonian rheology. Equipped with data processing and visualization routines in MATLAB and ParaView.
PDAC: Pyroclastic Dispersal Analysis Code, 3D model for the multiphase flow simulation of explosive eruption scenarios (volcanic plumes and pyroclastic density currents).
ASHEE: (ASH Equilibrium Eulerian) Finite volume code based on the C++ libraries of OpenFOAM. It solves the compressible transient 3D transport equations for a multiphase gas-particle mixture. The code is fully parallel (tested up to 4000 cores). Sub-grid turbulence is treated with dynamic LES models. Kinematic non-equilibrium between the gas and the particle phases is solved accurate and efficient up to Stokes number 0.2 (1 mm for volcanological applications). The code can be used to model explosive eruptions, from the buoyant plume column down to the turbulent dilute part of pyroclastic density currents. Pyroclasts coarser than 1 mm can be treated with the Lagrangian approach (up to 10 Mparcels). A series of bash, python and paraview scripts are available for pre and post processing.

• Installation VDCC.2: Fast Performing Models (FPMod). This installation includes three numerical codes (**CONDUIT4**, **MrLavaLoba**, **PLUME-MoM**), requiring small computational time, to solve the dynamics of magma ascent and eruption for specific volcanic phenomena and under simplifying assumptions which guarantee sufficient accuracy for a large range of applications, with small computational times. Individual access is provided for each code, as it will be specified in the related calls. All codes are documented in the INGV VMSG (Volcano Modelling and Simulation Gateway) http://vmsg.pi.ingv.it/index.php/en/software.

CONDUIT4: Fast and versatile FORTRAN77 software that solves the fluid dynamics of magma ascent along volcanic conduits. It is a steady-state, 1D model which includes volatile exsolution as a function of magma composition, pressure and temperature. It includes strain-induced fragmentation as a consequence of gas exsolution as the magmatic mixture ascends towards the surface at decreasing pressures. Recently the code has been extended to 1.5D by computing the radial distribution of vertical velocity due to non-Newtonian rheology.
MrLavaLoba: Python code that can be ascribed to the "probabilistic family" of lava flow simulation codes. Nevertheless, in contrast with other probabilistic codes, this code explicitly tackles not only the direction of expansion of the growing flow and the area covered, but also the volume of the emplaced lava over time, and hence the supply rate. The developer of the model will support users in the installation of the code, the setup of simulations and in the post-processing of model results. In addition, it will be shown how to use the model to perform sensitivity and uncertainty quantification analysis.

PLUME-MoM : FORTRAN90 code designed to solve the equations for a steady-state integral volcanic plume model, describing the rise in the atmosphere of a mixture of gas and volcanic ash during an eruption. Either a finite number of particle sizes, or a continuous distribution of particles size described with the method of moments, can be assumed. A suite of Python scripts to integrate PLUME-MoM with existing dispersal code and to perform uncertainty quantification and sensitivity analysis is provided..

The installation provided through Virtual Access (VA) is the following:

• Installation VDCC.3: Virtual Access Models (VAMod). This installation provides virtual access to three numerical codes (**MAMMA**, **SOLWCAD**, **PYBOX)** sufficiently fast to be run interactively. The Virtual Access to the Volcano Dynamics Computational Center at INGV Pisa (http://www.pi.ingv.it/progetti/eurovolc/) allows any user to run three different codes online, or to download executables and/or source code if needed. Each one of the three accessible codes allows users to:

i) perform web-based computations and download the results;

ii) download the open source code and perform computations on a personal PC.

Additionally, the SOLWCAD code allows users to download an open source routine that can be linked to user's codes to perform more complex computations, e.g., by embedding the SOLWCAD code for gas-melt thermodynamics within user's models for magma transport dynamics. Each code is complemented with a user manual, which provides detailed description of usage in the different modes above, with examples and explanation of input and output files. Relevant rferences are also provided.

SOLWCAD: models water and carbon dioxide phase partitioning in magmas of any composition;

MAMMA: describes steady-state magma ascent in volcanic conduits;

PYBOX: simulates the kinematics of pyroclastic density currents with the box-model approach.

The results are provided either on-screen after the salculations, or sent by email. User needs to register to access the infrastructure, by providing a valid email address.

Task 18.1 Trans-National Access (TA)

The first call for TA at the VDCC at INGV Pisa has been published, according to schedule, in July 2018. The call was preceded by abundant advertisement in the form of i) call alerts on the EUROVOLC and INGV-PISA websites; ii) a dedicated email sent to the Volcano Listserv, which reaches thousands of scholars and volcano observatory people worldwide; iii) direct contacts with colleagues at many Universities, Research Centers, and Volcano Observatories worldwide. Additionally, a web page has been dedicated to EUROVOLC TA and VA activities offered by the VDCC, accessible from the INGV-Pisa home page (Figure 1).

Figure 1: Screenshot of INGV Pisa home page, where the EUROVOLC box for VA is located.

The first call has resulted in two approved proposals: by Luca Caricchi from the University of Geneva, and Samantha Engwell from the British Geological Survey. A total of 25 access days in August-September 2019 was offered. The approved research proposals were:
CO2-flux (Luca Caricchi): Effects of CO_2 flushing on magma reservoir dynamics. Code accessed: GALES.
COL2PDC (Samantha Engwell): From collapsing column to pyroclastic density currents. Code accessed: PDAC.

Both projects were syccessfully carried out and re-proposed for the second call. The latter opened in July 2019, together with the second global TA call under EUROVOLC., advertised by a flyer (Figure 2) that has been widely disseminated, in particular at the April 2019 EGU (European Geosciences Union) and July 2019 IUGG (International Union of Geodesy and Geophysics) General Conferences.

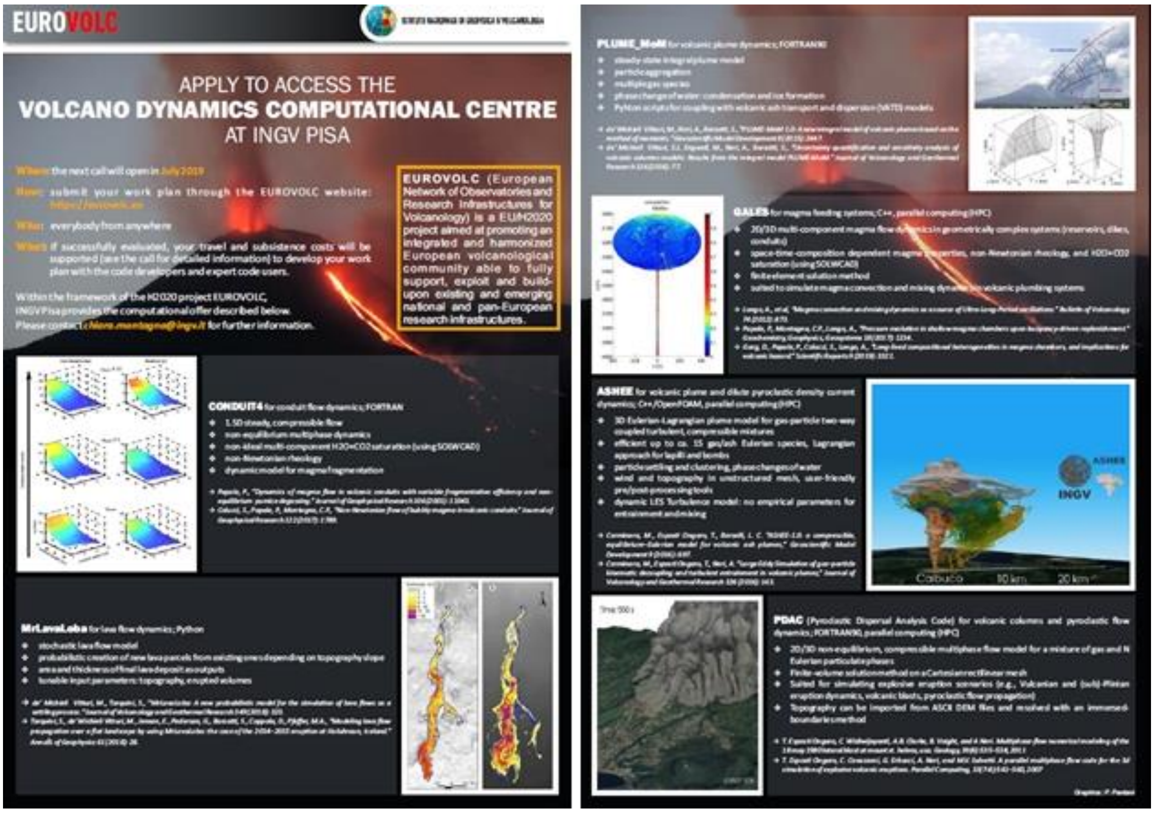

Figure 2: EUROVOLC flyer, widely distributed at international meetings, workshops and conferences during the second half of 2018 and first half of 2019, advertising the TA opportunities available at the VDCC of INGV Pisa.

The evaluation process this time included a first screening by the personnel at the centre providing the access, so to ensure that the proposals coming to the external evaluation committee were already judged as being technically feasible. Five applications were finally approved, two of which representing extensions of the work initiated with the first call and described above. The five proponents and their corresponding approved projects are the followings:

- Luca Caricchi, University of Geneva (Switzerland). **CO2-flux**: Effects of CO_2 flushing on magma reservoir dynamics. Code to access: GALES
- Samantha Engwell, British Geological Survey (United Kingdom). **FloW**: Flows over water: A numerical investigation. Code to access: PDAC
- Cristian Montanaro, University of Munich (Germany). **VOLPROXY**: VOLcanic conduit processes and their effect on PROjectile eXit dYnamics. Code to access: ASHEE
- Gro B. M. Pedersen, University Of Iceland (Iceland). **HeklaLavaHaz**: Lava flow hazards at Hekla volcano, Iceland. Code to access: MrLavaLoba
- Karen Strehlow, GEOMAR (Germany). **MAREX**: Dynamics and hazards of subMARine EXplosive eruptions. Code to access: PDAC, ASHEE

All accesses, originally scheduled for the period spring – fall 2020, had to be delayed because of the Covid19 pandemic. and were rescheduled for the spring – summer 2021, thanks to the 10 months extension of EUROVOLC. Due to the continuous unpredictable evolution of the pandemics, some of the accesses were carried out in multiple instances; some other were carried out remotely; finally, Karen Strehlow was not able to carry out the access due to unforeseen difficulties related to rescheduling. Specifically, the accesses for the second call were carried out as follows:

- Luca Caricchi: 3 visits from October 2020 to October 2021;
- Cristian Montanaro: 2 visits from June 2021 to October 2021;
- Samantha Engwell: remote, online access in Summer 2021;
- Gro Pedersen: remote, online access in Summer 2021;
- Karen Strehlow: canceled.

A summary of the main results of the TA projects is reported below.

CO2-flux

The code GALES, complemented by a second code developed at INGV Pisa (The code GALES, complemented by a second code developed at INGV Pisa (MagmaFOAM) and made available for this specific research, has been employed to study the dynamics of a carbon dioxide-rich gas phase immersed in a magmatic melt under different conditions. A first set of simulations considered the rise of a pure carbon dioxide gas phase through a volatile supersaturated rhyolitic magma chamber, either by placing an initial magma-gas interface or by considering the inlet of pure carbon dioxide from a fracture at magma chamber bottom. The results showed that contrary to the case of input by gas-rich magma, the pure gas phase rises, in the form of a large gas bubble, practically undisturbed through the magmatic fluid without giving rise to any vortex structure and without mixing with the melt, neither mechanically nor through diffusion, the latter due to too short gas phase ascent times (Figure 3).

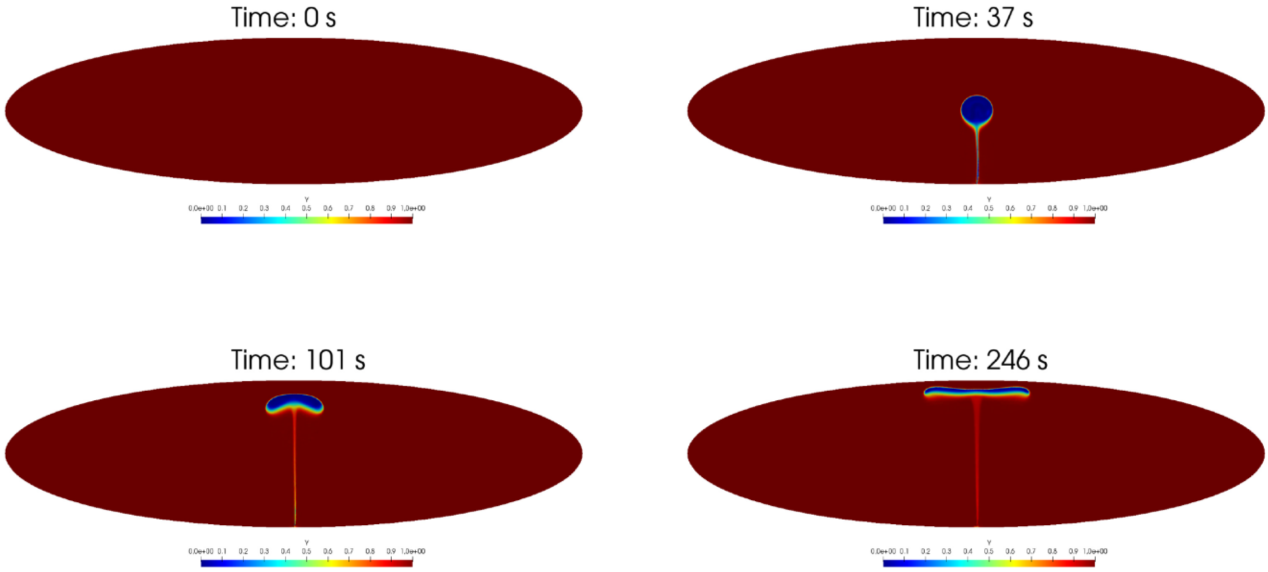

Figure 3: Example of the numerical results from one simulation of the input of a pure carbon dioxide gas phase at the bottom of a gas-supersaturated rhyolitic magma chamber. The results show relatively fast, nearly undisturbed ascent of a gas plume and

A second set of simulations was constructed in order to observe the two processes of bubble rise and diffusive growth together. A column filled with supersaturated basaltic magma (bubble diameters in the range 2-5 mm) was allowed to evolve in time. Gas bubbles progressively segregate from the melt rising towards the top of the column, causing non-linear space-time evolution of relevant quantities like pressure, gas volume fraction, and melt density and viscosity (Figure 4).
The above results suggest that a spectrum of dynamic conditions over which flushing by carbon dioxide-rich fluids operates in magmatic systems can be investigated with the available resources. This access led to plan further numerical simulation work aimed at creating a more complete set of results from which to draw robust conclusions relevant for the deep dynamics of magmatic systems.

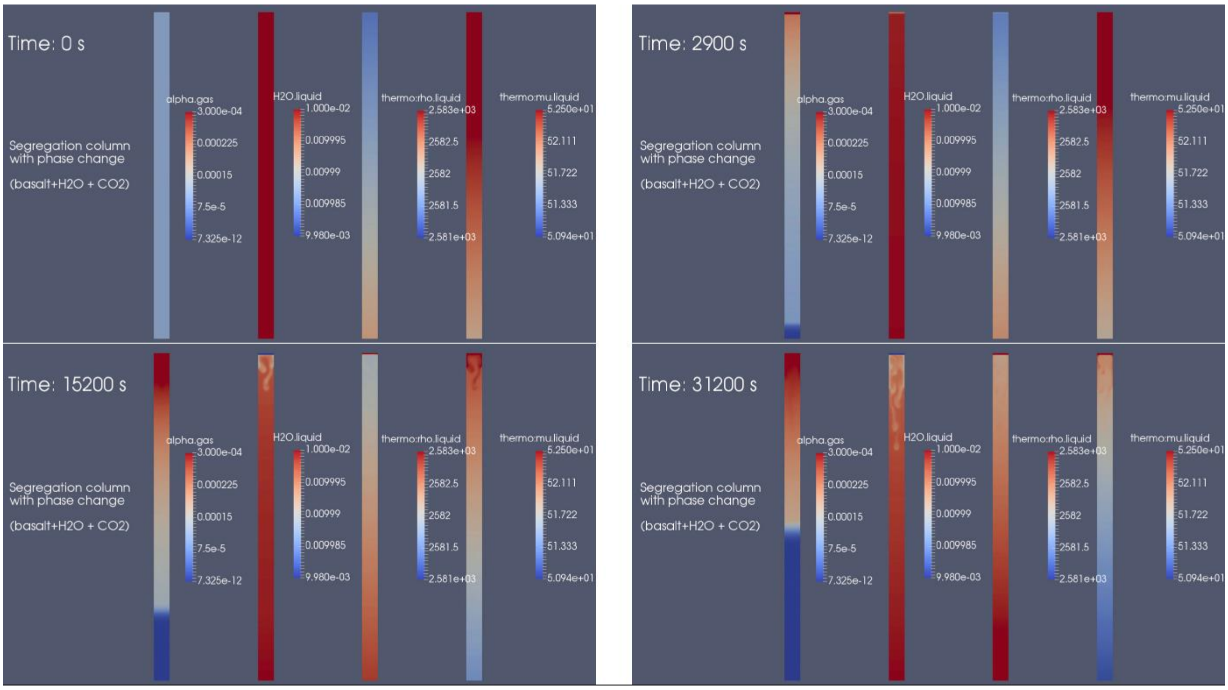

Figure 4: Evolution of relevant physico-chemical quantities in a volatile-supersaturated basaltic column.

Given these preliminary results, a second access was granted to follow up with the project. The main focus was to study flushing of CO_2-rich gas phases in volcanic systems, to understand how the interaction between magma and gas can modify both the physical properties of the magmas and the gas properties that we can record at the surface, such as fluxes and compositions. During the second access, the collaboration focused on thermodynamics modeling through SOLWCAD, and explored the details of CO_2-flushing at Stromboli volcano. The main results consist in a consistent picture of how the magma column responds to inputs of gas of different compositions, in terms of varying its volatile content and, as a cosequence, its physical properties, specifically viscosity. Alongside the evolution of the magma column, the project highlighted how the emitted gas fluxes and compositions are expected to vary in time as a consequence of prolonged flushing of the system (Figure 5).

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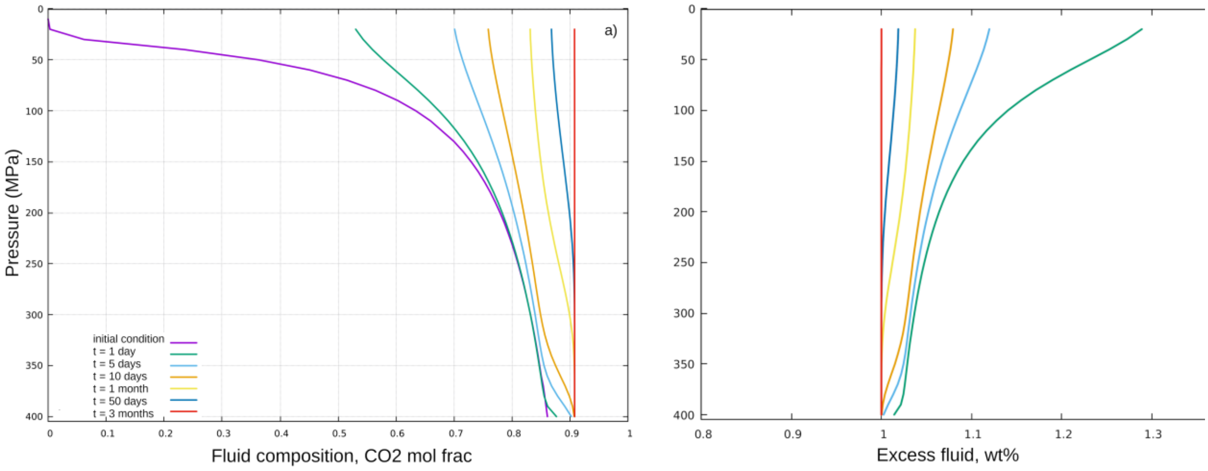

Figure 5: Variation in space and time of excess fluid properties as a magma column is flushed by CO2-rich gas. a) Excess fluid composition as a function of pressure (y axis, a proxy for depth). Lines of different colors represent differet times. b) Mass fraction of excess fluid composition as a function of pressure (y axis, a proxy for depth). Lines of different colors represent different times

Protractred CO_2 flushing results in progressive dehydration of the magmatic system, starting from depth and later reaching the surface. This results in regions of increased viscosity (related to dehydration) at different depths along the column, that might cause bubble accumulation and potentially larger explosions. The model predicts decreasing water and increasing CO_2 fluxes at the surface that, if matched with monitoring data, can provide hints as to the magnitude of the next eruption. This is of particular interest in systems like Stromboli, where there is no consolidated means of anticipating how large the next major explosion will be.

<u>COL2PDC+FloW</u>

The PDAC code was employed to start an investigation on the dynamics of large pyroclastic flows interacting with water. A well-documented example of an eruptive event that resulted in the propagation of PDCs over water is the 1883 eruption of Krakatau volcano, that was among the most destructive eruptions in historical time. In the COL2PDC TA project, insights from direct observations, deposits and numerical modelling were used together in order to investigate the behaviour of the pyroclastic flows, and therefore the tsunami source conditions at the volcano, during the climactic stages of the eruption (Figure 6).

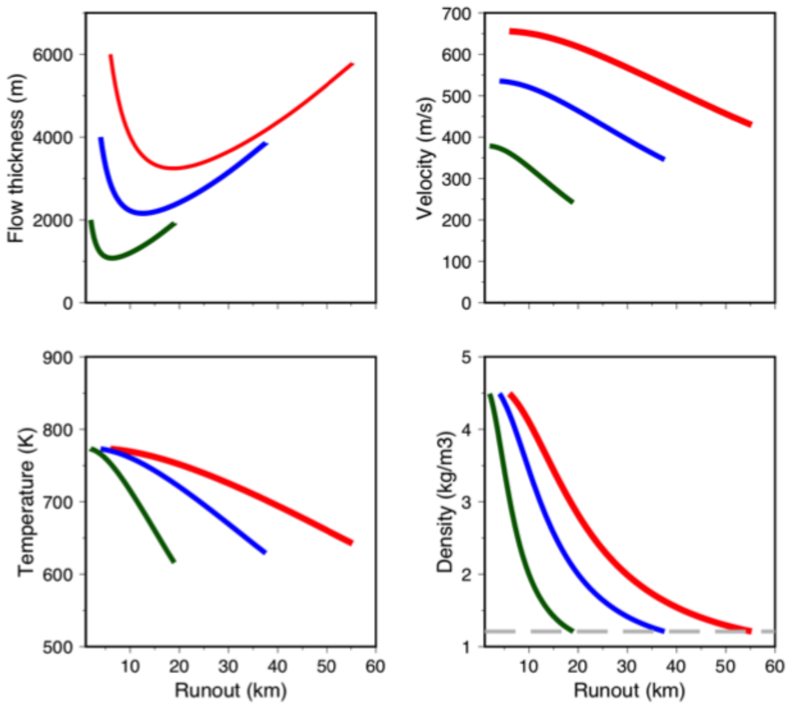

Figure 6: Results from the application of the PDAC code to the Krakatau eruption in 1883.

Large discrepancies between model results and observations emerged from this study, suggesting the need for substantial improvements in order to model pyroclastic flows interacting with water. The model has thus been implemented during the subsequent remote TA access (FloW). The model was tested through application to a theoretical eruption at a vent on the edge of the Taal caldera, using a radial initial source, with multiple pulses of emission. To investigate the effect of incorporating water vapor into the flow on flow dynamics and conditions, a dry simulation (no water involved) was compared with others that included propagation over water. Figure 7 shows transects through the propagating flow, with 0 on the x-axis representing the flow source, for both the ‘dry’ and ‘wet’ simulations. Outputs represent the characteristics of the flow at timestep 100 for both simulations. The thickness and velocity are similar for the two simulations, particularly evident in the flow thickness and velocities whereby peaks in thickness and velocity are achieved at greater distances from source. In both simulations, the four pulses are clearly seen in flow thickness and velocity with distance from source, however it appears that changes in flow thickness dissipate more quickly for the ‘wet’ simulation. Perhaps the most obvious difference in the simulations is that the ‘dry’ flow travels further in the given time compared to the ‘wet’ flow, related to longer periods with higher velocities.

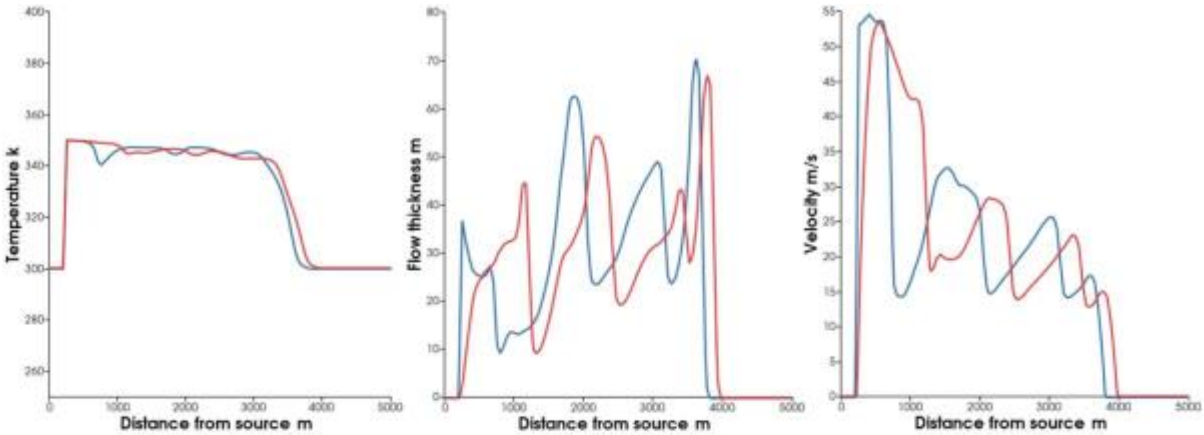

Figure 7: Comparison of flow characteristics along a transect for simulated flows with and without water vapor, where 0 represents the flow source.

<u>HeklaLavaHaz</u>

This access has been planned to study lava flow invasion at Hekla. The PI and other team members, though, were deeply involved in the real-time monitoring of the ongoing Fagradalsfjall eruption (from March 2021 onwards).The decision was therefore made to change the target location of the trans-national access (carried out remotely) from Hekla to Fagradalsfjall, since this event provided the unique opportunity to develop the lava flow code in critically beneficial ways in response to an ongoing eruption. This gave us great insight into the strengths and weaknesses of MrLavaLoba for this type of eruptive activity.

The main objective was to use and develop the lava-flow simulation code MrLavaLoba to address both short-term and long-term lava flow hazards prior to and during the eruption. Short-term simulations (up to 2 weeks) were run from the very start of the eruption (Figure 8), addressing different eruption phases including vent migration and growth of a highly compound lava field. In addition lava barriers designed to divert the lava were tested, both to consider different barrier design and to simulate the impacts of barriers after they had been built. Long-term scenarios (up to five years) were also run in order to assess long-term vulnerability of valuable infrastructure if the eruption would continue for a long time.

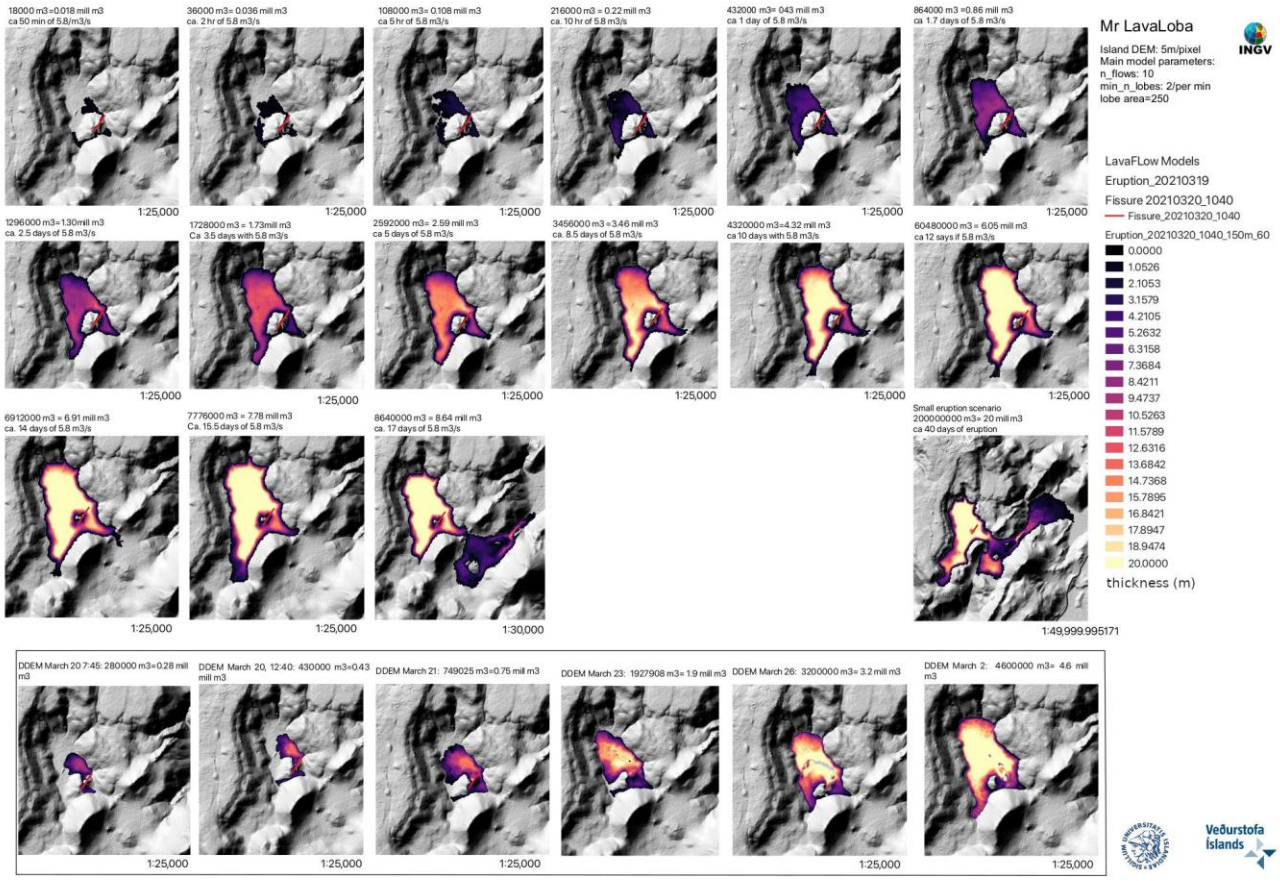

Figure 8: Comparison between simulations and the actual lava flow field for the initial phase. Above, simulations of up to 8.6 M m3 of lava. Frame below, real evolution of the lava flow field.

<u>VOLPROXY</u>

This TA project has tackled the modeling of conduit flow on eruption, and specifically the comparison between models and lab experiments of sudden decompression of a multiphase fluid. The phenomenology of the selected experiments has been studied and understood using multiphase compressible numerical models. The comparison between the observation and the model is good (Figure 9), opening research opportunities on the study of particle decoupling and conduit fast decompression after fragmentation. The link between the dynamics inside the autoclave and the pyroclasts speed outside the nozzle has been studied and interpreted.

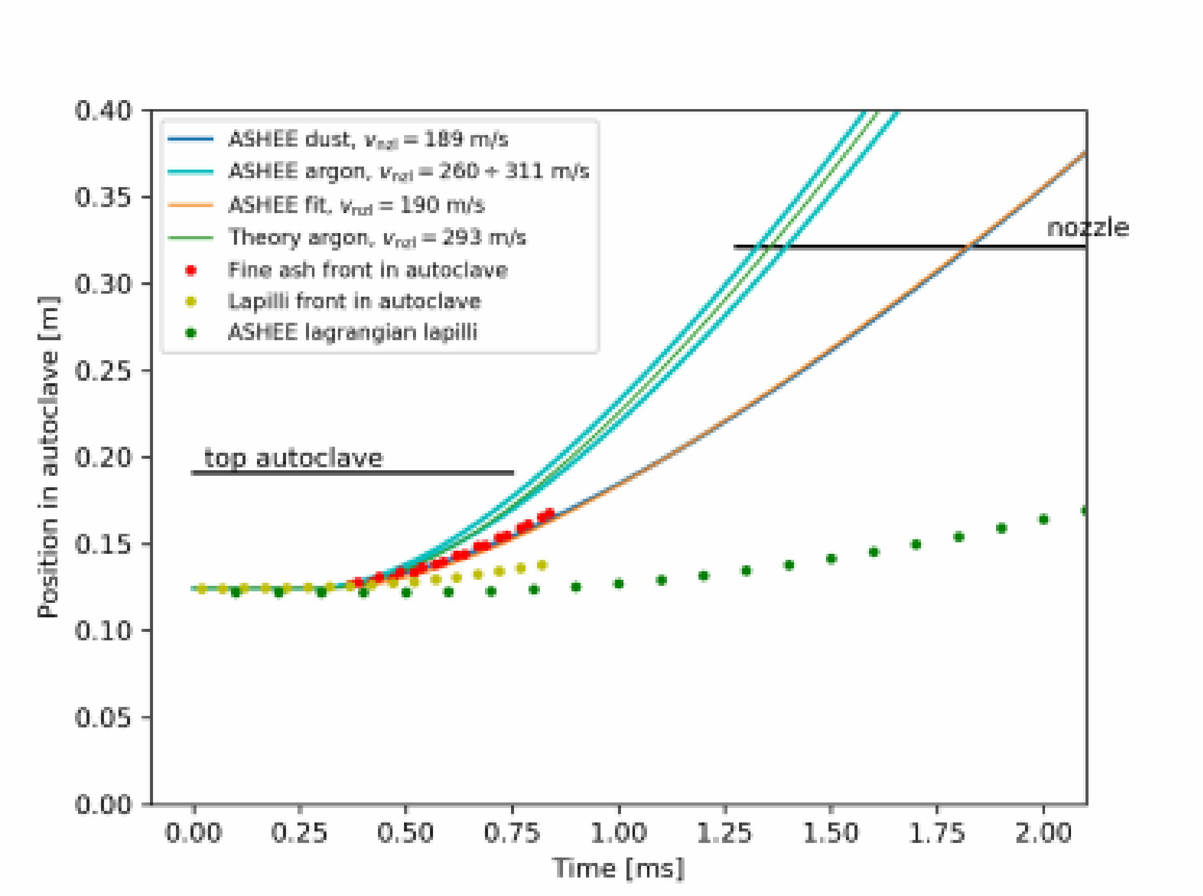

Figure 9: Comparison between laboratory data and numerical simulations of the particle dynamics inside the autoclave.

Task 18.2 Virtual Access (VA)

According to schedule, by March 2019 the VA at the VDCC had been opened, in the form of provision of three downloadable source codes as from the GA (MAMMA, for magma ascent dynamics; SOLWCAD, for computation of two-phase multi-component gas-melt equilibria; PYBOX, for pyroclastic flow dynamics), complemented with manuals for their use (Fig. 10).

Access to the VA offered by VDCC is provided through the same link describing TA in the home page of INGV Pisa (see figure above). In June 2019 the VA has been further expanded by allowing web-based computations for each one of the three codes above, and in one case (SOLWCAD) by providing, besides the stand-alone downloadable code, a routine version (in FORTRAN) that can be downloaded and linked to user-defined codes. Accordingly, the manuals have been extended to illustrate in detail the different accesses provided. Figure 11 shows the screenshot for web-based calculations for one of the codes provided (MAMMA).

Access to the VA by the VDCC at INGV Pisa is provided through registration and provision of a personal login and password.

Total online runs for the whole project duration have been roughly 1000, evenly distributed among the three codes available; the total number of downloads in the same period has been of about 1600 (Fig. 12). The distribution of downloads among countries shows that the accesses have been far-reaching. In particular, the number of accesses from US is considerable. At EU level, and besides Italy (largely dominating), Germany and France are the countries with the largest number of accesses. Overall, the rate of downloads has been fairly constant (with oscillations) during the entire VA opening period. This type of access seems to have been appreciated and exploited also by people from more remote locations, that have sometimes larger difficulties accessing software and publications otherwise.

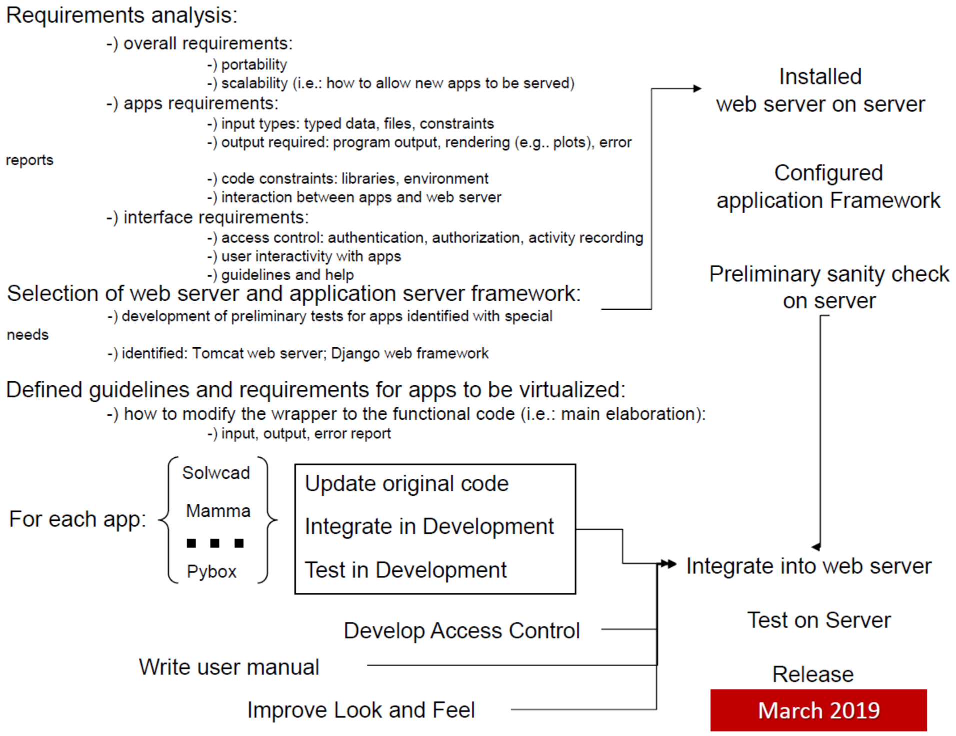

Figure 10. Technical elements of the Virtual Access at VDCC Pisa, released in March 2019 as from schedule.

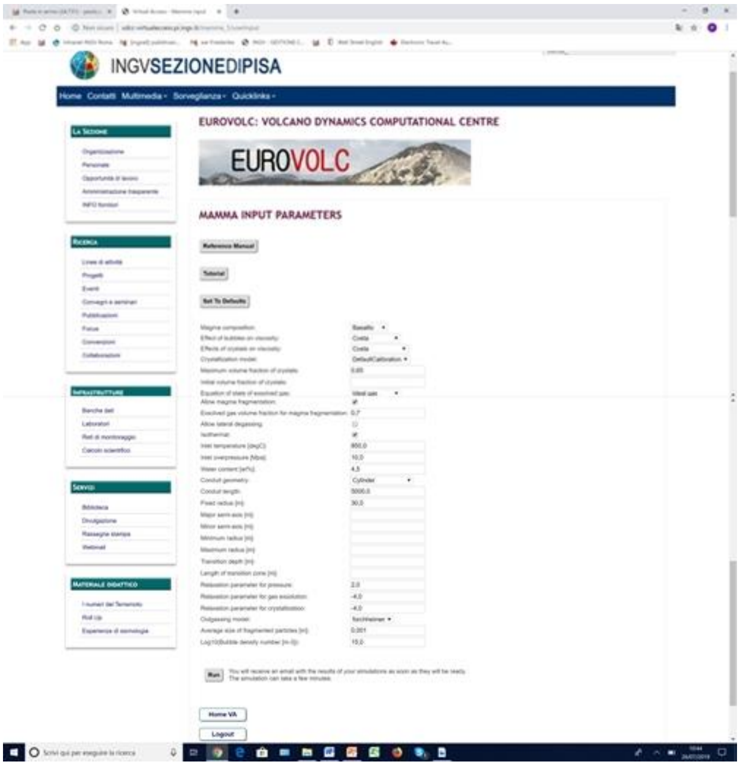

Figure 11: Screenshot for the web-based calculations of MAMMA.

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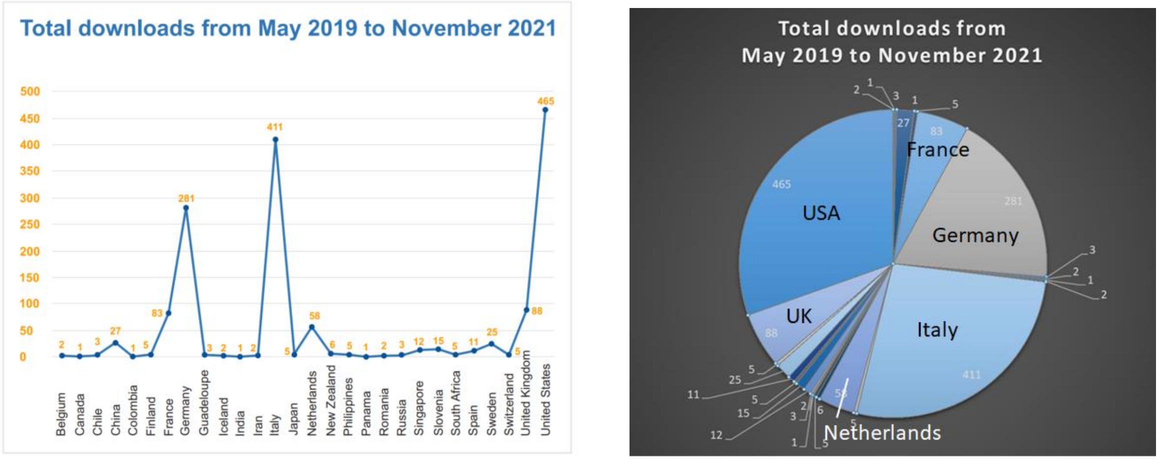

Figure 12. total downloads from the VA at the VDCC Pisa, in the period May 2019 – November 2021.