Université Clermont Auvergne
École Doctorale des Sciences Fondamentales

Habilitation à Diriger des Recherches

Contribution to the understanding of lava flow emplacement dynamics

Contribution à la compréhension de la dynamique de mise en place des coulées de lave

Mémoire présenté par

Oryaëlle CHEVREL

Devant le jury composé de :

1. Andrew Harris (Tuteur, Université Clermont Auvergne, France)
2. Ali Bouhifd (Président de Jury, Université Clermont Auvergne, France)
3. Alison Rust (Rapporteuse, Université Bristol, Royaume-Uni)
4. Alan Whittington (Rapporteur, Université du Texas San Antonio, États-Unis)
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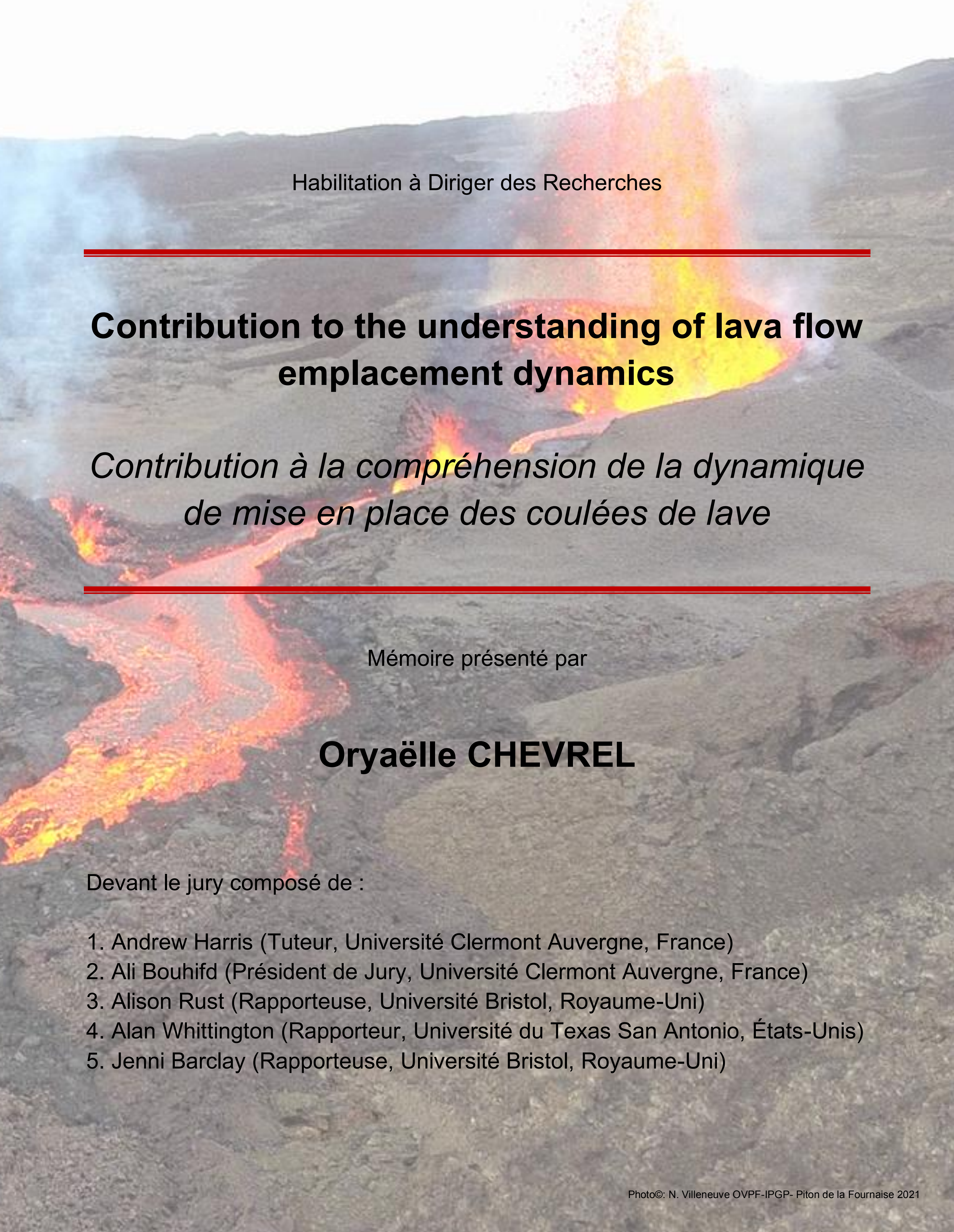

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Avant-propos

Les processus magmatiques - causes et conséquences de l'évolution des planètes solides du système solaire - sont à la source de ma curiosité scientifique. C'est au travers du volcanisme que ces processus s'expriment à la surface des planètes et façonnent les paysages tout en étant notre seul accès à ce qu'il se passe en profondeur. Étudier les systèmes volcaniques est donc le moyen de comprendre l'évolution tellurique des planètes et de comprendre le monde qui nous entoure.

J'ai fait mes premiers pas en volcanologie lors de ma thèse de doctorat à Munich, où j'ai découvert les expériences de laboratoire avec de la lave fondue à très haute température. Mes travaux depuis se sont concentrés sur les coulées de lave. Plus précisément je m'intéresse aux propriétés thermo-rhéologiques afin d'appréhender le mode de mise en place des laves tant à l'échelle atomique et microscopique (rôle de la composition chimique, des cristaux et des bulles de gaz) que macroscopique (aspect, morphologie, dimension des coulées). Je m'intéresse également à l'impact des coulées de lave sur l'environnent et les populations. Mes recherches voyagent donc au rythme d'aller-retour entre l'étude d'échantillons de lave au travers de leur analyse pétrographique et l'étude des coulées dans leur globalité au travers de travaux sur le terrain.

Ce mémoire est divisé en cinq chapitres. Le premier chapitre est consacré à une présentation détaillée de mon profil scientifique. Je retrace d'abord chronologiquement mon parcours en tant que chercheuse et j'y explique certains résultats et les choix qui m'ont amené à décrocher des bourses de recherche et un poste permanant à l'Institut de Recherche pour le Développement (IRD) au Laboratoire Magmas et Volcans de l'Université Clermont-Auvergne. Puis je présente mon *curriculum vitae*, mes activités d'enseignement et d'encadrement d'étudiants ainsi que la liste complète de mes publications et présentations lors de conférences. Dans les chapitres 2, 3 et 4 je développe mes axes de recherche principaux. Le chapitre 2 commence avec le cœur de mes recherches qui porte sur l'évolution des propriétés rhéologiques des laves que j'étudie par l'analyse de données de terrain et d'échantillons, par des mesures en laboratoire et par la modélisation numérique. Le chapitre

3 est dédié aux mesures de viscosité effectuées directement dans la lave qui s'écoule sur les volcans actifs, en utilisant une instrumentation dédiée. J'y présente une revue des études passées et mes contributions récentes. Dans le chapitre 4, je présente mon travail sur le suivi et la modélisation des coulées de lave lors des crises effusives du Piton de la Fournaise. Ce travail a permis de rendre ce suivi opérationnel et utile à la gestion de l'aléa volcanique. Enfin le chapitre 5 dévoile mes perceptives de recherches dans la continuité de mes thématiques de recherche. J'y présente également une thématique que je souhaite développer dans les prochaines années et qui porte sur la relation société – volcans, plus près des objectifs de l'IRD.

À la fin de ce mémoire, je fournis une sélection de plusieurs de mes publications (avec les liens de téléchargement gratuit). Parmi celle-ci certaines ont été utilisées pour la rédaction de ce mémoire, tandis que d'autres illustrent la diversité de mes travaux scientifiques.

Bien que cet avant-propos soit en français, le reste du mémoire est présenté en anglais. Je remercie donc mes lecteurs et lectrices francophones de leur compréhension et remercie également l'Université Clermont Auvergne d'accepter ce mémoire en anglais.

Preface

Magmatic processes, which are both the cause and consequence of the evolution of solid planets in the solar system, are the source of my scientific curiosity. Volcanism manifests these processes on the surface of planets, shaping landscapes and providing our only access to what happens beneath the surface. Studying volcanic systems is therefore a means to understand the tectonic evolution of planets and to comprehend the world around us.

I took my first steps in volcanology during my PhD in an experimental laboratory in Munich, where I discovered working with high-temperature molten lava. Since then, I have been interested specifically in lava's thermo-rheological properties, to understand lava flows emplacement at both the atomic and microscopic scales (the role of chemical composition, crystals, and gas bubbles) and the macroscopic scale (appearance, morphology, and dimensions of flows). I am also interested in exploring how the accumulation of lava flows on Earth's surface can impact the environment and civilizations. My research thus oscillates between studying solid or liquid lava samples through petrographic analysis, and examining flows in their entirety through fieldwork.

This dissertation is divided into five chapters. The first chapter introduces me and provides an overview of my scientific profile. I first chronologically trace my career as a researcher, explaining some main scientific results as well as certain choices that led to securing research grants and a permanent position at the French National Research Institute for Sustainable Development (IRD) at the Laboratoire Magmas et Volcans of the University Clermont Auvergne. I then present my *curriculum vitae*, my teaching and student mentoring activities, as well as the complete list of my publications. In chapters 2, 3, and 4, I develop my main research themes. Chapter 2 begins with the core of my research, which focuses on the evolution of the rheological properties of lava. I study this through the analysis of field data and samples, laboratory measurements, and numerical modeling. Chapter 3 is dedicated to viscosity measurements conducted directly in flowing lava using specialized instrumentation. In this chapter, I present a review of past studies and my recent contributions. In chapter 4, I present my work on monitoring and modeling lava flows during effusive crises at Piton de la Fournaise. This work has made lava flow monitoring fully operational and useful for volcanic hazard management. Finally, chapter 5 reveals my research perspectives in line with my main research themes. I also present a theme that I wish to develop in the coming years, which focuses on the relationship between society and volcanoes, aligning more closely with the objectives of IRD.

At the end of this dissertation, I provide a selection of several of my publications (with link to free open access). Some of these were used in the writing of this dissertation, while others illustrate the diversity of my scientific work.

Although this preface is also given in French, the rest of the dissertation is presented in English. I thank my French examiners, and readers for their understanding and also thank the University Clermont Auvergne for accepting this dissertation in English.

1. Scientific profile

1.1 Summary of past and ongoing research activities

Viscosity of Martian lavas: An experimental approach

My PhD thesis (2009-2013), carried out at the Ludwig Maximilians Universität in Munich, under the supervision of Prof. Don Dingwell and in collaboration with Dr. David Baratoux (University of Toulouse III), consisted in evaluating the viscosity of Martian lavas, particularly rich in iron compared to terrestrial lavas. My thesis focused first on the effect of iron on viscosity and then on the implications that this effect could have on the morphology of lava flows. I established the viscosity-temperature relationship from laboratory measurements for synthetic Martian basalts and quantified the decrease in viscosity when iron is added, under various redox states. The results showed that, at expected magmatic temperatures, the difference in viscosity between Martian and common terrestrial basalts could be an order of magnitude (Chevrel et al., 2013b, 2014). Samples produced during my PhD then led to the establishment of a model to determine the glass composition and redox state using Raman spectroscopy, which could be used for future extraterrestrial missions (Di Genova et al., 2016b, 2016a).

To evaluate the influence of viscosity on the morphology of solidified lava flows I set up a collaboration with researchers from the University of Berlin and the Deutsches Zentrum für Luft- und Raumfahrt (DLR), specialists in Martian volcanism. The results demonstrated that the viscosity inferred from the dimensions of a flow depends strongly on the details of the crystallization sequence and crystal shape and, as such, is not solely related to the overall chemical composition of the molten lava, and care should be taken when interpreting the flows' apparent rheology (Chevrel et al., 2013b).

By modeling the crystallization sequence of Martian basalts, I could interpret the morphology of Martian lava flows. I have thus shown that the morphologies of lava flows observed on the surface of Mars are indeed due to the iron-rich character of the magma and that the thickest lava flows, which appear to have high viscosities, are consistent with the presence of alkaline basalt, and do not necessarily require more siliceous compositions as previously stated (Chevrel et al., 2014).

During my thesis, I also developed a new experimental assembly and protocol to measure viscosity during lava crystallization and to capture the texture of the crystallizing samples. To this end, I supervised a master's project to produce a series of experiments on an andesitic lava. This work resulted in establishing the lava's rheological behavior under laboratory conditions and describing the effect of crystallization kinetics on rheology during such experiments (Chevrel et al., 2015; see chapter 2).

Andesitic lava flows in Mexico

To reconstruct the history of past lava flows, it is necessary to make field observations and to thoroughly analyzed hand samples. After studying the Martian mafic lavas, I wanted to know more about siliceous and therefore more viscous flows. I obtained a 2-year fellowship (2014-2015) at the Universidad Nacional Autónoma de México (UNAM), in collaboration with Prof. Claus Siebe. The objective of this project was to study the lava flows from the andesitic volcano El Metate (Michoacán-Guanajuato in central Mexico) in order to describe the eruptive history of the volcano, including the effusion rate, the temperature, the amount of volatiles involved, and the duration of the lava emplacement.

The conclusions of this work showed that this eruption, purely effusive, is the most voluminous (9 -10 km^3) of the Holocene era in the trans-Mexican volcanic belt (Chevrel et al., 2016b). The petrographic, geochemical and isotopic analyses I conducted on the sampled rocks allowed me to speculate on the source of the magma, the conditions of storage and crystal formation, as well as on the viscosity that the magma must have had at depth and during lava flowing at the surface. A thorough interpretation of the morphology of the lava flows led to the evaluation of the duration of the emplacement. We showed that this volcano is monogenic and that the eruption lasted between 30 and 270 years (Chevrel et al., 2016a; Mahgoub et al., 2017). Furthermore, the relatively young age of this volcano (ca. 1250 CE) has interesting implications for archaeology, as the area was probably inhabited. This eruption, although effusive and thus with only local in impact, must have forced the inhabitants of the region to migrate, which could have contributed to the growth of the Tarascan empire in the years 1350-1521 (Chevrel et al., 2016b).

During this post-doc and afterwards, I co-supervised three students (bachelor and master level) to conduct detailed mapping, flows' morphometric analysis and lava petrography on other thick viscous andesitic and dacitic lava flows in Mexico. These studies have allowed us to date eruption, constrain lava's viscosity and emplacement duration as well as to establish the relationship between the pre-Hispanic populations and their volcanic environment (Ramírez-Uribe et al., 2021, 2022; Reyes-Guzmán et al., 2018, 2021; see chapter 2).

Modelling of thermo-rheological properties and measurements on active lava flows

Through my research, it became clear that the reconstruction of the history of a lava flow or the anticipation of its evolution rely on our ability to quantify and model its thermo-rheological properties as it flows. I have thus obtained a postdoctoral fellowship for 2 years (2016-2017) at the Laboratoire Magmas et Volcans, ClerVolc Laboratory of Excellence, Université Clermont-Auvergne (UCA) where I mainly collaborated with Prof. Andrew Harris, to focus on modeling thermo-rheological properties of lava, and performing viscosity measurements in the field.

The only holistic model to model lava thermo-rheological properties, is FLOWGO (Harris and Rowland, 2001). FLOWGO is a well-known, largely used, a 1D model that calculates the heat budget and the resulting rheological properties of a volume of lava it travels from the vent to the front. Although FLOWGO existed in various forms (e.g., IDL, Visual Basic, Excel and MATLAB), I proposed to recode it under Python, to offer a greater flexibility for implementation while reducing the risk of errors. The produced code, named, PyFLOWGO is open and freely available at https://github.com/pyflowgo/pyflowgo (see section 2.3 and Chevrel et al., 2018a). The architecture of PyFLOWGO allows selecting or implementing a variety of models to calculate heat loss and rheology in order to test their effect on lava emplacement characteristics. All the variable used in PyFLOWGO can be modified and adapted for a wide variety of contexts. For example, in collaboration with the University of Pittsburgh, we analyzed the effect of thermal emissivity on the heat loss and physical properties evolution of lava flows from Tolbachik volcano (Kamchatka) (Ramsey et al., 2019). Recently, we tested the effects of an extraterrestrial environment such as on Venus on the flow emplacement (Flynn et al., 2023a).

Extrapolating viscosity measurements from laboratory experiments to the natural state of lava in the field is difficult because the conditions are not the same. In particular, in the laboratory it is difficult to account for the presence of gas bubbles, dissolved volatiles in the liquid phase, the redox state and the cooling rate during flow (see review made in collaboration with Universities of Buffalo and Munich (Kolzenburg et al., 2022)**.** Therefore, I decided to develop field viscosity measurements using dedicated instrumentation. These experiments are difficult to perform on site but produce extremely valuable data and only a few studies have focus on such experiments (see chapter 3 and the review Chevrel et al., 2019b). In 2016, I refurbished the only existing field rotational viscometer built in the 90's by one of the pioneer scientists in this topic, Prof. Harry Pinkerton from Lancaster University. This led to the first viscosity measurements using such instrument after more than 20 years, on an active lava flow on Kīlauea, Hawaii (Chevrel et al., 2018b). This work showed that in situ viscometry can provide a unique benchmark (i.e., ground truth) to which theoretical models of lava flow emplacement can now refer to. Although these field measurements were successful the Pinkerton's viscometer was extremely heavy and bulky. In the following years, I therefore conducted a project to build a new prototype that is now operational (see chapter 3; Chevrel et al., 2023). Recently, I also developed new collaborations, in industry (Rockwool, France) and in academy with the University of Buffalo (UB) to outspread field viscometry (see chapter 3).

Lava Advance into Vulnerable Areas

In the framework of the Agence National pour la Recherche (ANR) project lead by Prof. Andrew Harris named Lava Advance into Vulnerable Areas (LAVA 2016-2021) on risk assessment, risk reduction and effusive crisis management, I obtained a postdoctoral grant in order to address two objectives 1) to study the possible interactions between a lava flow and trees, and 2) to set up a protocol to anticipate the trajectory of lava flows at Piton de la Fournaise (La Réunion).

The LAVA project aimed at acquiring new and original knowledge on key processes which will allow to make more robust the physical modeling of lava flow on vulnerable and vegetated areas. In this framework, I actively participated in various tasks and co-supervised master's projects on the possible interactions between lava flows and trees. Through this work, we highlighted the viscosity threshold below which a tree can be preserved during lava flowing through a forest and lava-trees or lava molds could be formed, while above which the trees will be knocked over by the lava flow front (Chevrel et al., 2019a). A detailed analysis of the contact between lava and tree at the micrometric scale revealed some subtle thermal and chemical exchanges between the two (Biren et al., 2020). A third study on the destruction of an entire forest by a large lava flow and the mechanical and thermal interactions was also conducted (Harris et al., 2022a).

In collaboration with the Observatoire Volcanologique du Piton de la Fournaise (OVPF), a second objective of the LAVA project was to improve the existing protocol (Harris et al., 2017) to rapidly model the inundation area and distance that the lava flow can reach during an eruption. This approach integrates various satellite data and the combination FLOWGO with DOWNFLOW (a model that provides the distribution of probable flow trajectories Favalli et al., 2005) to anticipate where and how far a flow can go (Wright et al., 2008). My work has therefore been dedicated to integrating and validating this protocol. Thanks to PyFLOWGO, we built DOWNFLOWGO, that offers an all-in-one package to respond to effusive activity at Piton de la Fournaise (Chevrel et al., 2022; Harris et al., 2019b; Peltier et al., 2021;). Results allow to produce a short-term hazard map, representing the distribution of probable trajectories and the maximum distance the flow could reach based on a given volumetric flow rate. Over the years, I refined this model, in particular through close collaboration with OVPF and with the locale civil protection to deliver a fully operational product, now indispensable for crisis management by OVPF (Chevrel et al., 2022 ; see chapter 4). My work also included publication of the updated long-term lava flow hazard map of Piton de la Fournaise (Chevrel et al., 2021a; see chapter 4).

Integrating the Institut de Recherche pour le Développement

In 2019, I was laureate of the Institut de Recherche pour le Développement (IRD) national concours and obtained a permanent position at the Laboratoire Magmas et Volcans (UCA). Since then I have continued my research on lava rheology expanding it to various geodynamics settings and aimed at providing holistic approaches. For example, I was granted a project that focuses on the viscosity of submarine lavas offshore the island of Mayotte for which I am supervising a PhD student (co-supervised by Dr. Lucia Gurioli and Dr. Etienne Médard), Pauline Verdurme, who started in 2021 at UCA. Through this PhD project, we provided new viscosity data for melts with composition representative of the Mayotte submarine volcanic chain falling along the alkaline basalt to phonolite trend (Verdurme et al., 2023). A full analysis of the submarine lavas from the recent eruption of Fani Maore volcano (2028-2021) including textural characteristics was completed and a rheological map in space and time through the eruption was established (Verdurme et al., 2024a, 2024b). Additionally, through the collaboration with University of Buffalo (UB), where I am volunteer assistant professor since 2022, I'm aiming at further developing field rheometry and exploring the role of gaseous phases in lavas. In 2022, Martin Harris started his PhD under my supervision shared with Dr. Stephan Kolzenburg at UB. This work focuses on developing new field instrumentation and run in parallel laboratory measurements to unravel three-phase lava rheology. This work led to the development of a new viscometer (Harris et al., 2024b) and field measurements were performed in Iceland in July 2023 (Harris et al., 2024b; see chapters 4 and 5. I also continue to collaborate and established new collaborations with partners in Latin America (Mexico, Peru, Ecuador) where I have been supervising students (undergraduate and graduate levels) who focus on the relationship between the chemical and textural characteristics of rocks and the morphology of lava flows. These projects are offering opportunities for better volcanic hazard constrains (see chapter 5).

It is through observations that volcanology exists and hence volcano observatories are at the beating heart for volcano studies (e.g. Peltier et al., 2022). In 2020-2021, I led the edition a special edition (available in *open access* in Volcanica) that honors all the volcano observatories of Latin America in order to better understand their activity and to highlight the crucial importance they play in reducing the risks that populations may face from volcanic hazards (Chevrel et al., 2021b). The observatories are the link between the scientists who study the volcanic phenomenon and the authorities, who have the duty to serve the population. Serving as a reporter of the current activity and as an advisor, it is essential that an observatory is armed with tools allowing to correlate the different observations and to communicate them to the authorities by bringing essential elements to the understanding of the phenomenon. With this in mind, in 2022, I obtained a visiting researcher position (3 years) at the OVPF where I am currently working. As mentioned previously and as presented in chapter 4 and in Chevrel et al. (2022), it is through multiple exchanges with the local authorities that we have been able to improve the lava flow simulation maps so that they can be a useful tool for a better crisis management at Piton de la Fournaise. This work will serve as an example for developing such tools across the word where it is most needed (see chapter 5).

The consequences of a volcanic eruption can be dramatic. However, they can be beneficial by fertilizing soils, or by providing, for example, material for construction or for the production of everyday tools. One of my long-term research interests is therefore to study how societies have lived and survived eruptions and how they have learned to use volcanic products. For this, I have ongoing collaborations and future projects with various institutes in France and Latin America in order to bring a cross-section of volcanologists and archaeologists on the impact of volcanic eruptions on, in particular, pre-Hispanic civilizations. This work as already led to several publications mainly about the use of volcanic landforms and materials by local population (Chevrel et al., 2016b; Hamon et al., 2023, 2024; Reyes-Guzmán et al., 2023). This part of my research activity is still under-construction and I hope to extend it in the coming years toward preservation of our natural heritage to increase population resilience facing potential future volcanic events (see chapter 5).

1.2 Curriculum Vitae

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Currently at Observatoire Volcanologique du Piton de la Fournaise, Institut Physique du Globe de Paris
97418 La plaine des Cafres, France

ACADEMIC POSITIONS

2022 – 2025 Visiting researcher at the Observatoire Volcanologique du Piton de la Fournaise, Institut de Physique du Globe de Paris (OVPF-IPGP), La Réunion, France

Since 2022 Volunteer research assistant professor, Graduate Faculty of University at Buffalo (UB), USA

Since 2019 **Researcher at Institut de Recherche pour le Développement IRD**, Laboratoire Magmas et Volcans (LMV), Université Clermont Auvergne (UCA) - Clermont-Ferrand, France

April 2019 – Feb. 2020 Visiting researcher at OVPF-IPGP, La Réunion, France

2018 – 2019 Postdoc Researcher ANR funding, LMV, UCA, France
Subject: Monitoring lava flows at Piton de la Fournaise

2016 – 2017 Post-doc Fellowship, Région Auvergne funding, ClerVolc LMV, UCA, France
Subject: Towards a comprehensive description of lava emplacement dynamics: Linking the roles of chemistry, thermodynamics and rheology in determining lava flow morphology

2014 – 2015 Post-doc Fellowship, DGAPA funding, Universidad Nacional Autónoma de México (UNAM), Mexico
Subject: Eruptive activity and physical properties of magmas feeding enigmatic shield volcanoes in the Michoacán-Guanajuato Volcanic Field: El Metate case study

EDUCATION AND TRAINING

2009 – 2013 **Ph.D.** in Experimental and physical volcanology, Ludwig Maximilians Universität (LMU), Germany
Subject: Rheology of Martian Lava Flows: An Experimental Approach
Supervision: Prof. Don Dingwell, Dr. David Baratoux
Defended on May 8, 2013, awarded: "*summa cum laude*".

2008 – 2009 **Masters 2nd year** in Earth and Planetary Sciences, Université Toulouse III, France
Master's thesis: Fusion partielle d'amphibolites de la région de Barberton (Afrique du Sud) et implications pour la genèse de la croûte continentale
Supervision: Prof. Anne Nédélec

July 2008 Research internship. Institute for Study of the Earth's Interior (ISEI), Misasa, Japan
Subject: In-situ Raman and IR spectroscopic study of hydrous GeO_2 glass under pressure.
Supervision: Prof. Makoto Kanzaki,

2007 – 2008 **Masters 1st year** in Earth Sciences, Trans-Atlantic Science Student Exchange Program, University of Calgary, Canada

April 2007 Research internship. University of Calgary, Canada
Subject: Study of silica-undersaturated volcanic rocks from eastern Anatolia, Turkey.
Supervision: Dr. Paul Hoskin

2004 – 2007 **License** in Earth and Planetary Sciences, Université Toulouse III, France

OBSERVATORY ACTIVITIES

Since 2022 Participation in the on-call duty and guard at the OVPF (seismic data processing, activity monitoring). Field work during eruptions (lava sampling, GPS surveys). OVPF-IPGP, France

Since 2019 Near-real time provision of model-based lava flow trajectory in Civil Protection mandated format during eruptions at Piton de la Fournaise, OVPF-IPGP, France

April 2019 - Feb. 2020 Participation in the on-call duty at the OVPF (seismic data processing, activity monitoring). Field rwork during eruptions (lava sampling, GPS surveys). OVPF-IPGP, France

FIELDWORK EXPERIENCES

July 2023 Sampling and *in situ* viscosity and temperature measurements of an active lava flow, Litli Hrútur eruption, Iceland

2019-2023 Lava sampling an active lava flows, various field surveys during and outside eruptions at Piton de la Fournaise, France

March 2020 Mapping and sampling of the Sierra Negra eruption, Galapagos Ecuador

May 2018 *In situ* temperature and gas measurements of an active fumaroles and lava flow sampling and mapping at Vulcano, Italy

May 2018 Michoacán-Guanajuato archaeological survey on traditional grinding stones, *metates*. Trans-Mexican Volcanic Belt, Mexico

Nov. 2016 *In situ* viscosity and temperature measurements of an active lava flow and Kilauea lava flow mapping and sampling, Hawaii, USA

Jan. 2016 Workshop on monitoring active volcanoes, Santiaguito Volcano, Guatemala

2014-2016 Mapping, morphological interpretation, and sampling of volcanic deposits and paleosols in the Michoacán-Guanajuato monogenic volcanic field. Trans-Mexican Volcanic Belt, Mexico

2009-2014 Multiple field trips to study volcanic structures, mapping, geomorphological interpretations and sampling of volcanic deposits in various countries: Snake River Plain, USA; Western Volcanic Zone, Iceland; El Fuego Volcano, Guatemala; Etna, Italy.

May 2013 Monitoring of active volcanoes: one-week practice with NEMOH Network school. Stromboli, Italy

2007-2008 Structural geology and mineral exploration course in the Rockies. Alberta and British Columbia, Canada.

2004-2009 Geology and mapping in the Pyrenees. France and Spain.

FUNDINGS

IRD long term missions, mobilities and assignments abroad and overseas

2022 - 2025 Assignment to OVPF-IPGP, La Réunion, France - 3 years

2021 Research mobility for a researcher from *IG-EPN* to LMV UCA, France - 2 months

2020 Long-term mission at OVPF-IPGP, La Réunion, France - 3 months

Scientific projects

2024 « Tackling Multiphase Lava Rheology at its Origins » Co-I 50% (PI: Stephan Kolzenburg). 490 303$ National Science Foundation #2420723, UB, USA

2023 - 2024 « Measuring the viscosity of lava using the new portable field viscometer » PI 100%.10 000€ Clervolc, LMV, UCA, France

2023 « Rheology for near real time forecasting of lava flows » Collaborator (PI: Stephan Kolzenburg). 410 000$ National Science Foundation # 2223098, UB, USA

2022 « RAPID: Deployment of a Field Rheometer Prototype » Collaborator (PI: Stephan Kolzenburg). 15 000$ National Science Foundation, # 2241489 UB, USA

2021 « From magma ascent to deep-seated-ocean lava flow emplacement: the case study of the ongoing (since 2018) submarine eruption offshore Mayotte » PI 40% (co-Is: Lucia Gurioli and Etienne Médard). 125 000€ Clervolc, LMV, UCA, France

2020 « A new portable field viscometer » PI 100%. 10 000€ Chèque Recherche Innovation, Cap20-25, Isite, UCA France

2020 « Rheology of the lava flows of Sierra Negra, Galapagos, Ecuador ». PI 100%. 4 000€ ClerVolc, LMV, UCA, France

2017 « Building a new portable field viscometer ». PI 100%. 4 000€ Actions Incitatives of the Observatoire de Physique du Globe de Clermont-Ferrand, UCA, France

2016 « The thermo-rheological evolution of lava flows » PI 100%. Two years' salary + 10 000€, Auvergne Fellowship, ClerVolc, LMV, UCA, France

2014 « Eruptive activity and physical properties of magmas feeding enigmatic shield volcanoes in the Michoacán-Guanajuato Volcanic Field: El Metate case study ». PI 100%. Two years' salary. DGAPA, UNAM, Mexico

2009 PhD grant (3 years) from the International Graduate School, Network of Bavaria, LMU, Germany

Student travel grants

2013 IAVCEI, Kagoshima, Japan

2012 IAVCEI, Cities on Volcanoes 7, Colima, Mexico

2012 European Space Agency to participate at EGU, Vienna, Austria

2010 AGU, 2010 fall meeting, San Francisco, USA

2008 International Student Intern Program at Misasa, Institute for Planetary Materials (IPM), Okayama University (Misasa, Tottori), Japan

2007 Trans-Atlantic Science Student Exchange Program. University of Calgary, Canada

INVOLVMENT WITH THE SCIENTIFIC COMMUNITY

Editing and reviewing activities

Since 2018 Elected member of the editorial committee of the diamond open access journal VOLCANICA.

2020-2021 Editor in charge of the special issue collection of Reports from the official volcano monitoring agencies in Latin America at VOLCANICA.

Since 2018 Reviewer for funding agencies: CNRS/INSU (2022, 2023), Netherlands Space Office (2022), University of Perugia (2018), National Science Foundation USA (2024).

Since 2010 Reviewer for various A-ranked journals in the field of volcanology (Nature, Geology, Bulletin of Volcanology, Geophysical Research Letters, Journal of Geophysical Research, etc.)

Administrative responsibilities

2024 Elected member at the scientific council of the IRD

Since 2022 External member of the scientific council of the Observatoire Science de l'Univers - Réunion

2021- 2022 Member of the pedagogical council of the Écolde de l'Observatoire Physique du Globe de Clermont (OPGC)

Since 2021 Substitute member of the steering committee of the MARMOR project (Marine Advanced geophysical Research equipment and Mayotte multidisciplinary Observatory for research and Response)

Organization sessions at conferences and workshops

2023 Session: Physical properties of magma and lava and implications for Storage and Transport IAVCEI General Assembly, Rotorua, NZ

2021 Session: Properties of magmas: experiments, theories, models, and application to geochemistry and volcanology. AGU fall meeting New Orleans, USA.

2021 International Effusive crisis response (virtual) workshop during ANR-LAVA (ANR-16-CE39-0009) in collaboration with European Volcano Early warning system

2020 Virtual panel Careers outside academia, IAVCEI Early-Career Researchers Network (ECR-Net)

2020 Virtual panel Careers in academia, part I: Atlantic edition, IAVCEI ECR-Net

2020 Virtual panel Careers in academia, part II: Atlantic edition, IAVCEI ECR-Net

2020 Virtual panel Working at volcano observatories, part I: The Pacific IAVCEI ECR-Net

2020 Virtual panel Working at volcano observatories, part II: Africa, Europe and the Caribbean IAVCEI ECR-Net

2018 IAVCEI ECR-Net Workshop: Forming and enhancing partnerships between scientists and stakeholders. 10th Cities on Volcanoes. Naples, Italy

2018 Session: Looking toward the next generation volcanic hazard assessment efforts. Cities on Volcanoes 10. IAVCEI, Naples, Italy

2015 Session: Volcanic landscapes across the solar system: From field to remote sensing analysis. International Union of Geodesy and Geophysics; Prague, Czech Republic

2014 Pre-conference Field. Monogenetic volcanism of the Michoacán-Guanajuato Volcanic Field: Maar craters of the Zacapu basin and domes, shields, and scoria cones of the Tarascan highlands (Paracho-Paricutin region). 5th Maar Conference IAVCEI, Mexico

Other involvement

2020 – 2022 In charge of the seminar organization LMV, UCA, France
2017 – 2020 Representative of the Early Career Researcher Network of IAVCEI
2015 – 2016 In charge of the seminar organization UNAM, Mexico
2013 – 2020 Active member of the Early Career Researcher Network of IAVCEI
Since 2010 Member of International Association of Volcanology and Chemistry of the Earth's Interior, Collaborative volcano research and risk mitigation, European Geosciences Union et American Geophysical Union
2005 – 2009 Member of the student association MAGMA, University Toulouse III, France

DISSEMINATION OF SCIENTIFIC CULTURE

Invited seminars in universities or at international conferences

2023 Measuring the viscosity of lava in the field using a portable rotational rheometer. IAVCEI General Assembly, Rotorua, NZ
2023 Tracking and anticipating lava flow emplacement at Piton de la Fournaise. USGS Volcano Science Center seminar series, USA + UNAM, Charla de Volcanologia, Mexico
2022 Suivi et modélisation des coulées de lave. 1ère conférence internationale sur la gestion des volcans des Virunga, Goma, RDC
2022 Los volcanes y su monitoreo. Ministerio de Energia y Minas, Cuba
2021 Tracking and anticipating lava flow emplacement: Application to Piton de la Fournaise. University of Buffalo, USA and University of Michigan, USA
2021 Anticiper et surveiller les coulées de lave: application au Piton de la Fournaise. UCA, France and Université de la Réunion, France
2020 La reologia de los flujos de lava: medidas, observaciones y modelos. Instituto de Geofisica, Escula Polytechnica, Ecuador
2018 Constraining thermo-rheological properties of lava from lab and field experiments to applications for modelling. Cities on Volcanoes Conference, Naples, Italy
2017 Rheological control of lava flows emplacement. British Society of Rheology Mid-Winter Meeting, University of Bristol, UK
2015 La erupción del volcán escudo El Metate AD 1250 (Michoacán): La erupción mas voluminosa durante el Holoceno en México. Centro de Geosciencias, Quérétaro, México + UNAM, Charla de Volcanologia, Mexico + LMV, UCA
2014 The rheology of martian lava flows, UNAM, Mexico
2013 Volcanism on Mars: The rheology of lava flows, Universidad de Bogota, Colombia

Relation with society

2023 Organization of a stand « Qué hace esta lava en mi reserve y de donde viene? » 40 anniversario de la Reserva Ecologica del Pedregal de San Angel, UNAM, Mexico
2023 Mediation « carrefour au féminin » collège Plateau Goyave, La Réunion
2023 Seminar « Geosciences au féminin », Cité du volcan, La Réunion

2023 Seminar « La simulation des eruptions volcaniques », Cité du volcan, La Réunion
2022 Seminar « Modélisation de la probabilité de recouvrement par les coulées de lave au Piton de la Fournaise », Comité Technique Risques Direction de l'environnement, de l'aménagement et du logement (DEAL), La Réunion
2022 Public Q&A session « Fire of love » CGA Les ambiances, Clermont-Ferrand
2021, 2022 Festival Nuées Ardentes, Clermont-Ferrand
2022 Public Q&A session "Rencontre Montagnes et Science", Clermont-Ferrand
2022 Seminar "Des Volcans et des Femmes", Congres les femmes en Science, Paris
2021 Youpi Magasine n°393
2020 Review of the blog « Les Sciences Animées" de Christophe Wecker
Since 2019 Fête de la science, Cité du volcan, La Réunion
2019 Secondary school activity "femmes ingénieures" Lycée R Garros, La Réunion
2019 Primary school activity: "being a volcanologist" Saint-Joseph, La Réunion
2018 Seminar « L'activité récente au Kilauea, Hawaii », Les mercredis de la Science, UCA
2014 Primary school activity about volcanoes, Ecole Française, Mexico

Media

2022 TV interview Antenne Réunion. La Réunion
2021 TV documentary Le monde de Jamy "Quand nos volcans se déchainent" La Réunion
2021 TV documentary RMC Story: "Les volcans d'Auvergne vont-ils se réveiller ?"
2021 Radio interview : L'infiniment Chaud. France Culture
2020 TV interview, Réunion 1ère, Art du Feu, La Réunion
2019 TV interview Réunion 1ère sur l'éruption du 29 juillet 2019

AWARDS

2019 – 2023 Prime d'encadrement doctorale et de recherche, IRD, UCA, France
2018 Speed poster Awards. Workshop Interdisciplinaire sur la Sécurité Globale, Paris, France
2013 PhD defense awarded with "Summa cum laude", Munich, Germany
2011 Poster award, 9th Silicate Melt Workshop, La Petite Pierre, France

SCIENTIFIC PRODUCTION

2012 – 2024 47 peer-reviewed articles and more than 70 abstracts presented at international conferences. H-index Scopus (June 2024): 21 and 925 citations

1.3 Teaching and student supervision

Since the beginning of my scientific activities I have wanted to share my knowledge and to train students. I never had a teaching position and my current position does not include teaching duties, however I have always tried to get involved in teaching (although my teaching does not exceed a few hours per year), and in student supervision activities. I supervised my first student (master level) during my PhD in 2011-2012 and since then, I have co-supervised five undergraduate projects and eleven students at the masters' level. I have participated in several interviews and internship for secondary and high school pupils as part of their insertion into the professional world. I am currently co-supervising (40 and 50%) two Ph.D. students, one in France at LMV and the other in the United States at the University at Buffalo (UB). I am also currently a committee member of a PhD student at Drexel University, USA. I participated in three PhD defense juries as examiner, guest, and substitute member.

TEACHING ACTIVITIES

2022, 2023 "Le métier de volcanologue" (1h30) Licence 3*, UCA, France*

2022 "Haroun Tazieff, Les Scientifiques MADE IN France " (2h) École Doctoral des Sciences Fondamentales*, UCA, France*

Since 2014 Lectures on Effusive volcanism (2h/year) in the General Volcanology Course, Masters Level, UNAM, Mexico

2016 – 2017 Rock characterization and petrology of igneous rocks (15 h), first year university level, UCA, France

2014 – 2015 Lectures of volcanology and geodynamics (22 h) for undergraduate and graduate students at the Science faculty of the UNAM, Mexico.

2013 Lecture and exercise on lava rheology measurements for the NEMOH Network School (one day). LMU, Germany

2010 – 2012 In charge of the presentation of the high-temperature and rheological investigations lab for the international short course "Melts, Glasses and Magmas" LMU, Germany

STUDENTS SUPERVISION

Undergraduates

2023 R. Portigliatti-Presa. « Etude de la modélisation et du comportement visqueux d'une coulée de lave. » External supervision. Ecole des Mines-Telecom de l'Université de Lille

2022 E. Pasci. « Determination of morphometric parameters and simulation of lava flows in the Chachani Volcanic Complex – Arequipa. » External advisor. Supervision by Ben Van Wyk de Vries (LMV) and Nelida Manrique *INGEMMET, Pérou*

2022 E. Rodriguez. « Cartografía y análisis de la eruption 2018 del volcán Fernandina, Galápagos, Ecuador. » Co-supervision 30% with Benjamin Bernard *IG-EPN, Ecuador.*

2020 – 2021 H. Calderon. « Cartografía y análisis de la eruption 2018 del volcán Sierra Negra, Galápagos, Ecuador. » *IG-EPN, Equateur.* Co-supervision 30% with Benjamin Bernard and Silvia Vallejo *IG-EPN, Ecuador.*

2015 – 2016 N. Reyes-Guzman. « Geología volcánica de la región occidental de la cuenca lacustre de Zacapu, Michoacán y su importancia para la arqueología. » Co-supervision 50% with Claus Siebe *UNAM, Mexico.*

Masters

2024 - current J. Diamico « Automated Near-Real Time Rheological Flow Modeling for Nyiragongo Volcano (D. R. Congo) » Co-supervision 30% with Stephan Kolzenburg. *UB, USA.*

2022 T. Lemaire. « Using Volcflow as an operational tool for modelling lava flows at Piton de la Fournaise. » Co-supervision 50% with Karim Kelfoun. *Year 2, LMV, UCA, France.*

2022 L. Maingault. « Test du modèle thermo-rhéologique PyFLOWGO sur les coulées de lave de l'éruption de La Palma, 2021. » Co-supervision 50% with Andrew Harris*, Year 1, LMV, UCA. France.*

2022 S. Gueho. « Analyse texturale d'échantillons provenant de l'éruption de 2021 du Cumbre Vieja, La Palma. » Co-supervision 50% with Andrew Harris and Lucia Gurioli. *Year 1, LMV, UCA. France.*

2020 J. Fort. « Modélisation des coulées de lave au Piton de la Fournaise avec VolcFlow. » Co-supervision 50% with Karim Kelfoun. *Year 2, LMV, UCA, France.*

2019 A. Pawlak. « Remonté de péridotites par des laves basanitiques. » Co-supervision 50% with Didier Laporte*. Year 1, UCA, France.*

2018 – 2019 N. Reyes-Guzman. « Emplazamiento de los flujos de lava de la región occidental de la cuenca lacustre de Zacapu, Michoacán. » Co-supervision 50% with Claus Siebe. *UNAM, Mexico.*

2018 – 2019 I. Ramírez-Uribe. « Emplazamiento de los flujos de Rancho Seco y estructuras volcánicas vecinas (Michoacán, México). » Co-supervision 50% with Claus Siebe. *UNAM, Mexico.*

2018 P. Thao and J. Fort. « Le rôle de la viscosité dans les modèles de coulées de lave. » Co-supervision 50% with Andrew Harris*. Year 1, LMV, UCA. France.*

2017 A. Ajas. « L'influence des arbres sur l'avancée d'une coulée de lave, example au Kilauea, Hawaii. » Co-supervision 40% with Andrew Harris and Lucia Gurioli. *Year 2, LMV, UCA, France.*

2014 – 2016 JR de la Fuente. « Geología volcánica (radiometric dating, geochemistry) del area de Paracho-Cheran, Michoacán, Mexico. » Co-supervision 50% with Claus Siebe. *UNAM, Mexico.*

2011 – 2012 L. Debiasi. « The complex rheology of crystallizing melts. » Co-supervision 80% with Corrado Cimarelli. *LMU, Germany*.

PhD SUPERVISION

2022 – current Martin Harris « Measuring lava viscosity in the field. » Co-supervision 50% with Dr. Stephan Kolzenburg *University at Buffalo, USA*

2021 – 2024 Pauline Verdurme « Emplacement dynamics of the submarine eruption offshore Mayotte » (defending Nov. 2024). Co-supervision 40% with Dr. Lucia Gurioli and Dr. Etienne Médard *LMV, UCA, France*

PhD JURY MEMBER

2021 – 2024 Member of PhD committee for Jacob Brauner « Volcanic Hazards on Bioko (Equatorial Guinea) – Remote Sensing, Mapping and Modelling » *Drexel University, USA*

2022 Substitute member for the PhD defense of Francesco Massimetti « Thermal remote sensing of volcanic activity by using Sentinel-2 and Landsat-8: an improvement of the MIROVA system » *University of Turin, Italy*

2021 Examiner for the PhD defense of Jean-Marie Prival « On the emplacement dynamics of highly-viscous, silicic lava flows" » *LMV, UCA, France*

2017 Invited Examiner for the PhD defense of Silvia Vallejo « Numerical models of volcanic flows for an estimation and delimitation of volcanic hazards, the case of El Reventador volcano (Ecuador). » *LMV, UCA, France*

1.4 List of publications

Since my first publication in 2012 up to the time of the writing (June 2024), I have published 47 peer-reviewed articles. For 17 of them, I am 1st or 2nd author and for 13 I have co-authored with a student I mentored (these publications are marked with an Asterisk and the student's name is underlined). I have also published 4 non-peer-reviewed publications.

Open access articles are marked with the symbol and for non-open access articles, links to the post-print articles in the open archive platform HAL are given.

I also have more than 70 abstracts presented in international conferences, 15 of which are oral presentations. As of June 2024, my H factor was 21 on Scopus and 22 on google scholar.

PEER-REVIEWED

47*. Harris M, Kolzenburg S, I Sonder, **Chevrel O**. *(2024)* A new portable penetrometer for measuring the viscosity of active lava. *Review in Scientific Instrument. Vol. 95, 065103* https://doi.org/10.1063/5.0206776 , https://hal.science/hal-04663298

46*. Verdurme P, Gurioli L, **Chevrel MO**, Médard E, Berthod C, Komorowski JC, Harris A, Paquet F, Cathalot C, Feuillet N, Lebas E, Rinnert E, Donval JP, Thinon I, Deplus C and Bachèlery P. (2024) Magma ascent and lava flow field emplacement during the 2018–2021 Fani Maoré deep-submarine eruption insights from lava vesicle textures. *Earth and Planetary Science Letters. Vol: 636, 118720.* https://doi.org/10.1016/j.epsl.2024.118720 https://uca.hal.science/hal-04555016

45*. Hamon C, Pereira G, Aubry L, **Chevrel MO**, Siebe C, Quezada O, Reyes-Guzmán N. Quarrying volcanic landscapes: territory and strategies of metate production in Turícuaro (Michoacan). (2024) *Geofísica Internacional 63*(2), 929–948. https://doi.org/10.22201/igeof.2954436xe.2024.63.2.1760

44*. Hamon C, Pereira G, **Chevrel MO**, Aubry L, Siebe C, Quesada O, Reyes-Guzmán N. Present Use and Production of Metates and Molcajetes in Turícuaro (Michoacán, Mexico): Deciphering the Evolution of Food Preparation Practices (2023) *Ethnoarchaeology. Vol. 15, p. 208-2032* https://doi.org/10.1080/19442890.2023.2280379

43. **Chevrel MO**, Latchimy T, Batier L, Delpoux R, Harris M, Kolzenburg S (2023) A new portable field rotational viscometer for high-temperature melts *Review of Scientific Instruments: 94, 105116 (2023)* https://doi.org/10.1063/5.0160247, https://hal.science/hal-04262199v2

42. **Chevrel MO**, Villeneuve N, Grandin R, Froger JL, Coppola D, Massimetti F, Campus A, Hrysiewicz A, Peltier A, (2023) Report on the lava flow daily monitoring of the 19 September – 05 October 2022 eruption at Piton de la Fournaise. *Volcanica 6(2): 391–404. https://doi.org/10.30909/vol.06.02.391404*

41. Flynn ITW, **Chevrel MO**, Crown DA, Ramsey MSR. (2023) The Effects of Digital Elevation Model Resolution on the PyFLOWGO Thermorheological Lava Flow Model. *Environmental Modelling & Software, Vol. 167: 105768, https://doi.org/10.1016/j.envsoft.2023.105768.* https://hal.ird.fr/hal-04160976

40. Flynn ITW, **Chevrel MO**, Ramsey MSR. (2023) Adaptation of a thermorheological lava flow model for Venus conditions. *Journal of Geophysical Research: Planets*, *128*, e2022JE007710. https://doi.org/10.1029/2022JE007710

39*. Reyes-Guzmán N, Siebe C, **Chevrel MO**, Pereira G, Mahgoub AN, Böhnel H. (2023) Holocene volcanic eruptions of the malpaís de zacapu and its pre-hispanic settlement history. *Ancient Mesoamerica, 1–16.* https://doi.org/10.1017/S095653612100050X

38*. Verdurme P, Lelosq C, **Chevrel MO**, Pannefieu S, Médard E, Berthod C, Komorowski JC, Bachèlery P., Neuville D., and Gurioli L. (2023) Viscosity of silicate melts from the active submarine volcanic chain of Mayotte. *Chemical Geology (620) 121326* https://doi.org/10.1016/j.chemgeo.2023.121326, https://hal.uca.fr/hal-03965373

37*. Berthod C, Komorowski C, Gurioli L, Médard E, Bachèlery P, Bession P, Verdurme P, **Chevrel MO**, Di Muro A, Peltier A, Devidal JL *et al.* (2022) Temporal magmatic evolution of the Mayotte offshore eruption revealed by in situ submarine sampling and petrological monitoring. *Comptes Rendus. Géoscience, pp. 1-29.* https://doi.org/10.5802/crgeos.155

36. **Chevrel MO**, Harris A, Peltier A, Villeneuve N, Coppola D, Gouhier M, Drenne S. (2022) Volcanic crisis management supported by near real time lava flow hazard assessment at Piton de la Fournaise, *Volcanica* 5(2), pp. 313–334. https://doi.org/10.30909/vol.05.02.313334

35. Prival JM, Harris AJL, Zanella E, Test CR, Gurioli L., **Chevrel MO** and Biren J. (2022) Emplacement dynamics of a crystal rich, highly viscous trachyte flow of the Sancy stratovolcano (France) *GSA Bulletin 2022* https://doi.org/10.1130/B36415.1, https://hal.uca.fr/hal-04017179v1

34. Smittarello D, Smets B, Barrière J, Michellier C, Oth A, Shreve T, Grandin, R, Theys N, Brenot H, Cayol V, Allard P, Caudron C, **Chevrel MO**, Darchambeau F *et al.* (2022) Precursor-free eruption triggered by edifice rupture at Nyiragongo volcano. *Nature 609*, 83-88. https://doi.org/10.1038/s41586-022-05047-8

33. Harris A, Mannini S, Calabrò L, Calvari S, Gurioli L, **Chevrel MO**, Favalli M, Villeneuve N. (2022) Forest destruction by 'a'a lava flow during Etna's 2002-03 eruption: Mechanical, thermal and environmental interactions. *Journal of Volcanology and Geothermal Research.* 429:107621. https://doi.org/10.1016/j.jvolgeores.2022.107621, https://hal-insu.archives-ouvertes.fr/insu-03777178

32. Harris A, Rowland S., **Chevrel MO** (2022) Anatomy of a channel-fed 'a'a lava flow system. *Bulletin of Volcanology* 84:70 https://doi.org/10.1007/s00445-022-01578-0, https://hal.inria.fr/insu-03825083v1

31. Tadini A, Harris A, Morin J, Bevilacqua A, Peltier, Aspinall W, Ciolli, S, Bachelery P, Bernard B, Biren J, Brum da Silveiri A, Cayol V, **Chevrel MO**. Coppola D *et al.* (2022) Structured elicitation of expert judgement in real-time eruption scenarios: an exercise for Piton de la Fournaise volcano, La Réunion island. *Volcanica. 4(1):* 105 – 131. http://dx.doi.org/10.30909/vol.05.01.105131

30. Kolzenburg S, **Chevrel MO,** Dingwell D. (2022) Magma suspension rheology. *Reviews in Mineralogy and Geochemistry* 87 (1): 639–720. http://dx.doi.org/10.2138/rmg.2022.87.14 https://hal.science/hal-03849785

29*. Ramírez-Uribe I, Siebe C, **Chevrel MO**, Ferrés D, Salinas S. (2022) The Late Holocene Nealtican lava-flow field from Popocatépetl volcano: Emplacement dynamics and implications for future hazard scenarios and archaeology. *GSA Bulletin. 134 (11-12): 2745–2766.* https://doi.org/10.1130/B36173.1, https://hal.science/hal-03849746

28. Peltier A, **Chevrel MO**, Villeneuve N, Harris A (2022) Reappraisal of gap analysis for effusive crises at Piton de la Fournaise. *Journal of Applied Volcanology* 11, 2. https://doi.org/10.1186/s13617-021-00111-w

27. **Chevrel MO**, Favalli M, Villeneuve N, Harris A, Fornaciai A, Richter N. Derrien A, Boissier P, Di Muro A, Peltier A (2021) Lava flow hazard map of Piton de la Fournaise volcano. *Natural Hazards in Earth System Sciences,* 21, 1–22, 2021 https://doi.org/10.5194/nhess-21-2355-2021

26*. Reyes-Guzmán N, Siebe C, **Chevrel MO**, Pereira P (2021) Late Holocene Malpaís de Zacapu (Michoacán, Mexico) andesitic lava flows: rheology and eruption properties based on LiDAR image. *Bulletin of Volcanology* 83, 28. https://doi.org/10.1007/s00445-021-01449-0, https://insu.hal.science/insu-03708928v1

25*. Ramírez-Uribe I, Siebe C, **Chevrel MO**, Fisher CT (2021) Rancho Seco monogenetic volcano (Michoacán, Mexico): Petrogenesis and lava flow emplacement based on LiDAR images – *Journal of Volcanology and Geothermal Research.* Vol 411:107169 https://doi.org/10.1016/j.jvolgeores.2020.107169, https://hal.science/hal-03113443v1

24. Peltier A, Ferrazzini V Di Muro A., Kowalski P, Villeneuve N, Richter N, **Chevrel MO**, Froger J-L, and Hrysiewicz A, Gouhier M, Coppola D, Retailleau L, Beauducel F, Boissier P, Brunet C, Catherine P, Fontaine F, Lauret F, Garavaglia L, Lebreton J, Canjamale K, Desfete N, Griot C, Harris A, Arellano S, Liuzzo M, Gurrieri S, Ramsey M (2020) Volcano crisis management during COVID-19 lockdown at Piton de la Fournaise (La Réunion). *Seismological Research Letters*, Vol. 92 (1): 38–52. https://doi.org/10.1785/0220200212

23. Lormand C, Harris A, **Chevrel MO**, Calvari S., Gurioli L., Favalli M., Fornaciai A., Nannipieri L (2020) The 1974 west flank eruption of Mount Etna: A data-driven model for a low elevation effusive event. *Frontiers in Earth Science*, Vol. 8, p 572. https://doi.org/10.3389/feart.2020.590411

22. Biren J, Harris AJL, Tuffen H, **Chevrel MO,** Vlastélic Y, Schiavi F., Benbakkar M, Fonquernie C, Calabro L (2020) Chemical, textural and thermal analyses of local interactions between lava and a tree -case study from Pāhoa, Hawai'i. *Frontiers in Earth Science,* Vol. 8, p 233 https://doi.org/10.3389/feart.2020.00233

21. Harris AJL, Mannini S, Thievet S, **Chevrel MO,** Gurioli L. Villeneuve N, Di Muro A, Peltier A (2020) How shear helps lava to flow. *Geology,* Vol. 48 (2): 154–158., https://doi.org/10.1130/G47110.1, https://hal.inria.fr/hal-02401447/

20. Mannini S, Harris AJL, Jassop D, **Chevrel MO,** Ramsey MS. (2019) Combining ground- and ASTER-based thermal measurements to constrain fumarole field heat budgets: The case of Vulcano Fossa 2000-2019. *Geophysical Research Letters*, Vol. 46(21), p. 11868-11877 https://doi.org/10.1029/2019GL084013

19. **Chevrel MO**, Harris AJL, Pinkerton H. (2019) Measuring the viscosity of lava in the field: A review. *Earth-Science Reviews,* Vol. 196 : 1028853. https://doi.org/10.1016/j.earscirev.2019.04.024, https://hal.science/hal-02150640v2

18. Ramsey MS, **Chevrel MO**, Harris AJL, Coppola D. (2019) The Influence of Emissivity on the Thermo- Rheological Modeling of the Channelized Lava Flows at Tolbachik Volcano. *Annals of Geophysics,* Vol.62,2, VO222. https://doi.org/10.4401/ag-8077

17. Harris AJL, **Chevrel MO**, Coppola D, Ramsey MS, Hrysiewicz A, Thivet S, Villeneuve, N Favalli M., Peltier A., Kowalski P, Di Muro A, Froger J.-L, Gurioli L. (2019) Validation of an Integrated Satellite-data-driven Response to an Effusive Crisis: The April–May 2018 Eruption of Piton de La Fournaise. *Annals of Geophysics,* Vol.62,2, VO30. https://doi.org/10.4401/ag-7972

16*. **Chevrel MO**, Harris AJL, Ajas A, Biren J, Gurioli L, Calabrò L (2019) Investigating Physical and Thermal Interactions between Lava and Trees: The Case of Kilauea's July 1974 Flow. *Bulletin of Volcanology,* Vol.81 (2): 1–6. https://doi.org/10.1007/s00445-018-1263-8 https://hal.science/hal-01981448/

15. **Chevrel MO,** Harris A J L, James M R, Calabrò L, Gurioli L, Pinkerton H (2018) The viscosity of pāhoehoe lava: *In situ* syn-eruptive measurements from Kilauea, Hawaii. *Earth and Planetary Science Letters*, Vol. 493: 161-17 https://doi.org/10.1016/j.epsl.2018.04.028, https://hal.science/insu-03708970v1

14*. Reyes-Guzmán N, Siebe C, **Chevrel MO**, Guilbaud MN, Salinas S, Layer P (2018**)** Geology and Radiometric Dating of Quaternary Monogenetic Volcanism in the Western Zacapu Lacustrine Basin (Michoacán, México): Implications for Archeology and Future Hazard Evaluations. *Bulletin of Volcanology*, 80 (18): 1–20. https://doi.org/10.1007/s00445-018-1193-5, https://hal.science/hal-02401449v1

13. **Chevrel MO,** Labroquere J, Harris AJL, Rowland SK (2018) PyFLOWGO: An Open-Source Platform for Simulation of Channelized Lava Thermo-Rheological Properties. *Computer Geosciences*, Vol. 111: 167–80. https://doi.org/10.1016/j.cageo.2017.11.009 , https://hal.science/hal-01634842/

12. Rhéty M, Harris AJL, Villeneuve N, Gurioli L, Médard E, **Chevrel MO**, Bachèlery P (2017) A Comparison of Cooling-Limited and Volume-Limited Flow Systems: Examples from Channels in the Piton de La Fournaise April 2007 Lava-Flow Field. *Geochemistry, Geophysics, Geosystems*, Vol. 18 (9): 3270–91. https://doi.org/10.1002/2017GC006839

11. Mahgoub AN, Böhnel H, Siebe C, **Chevrel MO** (2017) Paleomagnetic Study of El Metate Shield Volcano (Michoacán, Mexico) Confirms Its Monogenetic Nature and Young Age (~ 1250 CE). *Journal of Volcanology and Geothermal Research,* Vol. 336: 209–18. https://doi.org/10.1016/j.jvolgeores.2017.02.024, https://hal.uca.fr/hal-01634724

10. **Chevrel MO,** Guilbaud MN, Siebe C (2016) The ~AD 1250 Effusive Eruption of El Metate Shield Volcano (Michoacán, Mexico): Magma Source, Crustal Storage, Eruptive Dynamics, and Lava Rheology. *Bulletin of Volcanology,* Vol. 78 (32): 1–28. https://doi.org/10.1007/s00445-016-1020-9, https://hal.uca.fr/hal-03849775

9. **Chevrel MO**, Siebe C, Guilbaud MN, Salinas S (2016) The AD 1250 El Metate Shield Volcano (Michoacán): Mexico's Most Voluminous Holocene Eruption and Its

Significance for Archaeology and Hazards. *The Holocene,* Vol.26 (3): 471–88. https://doi.org/10.1177/0959683615609757, https://hal.uca.fr/hal-03849772

8. DiGenova D, Hess KU, **Chevrel MO**, Dingwell DB (2016) Models for the Estimation of Fe3+/Fetot Ratio in Terrestrial and Extraterrestrial Alkali- and Iron-Rich Silicate Glasses Using Raman Spectroscopy. *American Mineralogist*, Vol. 101 (4): 943–52. https://doi.org/10.2138/am-2016-5534CCBYNCND

7. DiGenova D, Kolzenburg S, Vona A, **Chevrel MO**, Hess KU, Neuville DR, Ertel-Ingrisch W, Romano C, Dingwell DB (2016) Raman Spectra of Martian Glass Analogues: A Tool to Approximate Their Chemical Composition. *Journal of Geophysical Research Planets* Vol.121 (5): 740–52. https://doi.org/10.1002/2016JE005010

6*. **Chevrel MO**, Cimarelli C, DeBiasi L, Hanson JB, Lavallée Y, Arzilli F, Dingwell DB (2015) Viscosity Measurements of Crystallizing Andesite from Tungurahua Volcano (Ecuador). *Geochemistry, Geophysics, Geosystems* Vol. 16 (3): 870–89. https://doi.org/10.1002/2014GC005661

5. **Chevrel MO**, Baratoux D, Hess KU, Dingwell DB (2014) Viscous Flow Behavior of Tholeiitic and Alkaline Fe-Rich Martian Basalts. *Geochemica Cosmochimica Acta,* Vol. 124: 348–65. https://doi.org/10.1016/j.gca.2013.08.026

4. **Chevrel MO**, Platz T, Hauber E, Baratoux D, Lavallée Y, Dingwell DB (2013) Lava Flow Rheology: A Comparison of Morphological and Petrological Methods. *Earth Planetary Science Letters*, Vol. 384: 102–20. https://doi.org/10.1016/j.epsl.2013.09.022

3. **Chevrel MO**, Giordano D, Potuzak M, Courtial P, Dingwell DB (2013) Physical Properties of CaAl2Si2O8-CaMgSi2O6-FeO-Fe2O3 Melts: Analogues for Extra-Terrestrial Basalt. *Chemical Geology,* Vol. 346: 93–105. https://doi.org/10.1016/j.chemgeo.2012.09.004

2. Kremers S, Lavallée Y, Hanson J, Hess KU, **Chevrel MO**, Wassermann J, Dingwell DB (2012) Shallow Magma-Mingling-Driven Strombolian Eruptions at Mt. Yasur Volcano, Vanuatu. *Geophysical Research Letters*, Vol. 39 (21): 1–6. https://doi.org/10.1029/2012GL053312

1. Nédélec A, **Chevrel MO**, Moyen JF, Ganne J, Fabre S (2012) TTGs in the Making: Natural Evidence from Inyoni Shear Zone (Barberton, South Africa). *Lithos,* Vol. 153: 25–38. https://doi.org/10.1016/j.lithos.2012.05.029. https://hal.science/hal-00793452v1

NON-PEER-REVIEWED

4. Paris R, Bani P, **Chevrel MO**, Donnadieu F, Eychenne J, Gauthier PJ, Gouhier M, Jessop D, Kelfoun K, Moune S, Roche O, Thouret JC (2022) Volcanic Hazards in *Hazards and Monitoring of Volcanic Activity* Vol.1. Ed. JF Lénat ISBN : 9781789450439. 250pp, https://uca.hal.science/hal-03877139

3. **Chevrel O**, Wadsworth F, Farquharson J, Kushnir A, Heap M, Williams R, Delmelle P and Kennedy B (2021) Publishing a Special Issue of Reports from the volcano observatories in Latin America: Editorial to Special Issue on Volcano Observatories in Latin America. *Volcanica*, 4(S1), p.i-vi. https://doi.org/10.30909/vol.04.S1.ivi

2. **Chevrel MO** (2020) Mesurer la viscosité des laves. *Revue de l'Association Volcanologique Européenne*. ISSN 0982-9601. N°197 Mars 2020. p.27-31, https://uca.hal.science/hal-04663312

1. Siebe C, Guilbaud M-N, Salinas S, Kshirsagar P, **Chevrel MO**, De la Fuente, JR, Hernández-Jiménez, A, Godínez L (2014) Monogenetic volcanism of the Michoacán-Guanajuato volcanic field: Maar craters of the Zacapu basin and domes, shields, and scoria cones of the Tarascan highland (Paracho-Paricutin region). In: Field guide, Pre-meeting Fieldtrip for the 5th International Maar Conference (5IMC-IAVCEI). Querétaro, 13–17 November, 33 pp. https://doi.org/10.13140/RG.2.2.19817.51040

1.5 List of presentation at international conferences

2024

76. Brauner J, **Chevrel MO**, Vanderkluysen L, Walter T R. Lava flow hazard assessment on Bioko Island (Equatorial Guinea). CoV Guatemala
75. Ramírez-Uribe I, Siebe C, **Chevrel MO**, Ferres D, Salinas S. The late Holocene Nealtican lava-flow field, Popocatépetl volcano (Mexico): Emplacement dynamics and future hazards. CoV Guatemala
74. Campus A, Laiolo M, **Chevrel MO**, Peltier A, Villeneuve N, Coppola D. Lava flow velocity in effusive contexts: a space-based approach using thermal data acquired by VIIRS. CoV Guatemala

2023

73. **Chevrel MO**, Latchimy T, Batier L, Delpoux R, Harris M, Kolzenburg S , T. Parsons, I. Sonder, C. Berlie-Caillat**.** Viscosity measurement on an active lava flow: new instruments and first tests at Litli Hrútur lava flow in Iceland. 1ere rencontre de volcanologie française. Clermont-Ferrand
72. Verdurme P, **Chevrel MO**, Gurioli L Médard E, Berthod C, Komorowski JC, Bachèlery P., Vesicle Morphologies of Popping Rocks: Implication for degassing processes during the 2018-2021 Mayotte submarine eruption. 1ere rencontre de volcanologie française. Clermont-Ferrand
71. Farquharson J. I., **Chevrel M. O.**, Delmelle P., Heap M. J., Kennedy B., Kushnir A. R. L., Wadsworth F. B., Williams R. (2023) Five years of Volcanica. Volcanic and Magmatic Studies Group meeting abstracts, 4th – 6th January 2023, London
70. Harris M, Kolzenburg S, Parsons, T, SonderI, **Chevrel MO**. A new portable penetrometer for measuring the viscosity of active lava. Geological Society of America. Vol. 55, No. 6. Doi 10.1130/abs/2023AM-393560
69. Verdurme P, Gurioli L, **Chevrel MO**, Médard E, Berthod C, Komorowski JC, Harris A, Paquet F, Cathalot C, Feuillet N, Lebas E, Rinnert E, Donval JP, Thinon I, Deplus C and Bachèlery P.Degassing processes of popping rocks: a textural study of the 2018-2021 Fani Maoré submarine lava. AGU General Assembly, USA
68. Brauner J, **Chevrel MO**, Vanderkluysen L, Walter T R. Lava flow hazard assessment on Bioko Island (Equatorial Guinea). IUGG General assembly Berlin
67. Verdurme P, **Chevrel MO**, Gurioli L Médard E, Berthod C, Komorowski JC, Bachèlery P., Vesicle Morphologies of Popping Rocks: Implication for degassing processes during the 2018-2021 Mayotte submarine eruption. EGU General Assembly, Vienna, Austria
66. **Chevrel MO**, Verdurme P, Lelosq C, Pannefieu S, Médard E, Berthod C, Komorowski JC, Bachèlery P., Neuville D., and Gurioli L. Viscosity of silicate melts from the active submarine volcanic chain of Mayotte. EGU General Assembly, Vienna, Austria
65. Flynn I., Crown D, Ramsey M, **Chevrel MO.** Mapping and modeling venusian lava flows: implications for future missions. 54th Lunar and Planetary Science Conference. *The Woodlands, Texas USA*

64. Ramírez-Uribe I, Siebe C, **Chevrel MO**, Salinas S, Fisher CT, Guilbaud MN, Layer P. Geological and archaeological aspects of Rancho Seco and Mazcuta monogenetic volcanoes (Michoacán, Mexico) - Preserving our heritage and preparing for future eruptions. Morelia, Mexico
63. Hamon C., G. Pereira, L. Aubry, O. **Chevrel, O.** Quezada, N. Reyes. From the volcano to the tool: a long-term history of metate production around El Metate volcano (Michoacan). Celebrating the 80th anniversary of Parícutin volcano (Michoacán, Mexico) - Preserving our heritage and preparing for future eruptions. Morelia, Mexico
62. **Chevrel O**., T. Latchimy, S. Kolzenburg, M. Harris, I. Sonder, T. Parsons, C. Berlie-Caillat, L. Batier, R. Delpoux. Measuring the viscosity of lava using a portable rotational field rheometer. IAVCEI General Assembly NZ 2023 – online **invited oral**
61. **Chevrel MO**, Harris A, Peltier A, Villeneuve N, Coppola D, Gouhier M, Drenne S. Volcanic crisis management supported by near real time lava flow hazard assessment at Piton de la Fournaise. IAVCEI General Assembly NZ 2023 – online **oral**

2022

60. Hamon C., G. Pereira, L. Aubry, O. **Chevrel, O.** C. Siebe, O. Quezada. Present use and production of «metates» in Turícuaro (Michoacán, Mexico): An ethnoarchaelogical approach to deciphering the evolution of food preparation practices. Session A02-02. Breaking Bread and Raising a Glass: Bridging Ethnoarchaeological and Archaeological Researchon Food and Culinary Habits (J. Arthur and S. Valamoti org.) World archaeological congress
59. Villeneuve N, Martel F, Narbaud S, Labrosse B, Harris A, Finizola A. **Chevrel MO**, Peltier A. Attractivité d'un site incontournable, surfréquentation pendant les éruptions et crainte de l'accident ou Les ingrédients d'une gestion complexe des flux de visiteurs au Piton de la Fournaise. Assises nationales des risques naturels 2022 (ANRN). Strasbourg ; France – **poster**
58. **Chevrel MO**, Harris A, Peltier A, Villeneuve N, Coppola D, Gouhier M, Drenne S. Gestion des crises volcaniques par une évaluation des risques liés à la mise en place des coulées de lave en temps quasi-réel au Piton de la Fournaise, La Réunion. Assises nationales des risques naturels 2022 (ANRN). Strasbourg; France – **poster**
57. Mingo Mauro A., Widom E, Kuentz D, Siebe C, Larrea P, Chevrel MO, Marie-Noelle Guilbaud, and Salinas S. Evolution of the El Metate Shield Volcano, Michoacán–Guanajuato Volcanic Field, Mexico. Chapman conference, USA – **poster**

2021

56. Hamon C, Pereira G, Aubry L, **Chevrel MO**, Siebe C, et al.. « METATE » Anthropisation d'un milieu volcanique du 13e siècle à nos jours: l'activité meulière sur le massif d'El Metate, Michoacán (Mexique). Seminaire Labex Dynamite - GT Territorialités, 2021, Paris, France. ⟨hal-03724748⟩
55. Test CR, JM Prival, AJL Harris, E Zanella, L Gurioli, **MO Chevrel**. Paleomagnetic and Rock Magnetic Characterization of the Pietre Cotte Lava Flow (Vulcano, Italy) AGU Fall Meeting 2021- **poster**
54. Reyes-Guzmán N, Widom E, Siebe C, Larrea P, Kuentz D, **Chevrel MO.** Magmatic Evolution of a Monogenetic Volcano Cluster in the Michoacán-Guanajuato Volcanic Field, México: the Late Holocene Zacapu Cluster. ID# 892964 American Geophysical Union (AGU) Fall Meeting - **poster**
53. Smittarello D, Barrière J, d'Oreye N, Smets B, Oth A, Shreve T, Subira J, Mafuko Nyandwi B, Cayol V, Grandin R, Wauthier C, Derauw D, Geirsson H, Theys N, d'Archambeau F, Poppe S, Caudron C, Lesage P, Allard P, Samsonov S, Delhaye L, **Chevrel M O**, Mashagiro N,

Muhindo Syavulisembo A and F Kervyn. Propagation and arrest of the May 2021 lateral dike intrusion at Nyiragongo (D.R. Congo). ID# 854944 American Geophysical Union (AGU) –

52. Wadsworth F, JFarquharson, A Kushnir, M Heap, B Kennedy, **O Chevrel**, R Williams, and P Delmelle. Growing a diamond open access community initiative: Volcanica 3 years on. EGU21-15938 https://doi.org/10.5194/egusphere-egu21-15938 European Geosciences Union (EGU) General Assembly- **poster**
51. **Chevrel M.O**, Favalli M., Villeneuve N., Harris A., Fornaciai A., Richter N., Derrien A., Boissier P., Di Muro A. and A. Peltier (2021) Lava flow hazard map of Piton de la Fournaise volcano. EGU21-12266 https://doi.org/10.5194/egusphere-egu21-12266. European Geosciences Union (EGU) General Assembly- **poster**
50. Latchimy T., **Chevrel M.O**., Delpoux R., Batier L., Rossin C. Conception d'un rhéomètre appliqué à la mesure in-situ de la viscosité de laves volcaniques. École Technologique du Réseau National des Électroniciens

2020

49. Harris E., L Wilson, **MO Chevrel** Dynamics of Emplacement of Lava Flows on Elysium Mons, 2020. Mars, LPI, 1387
48. **MO Chevrel**, S Poppe, H Dietterich, R Fitzgerald, P Forte, J Hickey, L Freitas Guimarães, J Muller, J Eychenne. Conectar jóvenes volcanólogos a nivel mundial: el desafío de la Early-Career Researchers Network (ECR-Net) de la IAVCEI. 1er Congreso de la asociación latinoamericana de volcanología, Universidad Católica del Norte, Antofagasta, Chile – online **Oral**

2019

47. Barnoud A., Cayol A., Gailler L., Smittarello D., Bodart O., Hrysiewicz A., Dabaghi F., Froger JL., Peltier A., Chevrel M.O., Roult J., Chaput M. 2019 Towards joint modelling and inversion of surface displacements and microgravimetric temporal variations for the characterization of eruptive sources at the Piton de la Fournaise volcano, Rencontres RESIF 2019 – **poster**
46. Mannini, S.; Harris, A.; Jessop, D.; **Chevrel, MO**.; Ramsey, M. 2019 Combining ground- and ASTER- based thermal measurements to constrain fumarole field heat budgets: The case of Vulcano Fossa (2000-2015). European Geosciences Union (EGU) General Assembly- **poster**
45. Lo, M.; Wilson, L.; **Chevrel, MO**. 2019 The rheology and eruption conditions of fissure-fed lavas near Jovis Tholus, mars Name of the conference: The 50th Lunar and Planetary Science Conference (LPSC) – **poster**
44. **M.O. Chevrel**, Andrew J.L. Harris, Noé Bernabeu, Pierre Saramito, Diego Coppola, Michael S. Ramsey, Alexis Hrysiewicz, Simon Thivet, Nicolas Villeneuve, Massimiliano Favalli, Aline Peltier, Philippe Kowalski, Andrea Di Muro, Jean-Luc Froger, Lucia Gurioli. LAVA project: Modelling lava advance using an integrated satellite-data-driven response to an effusive crisis and the effect of vegetation. 27th International Union of Geodesy and Geophysics (IUGG) Montreal, Canada- **poster**
43. Harris, A. J.; Mannini, S. Thivet, **M.O. Chevrel**, L. Gurioli, N. Villeneuve, A. Dimuro, and A. Peltier. 2019 How shearing helps lava to flow. 27th International Union of Geodesy and Geophysics (IUGG) Montreal, Canada- **poster**
42. N. Reyes-Guzmán, C. Siebe**, M.O. Chevrel**, G. Pereira 2019 Emplacement of the El Malpaís de Zacapu lava flows in Michoacán, Mexico. 27th International Union of Geodesy and Geophysics (IUGG) Montreal, Canada- **poster**
41. Prival J.M., Harris A., Gurioli L., **Chevrel O**., Robustelli Test C., Kenderes S., Zanella E., Whittington A. (2019). A history of deformation within Pietre Cotte rhyolite flow (Vulcano). 27th International Union of Geodesy and Geophysics (IUGG) Montreal, Canada- **poster**

2018

40. **Chevrel, M.O;** Harris, A.; James, M.; Pinkerton, H; Rowland, S.; Gurioli, L.; Calabro, L.; Labroquère, J. 2018 Constraining thermo-rheological properties of lava: from lab and field experiments to applications for modelling. Cities on Volcanoes 10 (CoV), Naples, Italy - **invited/keynote talk**
39. Harris, A.; **Chevrel, M.O**; Coppola, D.; Ramsey, M.; Villeneuve, N.; Peltier, A.; Gurioli, L. 2018 Effusive crises at Piton de la Fournaise 2014–2015: Source term provision and quantification of uncertainty in lava flow modelling for a real time response. Cities on Volcanoes 10 (CoV), Naples, Italy - **invited/keynote talk**
38. JM Prival, AJL Harris, CR Test, E Zanella, J Biren, **MO Chevrel** Unravelling the emplacement dynamics of silicic lava flows: the case of the Grande Cascade trachyte flow (Monts Dore, France) Cities on Volcanoes 10 (CoV), Naples, Italy **- Poster**
37. Siebe, C.; Reyes-Guzman, N.; Mahgoub, A.; Salinas, S.; Bohnel, H.; Guilbaud, M-N; **Chevrel, M.O**; Pereira, G.; Dorison, A.; Darras, V.; Quezada, O. 2018 Geological map of the volcanically active western Zacapu lacustrine basin area (Michoacán, México) and its usefulness for archaeology and hazard assessment. Cities on Volcanoes 10 (CoV), Naples, Italy - **invited/keynote talk**
36. **Chevrel, M.O**; Siebe, C.; Guilbaud, M-N; Salinas, S.; Mahgoub, A.; Bohnel, H.; Hamon, C.; Pereira, G.; Aubry, L.; Quezada, O.; Vidales, N. 2018. The ~AD 1250 El Metate shield volcano (Michoacán): Mexico's most voluminous effusive Holocene eruption and its significance for archaeology and hazards. Cities on Volcanoes 10 (CoV), Naples, Italy - **oral communication**
35. Vallejo S., Kelfoun K., **M.O Chevrel .** (2018). Lava flow simulations with VolcFlow using simple and complex rheologies. Cities on Volcanoes 10 (CoV), Naples, Italy - **oral communication**
34. Vallejo S., Ramón P., Kelfoun K., **Chevrel M.O.**, Almeida M. (2018). Characterization of lava flows from an andesitic volcano as input data for numerical flow simulations, case El Reventador volcano (Ecuador). Cities on Volcanoes 10 (CoV), Naples, Italy - **oral communication**
33. Ramsey, M.; **Chevrel, O.;** Harris, A. 2018 Modeling the 2012-2013 lava flows of Tolbachik, Russia using thermal infrared satellite data and PyFLOWGO. American Geophysical Union (AGU) - **oral communication**
32. Poppe, S.; Chardot, L.; **Chevrel, M.O**.; Dietterich, H.; Fitzgerald, R.; Forte, P.; Freitas Guimarães, L.; Hickey, J.; Mueller, J. Setting up an early-career researchers' network to connect volcanologists: the IAVCEI ECR-Net. American Geophysical Union (AGU) - **oral communication**

2017

31. Prival, JM; Harris, A.; Robustelli Test, C.; **Chevrel, M.O**; Biren, J.; Zanella, E. 2017 Unravelling the emplacement dynamics of silicic lava flows: the case of the Grande Cascade trachyte flow (Monts Dore, France) International Association of Volcanology and Chemistry of the Earth Interior (IAVCEI) Meeting Portland, USA- **poster**
30. **Chevrel M.O.**; Labroquère, J.; Harris, A.; Rowland, S. 2017 PyFLOWGO: an open-source platform for simulation of channelized lava thermo-rheological properties International Association of Volcanology and Chemistry of the Earth Interior (IAVCEI) Meeting Portland, USA- **poster**
29. **Chevrel M.O.** 2017 Rheological control of lava flow emplacement Name of the conference: British Society of Rheology winter meeting, Bristol, United Kingdom - **invited/keynote talk**
28. Reyes-Guzman, N.; **O. Chevrel**; Siebe, C.; Guilbaud, 2017 Thick andesitic lava flows: Case of the western part of the Zacapu basin in the Michoacán-Guanajuato Volcanic Field, Mexico. International Association of Volcanology and Chemistry of the Earth Interior (IAVCEI) Meeting Portland, USA- **poster**

27. Harris, A.; Mannini, S.; Trivet, S.; Gurioli, L.; **M.O. Chevrel**; Villeneuve, N.; Peltier, A.; DiMuro, A. 2017: Unexpected rheological regime measured down an active lava channel. International Association of Volcanology and Chemistry of the Earth Interior (IAVCEI) Meeting Portland, USA- **poster**

2016

26. **Chevrel, M.O**; Guilbaud, M-N; Siebe, C. 2016 Eruptive history of the youngest Mexican Shield and Mexico's most voluminous Holocene eruption: Cerro El Meta Name of the conference: European Geosciences Union (EGU) General Assembly- **poster**
25. Reyes-Guzman, N.; Siebe, C.; **O. Chevrel**; Pereira 2016 Volcanic geology of the western Zacapu lacustrine basin (Michoacán, México) and its importance for archaeology. 9th Cities on Volcanoes conference (CoV) - **poster**

2015

24. **Chevrel M.O**; Cimarelli, C.; DeBiasi, L.; Hanson, J.B.; Lavallée, Y.; Dingwell, 2015 Viscosity measurements of crystallizing andesite from Tungurahua volcano (Ecuador) Name of the conference: International Union of Geodesy and Geophysics (IUGG), General Assembly Prague - **oral communication**

2014

23. **Chevrel M.O**; Siebe C.; GuilbaudM-N. 2014 Eruptive activity of enigmatic medium-sized volcanoes in the Michoac·n-Guanajuato Volcanic Field (MGVF), Central Mexico: The case of El Metate. American Geophysical Union (AGU) Fall Meeting- **poster**
22. **Chevrel M.O**; Siebe C.; Guilbaud M-N; DelaFuente JR; Salina, S. 2014 Eruptive style and properties of magma feeding enigmatic medium-sized volcanoes in the Michoacán-Guanajuato Volcanic Field: Cerros El Metate and Paracho case studies 5 International Maar Conference, Queretaro, Mexico - **oral communication**

2013

21. **Chevrel M.O.**; Debiasi, L.; Cimarelli, C.; D. B Dingwell. 2013 Rheology of crystallising lava: an experimental approach Example of andesitic lava Name of the conference: International Association of Volcanology and Chemistry of the Earth Interior Meeting (IAVCEI)- **poster**
20. **Chevrel M.O.;** D. Baratoux; K.-U. Hess; D. B Dingwell. 2013 Viscosity of Martian tholeiitic and alkaline lavas. International Association of Volcanology and Chemistry of the Earth Interior Meeting (IAVCEI) - **oral communication**

2012

19. **Chevrel M.O.;** Lavallée, Y.; Baratoux, D.; Cimarelli, C.; DeBiasi, L.; Hanson, J.B.; Dingwell, D. 2012 Rheological, petrologic and thermodynamic approaches in a transient system such as lava flows. 7th Cities on Volcanoes conference (CoV-) – **poster**
18. **Chevrel M.O.**; T. Platz; E. Hauler; Baratoux, D.; D. B Dingwell. 2012 Rheology of Icelandic lava flows as analogs for Mars: comparison between morphometric and experimental determinations
    Name of the conference: European Geosciences Union General (EGU) Assembly - **oral communication**
17. Kremers, S.; Hanson, J.B.; Lavallée, Y.; Hess, KU; **M.O. Chevrel**; Wassermann, J.; Dingwell, D. 2012 Shallow magma- mingling-driven Strombolian eruption at Mt. Yasur, Vanuatu, European Geosciences Union (EGU) General Assembly - p**oster**
16. DeBiasi, L.; **M.O. Chevrel**; Cimarelli, C.; Hanson, J.B.; Lavallée, Y.; Dingwell, D. 2012 The complex rheology of crystallization magmas Name of the conference: American Geophysical Union (AGU) Fall meeting **- poster**

15. **M.O. Chevrel**; DeBiasi, L.; Hanson, J.B.; Cimarelli, C.; Lavallée, Y.; Dingwell, D. 2012 Transient rheology of crystallization andesitic magma. The 22nd V.M: Goldschmidt conference - **oral communication**
14. **M.O. Chevrel**; DeBiasi, L.; Hanson, J.B.; Cimarelli, C.; Lavallée, Y.; Dingwell, D 2012 Transient rheology of crystallization andesitic magma Name of the conference: European Geosciences Union (EGU) General Assembly - **poster**
13. **M.O. Chevrel**; D. Baratoux; K.-U. Hess; D. B Dingwell. 2012 Viscosity of Iron-rich Synthetic Martian Basaltic Melts Name of the conference: American Geophysical Union (AGU) Fall meeting– **poster**

2011

12. **M.O. Chevrel**; D. Giordano; M. Potuzak; P Courtial; K-U Hess; D Dingwell. 2011 Physical properties of CaAl2Si2O8- CaMgSi2O6-FeO-Fe2O3 melts: analogues for extra-terrestrial basalt_ Silicate Melt Workshop- **poster**
11. T. Platz; E. Hauber; **M. O. Chevrel**; L. LeDeit; F. Trauthan; F. Preusker; R. Jaumann; Neukum, G. 2011 Preliminary results on lava morphologies and vent structures: an example from the Western Volcanic Province, Iceland- 42nd Lunar and Planetary Science Conference (LPSC) 42, pp. 2108 - 2108. **- poster**
10. E. Hauber; T. Platz; L. LeDeit; **M. O. Chevrel**; B. Hoffmann; L. Kuhlmann; F. Trauthan; F. Preusker; R. Jaumann. 2011 Mapping of Postglacial Icelandic Lava Flows as Analogues for Mars Name of the conference: 42nd Lunar and Planetary Science Conference (LPSC) 42, pp. 1749 - 1749. 03/2011. **- poster**
9. T. Platz; E. Hauber; **M. O. Chevrel**; L. LeDeit; F. Trauthan; F. Preusker; R. Jaumann; Neukum, 2011 Preliminary results on lava morphologies and vent structures: an example from the Western Volcanic Province, Iceland. European Geosciences Union (EGU) General Assembly **- poster**
8. **M.O. Chevrel**; T. Platz; E. Hauler; Ledeit, L; D. B Dingwell. 2011 Rheology of Icelandic lava flows derived from geometrical parameters and experimental techniques- International Union of Geodesy and Geophysics General (IUGG) Assembly - **poster**
7. **M.O. Chevrel**; D. B Dingwell; D. Baratoux; D. Giordano. 2011 Viscosity of extra-terrestrial lavas derived from experiments, an extension to empirical model. International Union of Geodesy and Geophysics (IUGG) - **oral communication**
6. D. B Dingwell; **M.O. Chevrel**; D. Baratoux. 2011 Viscosity of Synthetic Martian Basaltic Melts Name of the conference: American Geophysical Union (AGU) Fall meeting – **poster**
5. **M.O. Chevrel;** T. Platz; E. Hauler; Ledeit, L; D. B Dingwell. 2011 Rheology of Icelandic lava flows as analogs for Mars: comparison between morphometric and experimental determinations- American Geophysical Union (AGU). Fall meeting - **oral communication**

2010

4. **M.O. Chevrel**; K.-U. Hess; D. B Dingwell. 2010 Effect of Iron on Rheological Properties of HPG8 American Geophysical Union (AGU) Fall meeting - **poster**
3. **M.O. Chevrel;** D. B Dingwell; W. Ertel-Ingrisch; K.-U. Hess. 2010 Redox viscometry of ferropicritic melt - a synthetic Martian analogue basalt _ Experimental Mineralogy, Petrology and Geochemistry, (EMPG) meeting XIII - **poster**
2. D Dingwell; C. Romano; M. Potuzak; G Guili; **M. O. Chevrel**; P. Valenti. Fe and melt viscosity 20th General Meeting of the International Mineralogical Association - **oral communication** International Mineralogical Association (IMA)
1. **M. O. Chevrel**; M. Potuzak; D Dingwell; K-U Hess. 2010 Redox viscometry of ferropicrite melt. European Geosciences Union (EGU) General Assembly – **poster**

2. Rheological evolution of lava flows

2.1 Introduction

Understanding and describing the complexity of lava flow behavior is a major challenge and a long-term objective in modern volcanology. Modeling of lava flows leads to significant improvements in hazard assessment, as well as contributions to our understanding of volcanic activity and history on Earth and on other planets. Rheology, which is directly linked to the intrinsic chemical and physical properties of the magma (chemical composition, oxygen fugacity, volatile content, temperature, and shape and size of bubbles and crystals) is a key factor in the transport of magma from its source to the surface. Once the magma reaches the surface it has two fates. It can either be fragmented as in explosive eruption, or it can flow as in effusive eruption. In this last case, magma become lava and as it flows, cooling drives constant evolution of the material's physical properties. This continuous transformation leads to variations in lava's rheological properties (viscosity, yield strength, strain-rate dependency) which directly impact the dynamics of the flow emplacement.

In my work, I have been focusing mainly on constraining the thermo-rheological evolution of lava as flowing occurs to understand the flow behavior and hence the final morphology as key to modeling and preventing future disasters as well as to interpreting planetary surfaces. This chapter focuses on how the thermo-rheological evolution of lava flow can be constrained from field observations and sampling, high temperature laboratory measurements and numerical modelling. Here I do not mention *in situ* field viscometry which is the subject of chapter 3. This current chapter is a medley of a large number of publications and includes sections and concepts from the following articles:

Chevrel MO, Platz T, Hauber E, Baratoux D, Lavallée Y, Dingwell DB (2013) Lava Flow Rheology: A Comparison of Morphological and Petrological Methods. *Earth Planetary Science Letters*, Vol. 384: 102–20. https://doi.org/10.1016/j.epsl.2013.09.022

Chevrel MO, Labroquere J, Harris AJL, Rowland SK (2018) PyFLOWGO: An Open-Source Platform for Simulation of Channelized Lava Thermo-Rheological Properties. *Computer Geosciences*, Vol. 111: 167–80. https://doi.org/10.1016/j.cageo.2017.11.009 , https://hal.science/hal-01634842/

Harris AJL, Mannini S, Thievet S, **Chevrel MO,** Gurioli L. Villeneuve N, Di Muro A, Peltier A (2020) How shear helps lava to flow. *Geology,* Vol. 48 (2): 154–158., https://doi.org/10.1130/G47110.1

Kolzenburg S, **Chevrel MO,** Dingwell D. (2022) Magma suspension rheology. *Reviews in Mineralogy and Geochemistry* 87 (1): 639–720. http://dx.doi.org/10.2138/rmg.2022.87.14

and other personal publications on the subject:

Chevrel MO, Giordano D, Potuzak M, Courtial P, Dingwell DB (2013) Physical Properties of CaAl2Si2O8-CaMgSi2O6-FeO-Fe2O3 Melts: Analogues for Extra-Terrestrial Basalt. *Chemical Geology,* Vol. 346: 93–105. https://doi.org/10.1016/j.chemgeo.2012.09.004

Chevrel MO, Cimarelli C, DeBiasi L, Hanson JB, Lavallée Y, Arzilli F, Dingwell DB (2015) Viscosity Measurements of Crystallizing Andesite from Tungurahua Volcano (Ecuador).

Geochemistry, Geophysics, Geosystems Vol. 16 (3): 870–89. https://doi.org/10.1002/2014GC005661

Rhéty M, Harris AJL, Villeneuve N, Gurioli L, Médard E, **Chevrel MO**, Bachèlery P (2017) A Comparison of Cooling-Limited and Volume-Limited Flow Systems: Examples from Channels in the Piton de La Fournaise April 2007 Lava-Flow Field. *Geochemistry, Geophysics, Geosystems*, Vol. 18 (9): 3270–91. https://doi.org/10.1002/2017GC006839

Chevrel MO, Harris AJL, Ajas A, Biren J, Gurioli L, Calabrò L (2019) Investigating Physical and Thermal Interactions between Lava and Trees: The Case of Kilauea's July 1974 Flow. *Bulletin of Volcanology,* Vol.81 (2): 1–6. https://doi.org/10.1007/s00445-018-1263-8

Ramsey MS, **Chevrel MO**, Harris AJL, Coppola D**.** (2019) The Influence of Emissivity on the Thermo- Rheological Modeling of the Channelized Lava Flows at Tolbachik

Lormand C, Harris A, **Chevrel MO**, Calvari S, Gurioli L, Favalli M, Fornaciai A, Nannipieri L (2020) The 1974 west flank eruption of Mount Etna: A data-driven model for a low elevation effusive event. *Frontiers in Earth Science*, Vol. 8, p 572. https://doi.org/10.3389/feart.2020.590411

Harris A, Rowland S., **Chevrel MO** (2022) Anatomy of a channel-fed 'a'a lava flow system. *Bulletin of Volcanology* 84:70 https://doi.org/10.1007/s00445-022-01578-0

Verdurme P, Lelosq C, **Chevrel MO**, Pannefieu S, Médard E, Berthod C, Komorowski JC, Bachèlery P., Neuville D., and Gurioli L. (2023) Viscosity of silicate melts from the active submarine volcanic chain of Mayotte. *Chemical Geology (620) 121326* https://doi.org/10.1016/j.chemgeo.2023.121326

Chevrel MO and Harris AJL. (2024) Monitoring lava flows. *Chapter in IAVCEI Book Modern Volcano Monitoring Springer* Ed. Spica and Caudron. *Accepted 16/05/23. https://uca.hal.science/hal-04160974*

2.2 Lava flow rheology from field observation and sampling

Thanks to the many field surveys made on basaltic lava flows (inactive or active), there now exists a large database that can be used to reconstruct flow emplacement dynamics as well as anticipate flow behavior for future eruptions. However, although theses lava flows are frequent and well-studied, and seem easy to approach, a large number of unknowns still remained. Data collection on active flows include mapping, flow dimensions, velocity, temperature (surface and core), sampling, and rarely viscosity measurements (see chapter 3). These data are key parameters for (i) monitoring lava flows (see review by Chevrel and Harris 2024), (ii) responding to ongoing effusive crises (e.g. Harris et al., 2019a), and (iii) research purposes (Biren et al., 2020; Chevrel et al., 2019a). When studying past lava flows there is often no knowledge on the flow dynamics that involve effusion rate, velocity of emplacement and eruption duration. The only accessible element is the solidified flow. Two categories of data set can be extracted:

1) the morphological parameters of the flow that include the (i) appearance characteristics (i.e. the lava flow type, surface appearance - smooth, brecciated, blocky-,

morphological features such as lobes, channels, levees, etc.) and (ii) the geometrical dimensions (length, width, thickness and volume),

2) the rock samples from which we can extract petrology and textural analyses including the chemical bulk chemical composition, the proportion, size and type of crystals and vesicles and the interstitial glass chemistry.

Both data sets can be used to estimate the rheology. The former (morphological parameters) informs on the rheology of the flow as a whole, while the latter (rock sample characteristics) provides the rheology of the material itself (i.e. the lava). I hence define these as 1) the flow apparent rheology and 2) the lava rheology, respectively. Both are theoretically linked. If the flow is composed of a uniformed and homogeneous isoviscous material, hence the flow parameters (viscosity, dimensions) are directly correlated to the material properties itself. However, when lava is flowing on planetary surfaces, its properties change greatly as it cools, crystallizes and degases which varies through the flow width, thickness and length. A lava flow is hence heterogeneous and has transient thermo-rheological properties. How can we then constrain the solidified lava flow dynamics? How can we use the flow final morphology to extract the lava thermo-rheological history during emplacement? How the lava rheology, as it flows and cools, will in turn influence the flow morphology and dimensions? Can we model this evolution and hence anticipate lava flow dimensions, specially runout distances, for hazard assessment purposes?

Apparent flow dynamics can be obtained from the flow's dimensions, known as the morphological approach. This assumes that the lava flow behaves as simple viscous body. Considering a smooth and laminar flow (which is always the case except for very low viscosity lava that may be turbulent) and a Newtonian behavior (which is a first order approximation), Nichols (1939) proposed to use the Jeffreys' equation (Jeffreys, 1925) to determine the apparent flow viscosity. Jeffreys' equation calculates the average velocity of a Newtonian liquid (specifically water) flowing on a slope and of known depth, considering that the flow is much wider than deep (see Lev and James 2014 for details about effect of channel cross-sectional geometry). Recognizing that lava may no longer behave as a Newtonian fluid as it cools and crystallizes, but may follow a Bingham law, a method was later proposed by Hulme (1974) to estimate the flow yield strength from its morphological dimensions. Moore (1987) then adapted the Jeffreys' equation to estimate lava velocity from the viscosity and the yield strength of the flow. Experiments with analogue materials having a known rheological behavior confirm that the morphology of a lava flow and its advance rate can be used to infer the flow rheology (e.g., Fink and Griffiths, 1992; Gregg and Fink, 1996, 2000; Lyman et al., 2004). Some authors proposed that the heat transfer is dominated by thermal diffusion along the flow and represented by the Grätz (G_z) number (Hulme et al., 1977; Knudson and Katz, 1958; Wilson et al., 1987). To relate the length of lava flow to the amount of cooling taking place in the lava channel and considering the velocity of emplacement, it was proposed that cooling-limited basaltic flows on Etna and Hawaii stop advancing when their G_z number had fallen below a critical value of 300 (Pinkerton and Sparks, 1976; Pinkerton and Wilson, 1994). Considering this G_z number approach, it is thus possible to recover the viscosity of a lava flow from its dimensions and without previous knowledge of the velocity. This approach is valid for cooling-limited lava flows that flow in a laminar fashion with no inflation. This method considers that the flow is controlled by the behavior of the viscous core and not by the resistance of the solidifying crust. To go further some of these authors attempted to find the direct relationship between the viscosity or the yield strength of a flow and the bulk silica content of the lava (Hulme, 1974; Moore et al., 1978; Pinkerton and Wilson, 1994; Walker, 1973). This had led to numerous studies to interpret the viscosity and hence the composition of past lava flows on other planets, as for example on Mars (e.g., Glaze and Baloga, 2006; Hiesinger et al., 2007; Vaucher et al., 2009; Wilson et al., 2009; Wilson and Head, 1994; Zimbelman, 1985, 1998).

The approximation that a lava flow has one single viscosity value neglects important physico-chemical processes, which are expected to affect considerably the rheology of lava (Cashman et al., 1999; Crisp et al., 1994; Ryerson et al., 1988; Shaw, 1969). For example, during emplacement of basaltic lava flows, heat loss induces crystallization and consequently provokes evolution of the residual liquid composition, which both increase the apparent viscosity of the lava by several orders of magnitude from the vent to the point where the flow halts. During lava flow emplacement, the viscosity of lava is therefore transient, and further evaluation of the validity of interpretations made from morphological methods is imperative.

This leads us to the second approach to estimate the viscosity of lava that focuses on the petrography and geochemistry of rock samples. This is what I call the petrographic method (or phase characteristics model-based) (Chevrel et al., 2013a). Defining the lava rheology from sample characteristics must be performed on samples collected along the flow. This approach is actually being employed either on collected samples after emplacement (care should be taken to ensure no post emplacement cooling when sampling, e.g. Chevrel et al., 2019a; Chevrel and Harris, 2024; Harris et al., 2022b) or from in situ sampling of active lava flow by quenching the molten lava (Chevrel et al., 2018b; Harris et al., 2020). Lavas are made up of three phases: the liquid, the solid (crystals) and the gas (bubbles). Most lavas are defined as suspensions, meaning that their crystal cargo is less than the random maximum crystal packing. A simple approach, known as the effective medium theory, can be applied. This involves the viscosity of lava being calculated as function of the effect of each phase (crystals and bubbles of various shapes and sizes) in a liquid phase (that is a silicate melt):

$$\eta_{app} = \eta_{melt} \cdot \eta_r = \eta_{melt}(T, X) \cdot \eta_{rc}(\phi c, r, \dot{\gamma}) \cdot \eta_{rb}(\phi b, Cx)$$

where the viscosity of the melt phase (η_{melt}) depends on temperature (T) and composition (X). The relative viscosity due to the presence of a crystalline phase (η_{rc}) depends on the volumetric abundance of crystals (ϕc) and their aspect ratio (r), as well as the strain rate ($\dot{\gamma}$). The relative viscosity due to the presence of bubbles (η_{rb}) depends on the volumetric abundance of bubbles (ϕb) and their capillarity parameter (Cx; Mader et al., 2013), which depends on the melt viscosity, bubble surface tension and strain rate. The viscosity of the interstitial melt is Newtonian. Its chemical composition can be measured where the glass phase has been well preserved (*in situ* quenching or naturally quenched crust) using a microprobe; and emplacement temperature can be estimated from geothermometers (e.g. Putirka 2008). Melt viscosity can then be estimated using a composition-based model (see Russell, et al. 2022 for review) or by measuring the temperature-viscosity relationship in the lab (see section 2.2). Conversely, if the glass has not been preserved, but instead there is a microcrystalline groundmass, an alternative method is to calculate the groundmass bulk composition by subtracting the phenocrystal and microlite chemical composition using the average mass density of the crystals to the bulk chemical composition (Ramírez-Uribe et al., 2021). To estimate the effect of crystals (η_{rc}) and bubbles (η_{rb}) on the suspension's viscosity a detailed textural analysis is necessary. This must include quantification of the particle sizes, shapes (aspect ratio) and abundances (fraction). These characteristics are usually obtained from image analyses of thin sections and microphotographs acquired using microscopes and scanning electron microscopes (Cashman et al., 1999; Chevrel et al., 2019a; Crisp et al., 1994; Dietterich et al., 2018; Robert et al., 2014; Shea et al., 2010). Once the key parameters are extracted from images, the relative effect of each phase can be estimated following one of numerous two phases (melt + crystals or melt + bubbles) models (see review by Kolzenburg et al., 2022 and see the protocol proposed by Mader et al. 2013). Applying the effective medium theory consists of estimating the relative effect of one phase (the smallest, either crystals or bubbles) with the melt. This mixture is then designated as the effective medium and will be used to estimate the influence of the other phase relative to it (Harris and Allen, 2008; Phan-Thien and Pham, 1997). Although the effective medium theory is very convinient it neglects interactions between crystals and gas bubbles (see chapter 5).

In Chevrel et al. (2013a) the viscosity of a lava flow estimated from its morphology and from sample analyses were compared to evaluate the physical meaning of such estimates, and answer some of the previously mentioned questions. For this, we have constrained the transient rheology of the erupted lava considering the crystallization sequence observed in the samples (chemical composition, crystal content and shape, and geothermobarometric data) and modelled through MELTS (Ghiorso and Sack, 1995). We show that the lava viscosity depends strongly on the crystallization sequence and history. Results demonstrated that the lava viscosity is inevitably increasing by several orders of magnitude during flow emplacement from the vent to the flow front (Figure 1). The lava viscosity quickly becomes non-Newtonian as the groundmass crystallizes. We show that flow rheological properties, obtained from the flow's morphology, are distinct from the lava behavior at the eruption onset and during most of its emplacement, but corresponds to the conditions occurring near flow cessation, i.e. the upper rheological limit also defined as the rheological cut-off (Figure 1).

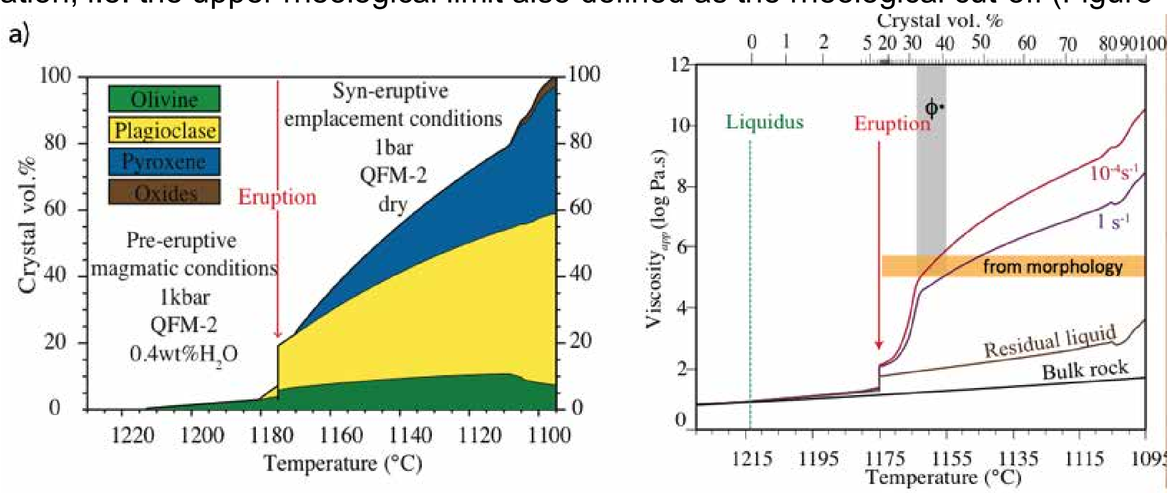

Figure 1: a) Modeled crystallization sequence of the lava at pre and syn-eruptive conditions; b) Comparison of the increase of viscosity at pre-and syn-eruption conditions due to the crystallization sequence and viscosity estimated form morphology. Phi represents the crystal maximum packing fraction, a proxy for the rheological cut off conditions. Modified from* ***Chevrel et al. 2013b.***

Reaching the rheological cut-off due to increasing crystallinity is true for basaltic lavas, because their low viscosity and high element diffusivity enable crystallization and volatile exsolution, as well as outgassing, resulting in a significant viscosity increase of several orders of magnitude during emplacement. Referred to as cooling-limiting conditions the lava stops flowing when reaching the upper limit that is the apparent solidified flow viscosity (Wilson and Head, 1994). However, this rheological cut-off depends not only on the final thermo-rheological conditions, but also on crystallization and cooling history, pre- and syn-eruption kinetics, strain rate, and oxygen fugacity. Basaltic lava flows may undergo a transition from pahoehoe to ʻaʻā morphologies, characterized by a change in rheological flow behavior making the lava more viscous and susceptible to shear-stress. This non-Newtonian behavior causes the crust to tear apart and form fragments. This transition is dependent on the increase of both viscosity during cooling and shear rate with increasing flow velocity, due to steep slopes or high effusion rates (Di Fiore et al., 2021; Hon et al., 2003). Such transition can also be seen when a lava flow enters a forest. In Chevrel et al. (2019a) we show that the pāhoehoe–ʻa'ā transition of the Kīlauea's July 1974 flow occurs at a viscosity of 10^3 Pa·s and this appears to be a threshold below which lava-trees can form so as to behave as a network of obstacles where lava trees and molds can form, and above which they cannot, the trees being knocked over by the advancing lava flow front.

Down-flow degassing will likely cause loss of volatiles and undercooling of the melt to trigger microcrystallization, both of which will increase the viscosity of the lava mixture (Sparks and Pinkerton, 1978). The evolution of bubble quantity and shape during lava flow emplacement affects rheology (Cashman et al., 1994; Polacci et al., 1999; Riker et al., 2009) where the mixture viscosity will decrease or increase depending on whether bubbles are able to deform or not (Llewellin and Manga, 2005). In Chevrel et al. (2018b), we show that application of current physico-chemical models based on sample characterization (petrographic approach), gave viscosity estimates that were approximately compatible with *in situ* viscosity measurement (see chapter 3). This highlighted the sensitivity of model-based viscosity estimates on the effect of deformable bubbles. In Harris et al. (2020), we constrain and link changing bubble states with flow dynamics down a lava channel. Analysis revealed that with distance from the vent, the channelized lava evolved into a central channel plug (made of undeformed foam-like lava) flanked by narrow shear zones in which bubbles were highly deformed, and hence where the effective viscosity was low. This causes the flow to initially accelerate, helped by bubble shearing in narrow lateral shear zones, until cooling takes over as the main driver for viscosity increase and, hence, velocity decrease.

A note on intermediate and silicic lavas

Intermediate (andesite) and silicic (dacite, rhyolite) lavas are more viscous than basaltic lavas and can reach thicknesses of up to hundreds of meters. These lavas often contain a high proportion of crystals and have a low porosity as for example andesitic lavas (Chevrel et al., 2016a; Ramírez-Uribe et al., 2021, 2022); or dacitic lavas (Harris et al., 2004; Prival et al., 2022), while they may also appear glassy, near aphyric, and possess highly bubbly layers, as in obsidian flows (Fink, 1980). During flow and cooling, crystallization is retarded by the high viscosity and low element diffusion, and hence crystallization does not appear to be the key component that triggers flow halt, as it is the cased for cooling-limited basaltic flows. Besides, the lava is usually already degassed with no clear evidence of downflow variation, but there is evidence of degassing through surface vesiculation forming a scoriaceous carapace (Anderson et al., 1995). Two theories exist regarding thick block lava flows: they advance either like a caterpillar (similar to ʻaʻā flows) where the core is a molten material moving as a viscous flow capable of folding (Fink, 1980); or like glacier, the flow slides on a shear zone over a brecciated surface (Latutrie et al., 2017; Prival et al., 2022) and present ogives formed by fracture-bound structures (Andrews et al., 2021).

Intermediate to silicic lavas erupt at temperatures around 900 to 1100°C, resulting in lava viscosities often higher than 10^5 Pa·s. However, the bulk apparent flow viscosity (considering that they move as a viscous material) is several orders of magnitude larger than the viscosity of the molten lava in particular because of the formation of a resistant crust (e.g., Castruccio et al., 2013; Fink and Griffiths, 1992; Kerr and Lyman, 2007). Thus, such thick flows come to a halt dominantly due to the increasing thickness and yield strength of the growing crustal carapace (Kilburn and Lopes, 1991) or, in the case of crystal-rich silicic flows, predominantly controlled by the yield strength of the flow's core (Castruccio et al., 2010, 2013; Magnall et al., 2017). To constrain the viscosity from flow morphology and estimate emplacement duration, Kilburn and Lopes, (1991) developed a simple relation linking flow field dimensions and underlying slope to eruption duration, independent of terms involving gravity or lava chemistry and rheology.

Extracting the lava dynamics to understand past eruption of thick block flows hence required hand samples and flow dimension analyses. In several studies I led or contributed to, we attempted to constrain the rheology and flow duration of solidified thick andesitic to dacite lava flows (Chevrel et al., 2016a, 2016b; Ramírez-Uribe et al., 2021, 2022; Reyes-Guzmán et al., 2018, 2021). These studies revealed that with the different methods cited above, we can constrain magma viscosities at pre-eruptive conditions, lava viscosities during flow emplacement, flow apparent viscosity and hence obtained estimation of emplacement durations. For instance, in Chevrel et al. (2016a, 2016b), we studied El Metate monogenetic volcano, the largest effusive eruption during the Holocene in the Trans-Mexican Volcanic Belt (also recognized as the most voluminous andesitic effusive eruption known worldwide for this period) and assessed that magma viscosity increased from 10^2–10^3 Pa·s prior to eruption through 10^6–10^8 Pa·s during ascent, and to 10^9–10^{11} Pa·s over lava emplacement. We estimated emplacement duration at 2 to 7 years for the longest (15 km) and the thickest lava flow (150 m), respectively. We concluded that successive emplacement of all flows that constitute this volcano, representing a total of 9.2 km^3, probably took around 35 years. Conversely, in Ramírez-Uribe et al. (2022), we found that the effusive phase of the Popocatepetl volcano, namely the Nealtican lava-flow field, may have lasted the same amount of time (~35 years) but for half the emitted lava volume (4.2 km^3). This crystal rich lava flows had slightly higher viscosities and emplacement durations up to several years, depending on the flow unit and morphological method employed.

The number of studies focusing on the rheological behavior of silicic thick lava flows remains lower than that for basaltic flows. Furthermore, in Prival et al. (2022), we concluded that the emplacement dynamics and associated structures of crystal-rich, silicic lava flow are very different from those of their crystal-poor counterparts, which argues for a global reassessment of silicic lava flow emplacement based on crystal content. A holistic review on thick lava flows rheology is yet to be written.

2.3 Lava rheology in the lab

From super-liquidus to crystallizing conditions, lava can span over several orders of magnitude and involve both Newtonian and non-Newtonian behavior. A complete rheological characterization of a magmatic suspension therefore requires a combination of several experimental methods (Kolzenburg et al., 2022). The most frequently used methods for high temperature suspension rheometry are the rotational viscometry via concentric cylinder (Dingwell and Virgo, 1988; Spera et al., 1988), the uniaxial compression using parallel plate (Bagdassarov and Dingwell, 1992; Hess et al., 2005) and torsion viscometry in Paterson-type devices (Caricchi et al., 2007; Paterson and Olgaard, 2000).

To constrain lava rheology, temperature–viscosity relationship of the liquid phase is first required to quantify the contribution of crystals and/or bubbles on the rheology of the bulk lava suspension. For measuring the viscosity of silicate melts at super-liquidus temperatures the concentric cylinder viscometry has long been a go-to technique. It is commonly employed in combination with viscosity measurements near the glass transition temperature, e.g., via micro-penetration viscometry (Hess and Dingwell, 1996) or estimation of the melt viscosity by application of shift factors to calorimetric data (Gottsmann et al., 2002) to interpolate the theoretical non-Arrhenian temperature-dependent viscosity of the pure melt across the crystallization interval. The temperature range covered by concentric cylinder viscometry spans from 800 to 1700°C for viscosities commonly around 10^1 to 10^4 Pa·s. Measurements are usually performed at atmospheric pressure and in air but experimentation under controlled atmospheres (e.g., more reducing conditions) is possible (Dingwell and Virgo, 1987). The importance of measurements at varying oxygen fugacity is increasingly recognized due its effect on melt viscosity (increasing Fe^{2+} over Fe^{3+} decreases viscosity, Chevrel et al., 2014, 2013b) as well as on the onset of crystallization and phase equilibria (Kolzenburg et al., 2018b). A large compositional range have been measured (Russell et al., 2022 for review), including extraterrestrial lava (Chevrel, 2013; Chevrel et al., 2014; Morrison et al., 2019; Sehlke and Whittington, 2016; Vetere et al., 2017), as well as alkaline lava from submarine environment (Verdurme et al., 2023). To date, no apparatus exists that allows for concentric cylinder viscometry under pressure, a key component affecting crystal phase assembly and bubble nucleation and growth dynamics in magmatic system.

Below the liquidus, crystallizing lava of low viscosity are measured via concentric cylinder viscometry (commonly below ~10^4 Pa·s, usual limit of most apparatus) and at low degrees of undercooling (i.e., near the liquidus). The bulk compositions used in this approach usually span silica contents between ~35 to 55 wt. % SiO2, i.e., Basalts and Foidites to Andesites. This is because of their relatively low viscosity and comparatively fast crystallization kinetics, which allow steady state conditions in texture and suspension viscosity to be reached on the timescales of hours to days and permit quenching of the samples for textural characterization. The fast kinetics also allow for experimentation at near natural conditions (i.e., in thermal, textural and chemical disequilibrium). In contrast, high viscosity suspensions (commonly above ~10^6 Pa·s) with bulk compositions usually > 60 wt.

% SiO_2 (i.e., Andesites to Rhyolites) are measured via parallel plate viscometry in uniaxial compression or via torsion viscometry. These experiments are typically performed just above the melt's glass transition temperature (i.e., in the supercooled liquid state). This is because these high viscosity systems have comparatively slow crystallization and vesiculation kinetics, which allows negligible textural and or chemical change of the sample over the course of the experiment and to maintain a steady state suspension viscosity over the measurement timescales (minutes to hours).

Concentric cylinder experiments allow for continuous viscosity measurement as a function of varying experimental conditions or textural changes in the sample, and infinite strain. However, in early investigation of subliquidus concentric cylinder measurements, the tested lava was only measured once equilibrium was reached (Pinkerton et al., 1995a), and often was not sampled during crystallization, instead crystal content was estimated independently using the liquid line-of-descent provided by petrological thermodynamic models (Ryerson et al., 1988; Shaw, 1969). Later, viscosity was recorded at progressively lower temperatures and the molten material attached to the spindle used to measure viscosity was quenched and analyzed to estimate the crystal content (Ishibashi, 2009; Ishibashi and Sato, 2007; Sato, 2005). Despite the very informative nature of these tests, the method has several shortcomings, including the lack of continuous viscosity recording, disturbance of crystalline textures by the spindle, limited representativeness of the sampled melt, and the potential reactivity of the alumina spindle with the melt. To overcome such disadvantages, Vona et al. (2011) continuously monitor the rheological consequences of the crystallization lava during cooling and crystallization until thermodynamics equilibrium. They show a general trend with an initial viscosity increase due to thermal relaxation of the melt at the dwell temperature; followed by time-invariant viscosity of the metastable liquid before crystallization (incubation time); then viscosity distinctly increases due to crystallization until it reaches a time-invariant viscosity plateau with a stable crystal content (equilibrium). This method has been then employed in various studies to establish the temperature-viscosity-crystal content relationship (e.g. Morrison et al., 2020; Sehlke et al., 2014; Sehlke and Whittington, 2016; Soldati et al., 2014; Vetere et al., 2013, 2017; Vona and Romano, 2013). In these experiments, the spindle had to be removed at the end of the experiments before the crucible full with lava could be quenched, for further textural analyses.

To provide a complete analysis of the undisturbed textures during quench and to preserve all original attributes of the crystalline phase distribution and orientation produced during the viscosity measurement, I developed a new kind of disposable spindle (Chevrel et al., 2015). This spindle was made of alumina ceramic wrapped in thin Pt-foil, allowing to maintain the entire sample undisturbed during quench without sacrificing much precious metal lab ware. The inspection of products quenched during the crystallization process in the concentric cylinder reveals evidence for heterogeneous crystal nucleation at the spindle and near the crucible wall, as well as crystal alignment in the flow field. At the end of the crystallization, defined when viscosity is constant and thermodynamic equilibrium, crystals are homogeneously distributed throughout the crucible, and mostly aligned along circular flow lines. In these experiments, we show that the crystallization kinetics were affected by the stirring conditions of the viscosity determinations. From the continuous record of the viscosity and sample analyses at different stages of the experiment, we constructed a TTT (Time-

Temperature-Transformation) diagram illustrating the crystallization ‘‘nose’’ (Figure 2; Chevrel et al., 2015). I further note that at a given crystal content and distribution, the high aspect ratio of the acicular crystals yields a shear-thinning rheology at crystal contents as low as 13 vol. %, and that the relative viscosity is higher than predicted from existing viscosity models. We concluded that such viscosity experiments hold the potential for delivering insights into the relative influences of the cooling path, undercooling, and deformation on crystallization kinetics and resultant crystal morphologies, as well as their impact on viscosity. Recently, such TTT diagrams build from viscosity measurements were used to illustrate the changes in lava flow behavior and morphology (Di Fiore et al., 2021, 2023).

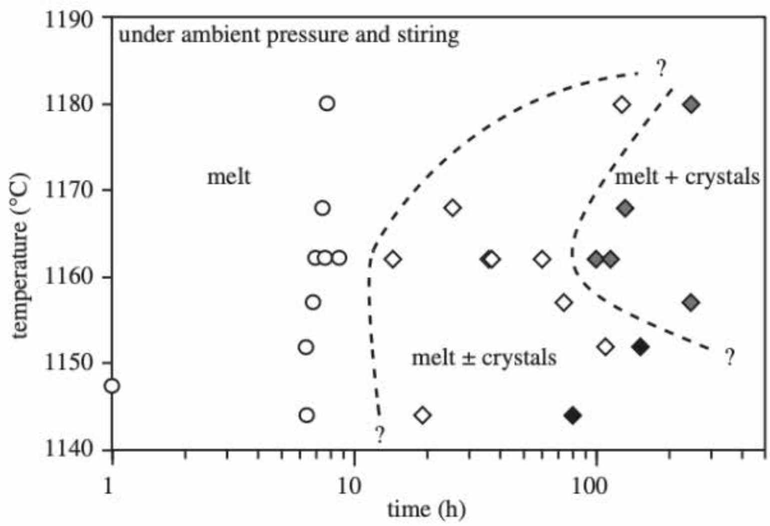

Figure 2: Time-Temperature-Transformation (TTT) diagram built from the kinetic variation of viscosity measured via concentric cylinder. Open circles correspond to pure melt phase (melt relaxed at the given temperature), open and black diamonds correspond to the presence of crystals in some amount but not in equilibrium (continuous increase of viscosity) and gray diamonds correspond to the presence of crystals in constant amount (at thermodynamic equilibrium when viscosity is constant. Figure from Chevrel et al. 2015

Conditions during magma ascent and flow of lava on planetary surfaces are dynamic inducing disequilibrium. Therefore, evaluating lava emplacement dynamics requires characterizing rheological properties under non-isothermal and non-equilibrium conditions. The importance of disequilibrium effects on crystal growth has been long recognized (Walker et al., 1976) and has inspired experimental studies investigating the effects of cooling rate, shear-rate and oxygen fugacity as well as their interdependence (Giordano et al., 2007; Kolzenburg et al., 2016, 2017, 2018a, 2018b, 2020; Vetere et al., 2020). These experimental data show a systematic sub-liquidus rheological evolution, where the apparent viscosity initially follows the pure liquid curve and once crystallization begins, the viscosity of the suspension increases, deviating from the liquid curve. During undercooling experiments, viscosity continues to rise until it reaches the rheological cut-off temperature (T_{cutoff}), beyond which the lava can no longer flow. Increasing the cooling rate delays crystallization, lowering both the initial departure temperature from the liquid curve and T_{cutoff}. This rheological cut-off corresponds to the stopping condition of a cooling-limited lava flow (see section 2.2 above) but systematic experimental determination of these conditions only started over the past few years. Future works should concentrate in implementing experimentally determined rheological cut-off values into models for lava transport.

The majority of the above-mentioned studies address the effect of crystals on suspension rheology and only few concentric cylinder experiments measured bubble bearing melts (Bagdassarov and Dingwell, 1993; Stein and Spera, 1992, 2002). This is largely due to the thermal and mechanical constraints of the method. Retaining bubbles in a melt at high temperatures for the duration of rheology experiments (several hours to days) requires relatively high melt viscosities (>10^5 Pa·s) to minimize bubble percolation (i.e., volatile exsolution and loss upwards through the melt). And thus, this requires a device design that permits high torques, not yet available for concentric cylinder viscometry. The effect of bubbles on lava has then be mostly measured from analogue material or parallel plates and torsion experiments (Bagdassarov and Dingwell, 1992; Lejeune et al., 1999; Llewellin et al., 2002; Pistone et al., 2012; Rust and Manga, 2002); and see review (Kolzenburg et al., 2022).

I am convinced that field rheometry can serve as a fundamental method for measuring the rheology of bubble-bearing low viscosity suspensions (Chevrel et al., 2018b; see chapter 5). However, to date no systematic study has been published and so is a gap to be filled.

2.4 Modelling thermo-rheological properties with PyFLOWGO

Harris and Rowland (2001) produced a 1-D model called FLOWGO in which the velocity of a lava control volume flowing down a channel is computed via the Jeffreys' equation modified for a Bingham fluid (Moore, 1987). In this approach velocity depends on the lava rheological properties computed according to the cooling and crystallization path of the control volume as estimated via a heat balance box model (Figure 3). The heat box model includes the main heat transfer mechanisms including heat loss via radiation to the surface, air (free or forced) convection at the surface, conduction through the ground and the levees, and heat gain through crystallization. Other heat transfers such as heat loss due to rain or heat gain by viscous heating can be added.

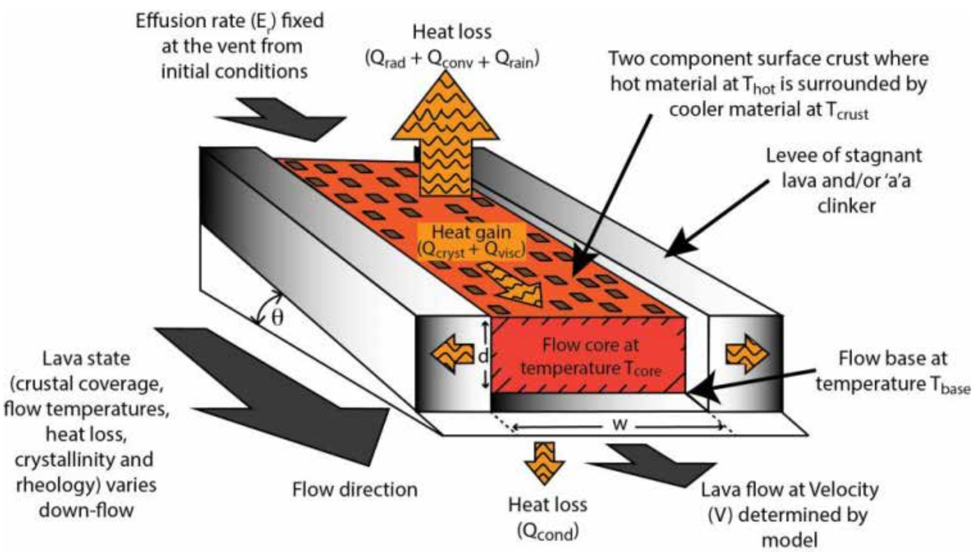

Figure 3: Schematic view of the thermo-rheological model FLOWGO illustrating the heat box model of the control volume of lava advancing through a channel (from Harris and Rowland, 2001).

FLOWGO is thus a framework within which thermo-rheological models can be integrated to test fits between output parameters and natural data. By selecting appropriate models to place within this framework it is possible to simulate the down flow heat budget, cooling, crystallinity, viscosity, yield strength, velocity, channel width and maximum length of lava flows (Harris and Rowland, 2001). FLOWGO is often cited, being recognized as the only thermo-rheological-based model. It has been largely used on Earth: Hawai'i (Harris et al., 2022b; Harris and Rowland, 2001, 2015; Mossoux et al., 2016; Riker et al., 2009; Robert et al., 2014; Rowland et al., 2005; Thompson and Ramsey, 2021), Mt Etna, Italy (Harris et al., 2007, 2011; Wright et al., 2008), La Reunion (Chevrel et al., 2018a, 2022; Harris et al., 2015, 2019a; Peltier et al., 2021; Rhéty et al., 2017), Mt Cameroon (Wantim et al., 2013), Virunga volcanoes, D.R. Congo (Mossoux et al., 2016), Galápagos (Rowland et al., 2003), and on other planets Mars (Flynn et al., 2022; Rowland et al., 2004), Mercury (Vetere et al., 2017), the Moon (Lev et al., 2021), and Venus (Flynn et al., 2023a).

Since the inception of this approach in 2001, the basic physical principles on which FLOWGO is based have not changed. In 2015, an alternative model to compute the melt phase viscosity that is based on lava composition, rather than on a given assumed viscosity as originally proposed has been incorporated in FLOWGO (Harris et al., 2015; Harris and Rowland, 2015). The authors also introduced a three phases rheological model to estimate the effect of crystals and bubbles on viscosity. To correctly simulate the evolution of thermo-rheological parameters down flow using FLOWGO the user thus is allowed a degree of flexibility so as to best-fit the natural cases, while changing thermo-rheological models and variables within plausible limits (Harris et al., 2007). Originally, (Harris and Rowland, 2001) wrote FLOWGO in the programming language IDL (Interactive Data Language) but due to license price and other computing issues this code was set aside. Other languages (MATLAB etc.) were also employed, and an Excel version was officially published in Harris et al. (2015). This was freely shared when needed to other scientists. Although Excel is a convenient tool and is easily and widely used by geologists, it has limited applications, a poor flexibility for model evolution, and when many equations and input parameters are stacked in sequence, it becomes too easy to key in a hidden (or very-hard to find) error. Besides, it cannot be easily incorporated into other software. Lava modeling capabilities and computer processing power has improved over the past decade, and Chevrel et al. (2018a) proposed a new version of FLOWGO in a modern and flexible language such as the object-oriented programming language Python v3. Over the last decade, Python has been widely adopted in scientific computing and has been described as "*the next wave in Earth Sciences Computing because it simply enables users to do more and better science*" (Lin, 2011). Furthermore, Python can be run on any operating system which guarantees portability, provides useful libraries, is open-source, and its object-oriented approach allows for great flexibility.

The new code, named PyFLOWGO, thus allows a degree of flexibility so as to best-fit the natural cases by changing thermo-rheological models and variables within plausible limits, while reducing errors. PyFLOWGO is constructed in a similar manner as FLOWGO to allow estimation of all parameters involved in the thermo-rheological evolution of a control lava volume flowing down a channel. The code has been designed to allow the user to switch between any existing models and add new models as they become available, without modifying the architecture of the code (Chevrel et al., 2018a). The software acts as a framework that provides interfaces to implement multiple models, and calls them in the correct sequence to build the lava flow differential equations and solve them using a numerical approach. The interfaces basically define the methods necessary for the solver to work and can be implemented with specific models depending on the desired simulation. The top level of the architecture is the *integrator* which solves the differential equations depending on heat fluxes and on input physical characteristics of the lava (described by the *material lava class*), terrain conditions and a given crystallization rate model (Figure 3). The integrator solves the differential equations and updates accordingly the current l*ava state* (temperature, crystallization, position, etc.) which is then used for the next integration step. This process is iterated until termination conditions are reached. The *material lava class* is composed of multiple models such as the *melt viscosity model*, the *relative viscosity model*, the *yield strength model* and the *vesicle fraction model*. Each model is defined by the same interface that governs inputs and outputs delivered to and from the model. As an example, to compute the melt viscosity, all the models available to the user share a common interface called base melt model viscosity (Figure 4). This interface makes sure that the model receives the *state of the lava* in order to deliver the viscosity value in the expected unit, that is Pa·s. In the same way, all heat fluxes that compose the differential equation share the same interface called *base flux* (Figure 4). In this case, the interface provides a unique method to compute and return the flux in W/m based on the state and channel dimensions as input parameters. With this architecture, new physical models or heat fluxes can then easily be added by implementing the given interface it depends from. Communication is carried out only between the interfaces, and models can be switched from one to another with no modification of the code structure, thus avoiding implementation errors and allowing a great flexibility (Chevrel et al., 2018a).

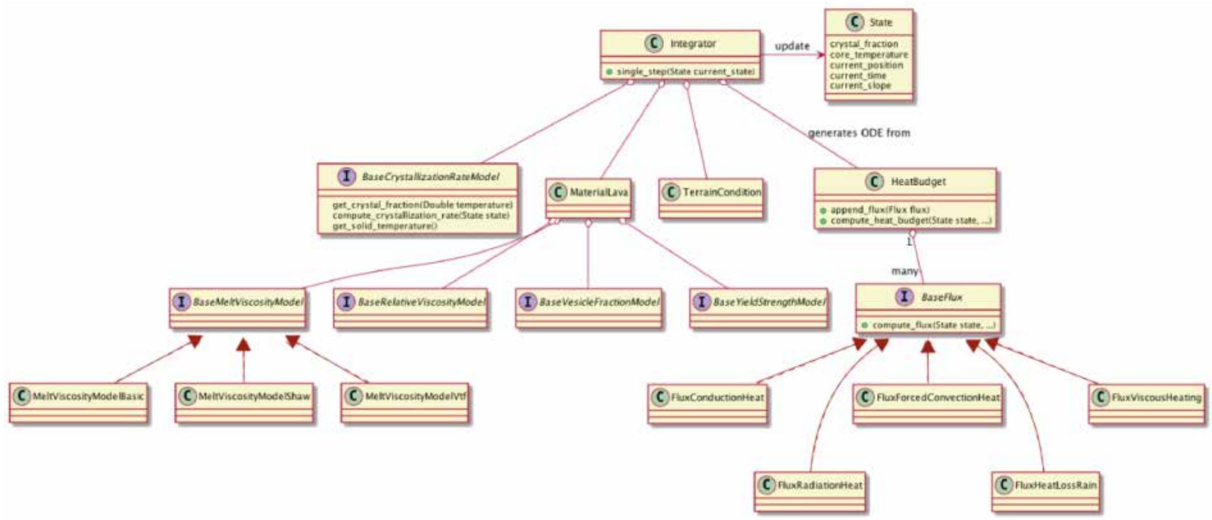

Figure 4: PyFLOWGO UML class diagram - top level. The interfaces (labeled "I" and with the prefix "base") provide parameters to main classes (labeled "C") that enable the Integrator to update the flow State at discrete positions along a slope. Example of 1) base melt viscosity model, with the various models to compute the melt viscosity, the user is free to choose which model to consider or implement a new one and 2) the base flux, where the user is free to choose which fluxes to consider or implement a new flux.

Since 2018, PyFLOWGO has been implemented by several authors. Some are unpublished works made by myself or by students through master projects, while others were the focus of published articles. Among them, (Ramsey et al., 2019) is the first study to implement two-component emissivity into thermo-rheological modeling of lava flows. For this, we focused on the 2012 Tolbachik lava flow (Russia), relying on data from orbital sensors and field observation to constrain the model input parameters and using PyFLOWGO, we show that the two-component emissivity adaption produced better fits to the final flow length, directly related to the crust cover percentage (Ramsey et al. 2019). We concluded that emissivity is an important factor for modelling accurately large, high effusion rate flows as well as for our understanding of older flows on Earth and other planets. Later (Thompson and Ramsey, 2021) proposed a new variable emissivity module and integrated it into PyFLOWGO. They simulated the 2018 fissure 8 lava flow emplacement at Kīlauea volcano (Hawaii) and showed that the new variable emissivity module produced a lower final heat flux (~ 75%) and a more accurate length fit (increased by ~ 7%; ~ 2 km) compared to using a constant emissivity. They concluded that their new module improved the accuracy of calculated thermo-rheological properties during flow propagation and cooling. Another recent example is (Flynn et al., 2023b) where we adapted PyFLOWGO to Venusian environmental and planetary conditions to assess how each change affects the dynamics of a channelized lava flow emplacement. For this, we implemented PyFLOWGO with a coupling atmospheric convective and radiative heat flux as given by Snyder (2002). The coupling of atmospheric convective and radiative heat flux causes significant change between a Venusian channelized flow and its terrestrial equivalent. This resulted in a significant reduction in overall heat flux and subsequently increased the flow length by ~75% (Figure 5; Flynn et al., 2023a).

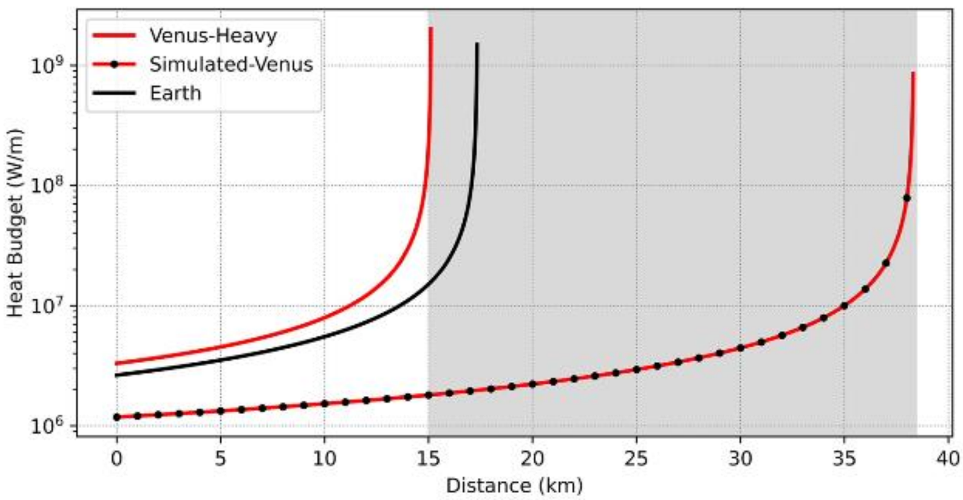

Figure 5 Variations in modeled channel length with distance from the vent for the total heat budget for the "Earth," "Venus-Heavy," and "Simulated-Venus" cases. The gray region indicates the stopping range between the "Venus-Heavy" case and the "Simulated-Venus" case. From Flynn et al. 2023

To conclude, PyFLOWGO will continue to be improved, implemented and expanded. As an open-source community code, it is available to everyone. Its architecture is designed to support an infinite number of models, allowing users to introduce and test new ideas. This flexibility makes it suitable for educational purposes as well as for testing various variables. PyFLOWGO's open nature encourages collaboration and innovation within the community, ensuring its ongoing development and relevance. It was shown that FLOWGO can be combined with a probabilistic model to provide volcanic hazard assessments (Harris et al., 2017; Wright et al., 2008), and it can be used to produce hazard maps (Harris et al., 2011; Rowland et al., 2005). In chapter 4, I will present how I combined PyFLOWGO with the probabilistic model DOWNFLOW (Favalli et al., 2005) to create an operational tool that is able to deliver a lava flow hazard map on demand. This tool is currently employed by the Observatoire Volcanologique du Piton de la Fournaise to produce near-real-time lava flow assessments during each eruption (Chevrel et al., 2022; Harris et al., 2019a).

3. Field rheology

3.1 Introduction

I decided to have this chapter as independent from the previous one mainly because field rheology is not yet a common method to constrains rheological evolution of lava flow. Nonetheless, in the future it might become one, as you will read later in this chapter and in the chapter 5. Also, “field rheology“ is presented as an independent chapter because this scientific thematic has taken a special place in my research activities over the last decade. It has never been the very heart of my activities but has always been present. Besides, this research activity comprises a lot of different skills including engineering, innovation, as well as scientific and technological development. As you will read, I started this topic with a first effort in 2016-2018 achieving the first field measurement since 20 years and publishing a review (Chevrel et al., 2018b, 2019b). Then it took me some years to develop a new instrument, and new collaborations that brought this topic to the foresight of the scientific community. A PhD thesis under a shared supervision has started in 2022 at UB and two recent studies were published (Chevrel et al., 2023a; Harris et al., 2024b). Additionally, with Stephan Kolzenburg from UB, we obtained a grant (that I co-Pi 50%) on the subject that promises futures great advances (NSF # 2420723 Tackling Multiphase Lava Rheology at its Origins).
This chapter is hence an overview of all this work. It is based on the review article:

Chevrel MO, Harris AJL, Pinkerton H. (2019) Measuring the viscosity of lava in the field: A review. *Earth-Science Reviews,* Vol. 196: 1028853. https://doi.org/10.1016/j.earscirev.2019.04.024

and other personal publications on the subject:

Harris M, O **Chevrel,** T Parsons, T Latchimy, WM Moreland, T Thordarson, A Holskuldsson, M Clerc-Payet, S Kolzenburg, In-situ viscosity mapping along Litli Hrútur 2023 lava flow, Iceland, *Submitted at Geology*, June 2024

Harris M, Kolzenburg S, I Sonder, **Chevrel O**. A new portable penetrometer for measuring the viscosity of active lava. *Review in Scientific Instrument. Vol. 95, 065103 (2024) https://doi.org/10.1063/5.0206776*

Chevrel MO, Latchimy T, Batier L, Delpoux R, Harris M, Kolzenburg S. A new portable field rotational rheometer for high-temperature melts. *Review in Scientific Instrument. Vol 94, 105116 (2023) https://doi.org/10.1063/5.0160247*

Chevrel MO, Harris A J L, James M R, Calabrò L, Gurioli L, Pinkerton H (2018) The viscosity of pāhoehoe lava: *In situ* syn-eruptive measurements from Kilauea, Hawaii. *Earth and Planetary Science Letters*, Vol. 493: 161-17 https://doi.org/10.1016/j.epsl.2018.04.028

Kolzenburg S, **Chevrel MO,** Dingwell D. (2022) Magma suspension rheology. *Reviews in Mineralogy and Geochemistry* 87 (1): 639–720. http://dx.doi.org/10.2138/rmg.2022.87.14

3.2 Review of past studies

As mentioned in chapter 2 numerous studies have estimated lava viscosity either from the dynamics of the active lava flow using the velocities of lava flowing within channels and at flow fronts (e.g. (Harris et al., 2004; James et al., 2007; Krauskopf, 1948; Nichols, 1939; Rose, 1973; Walker, 1973) or from solidified flows, using their final dimensions e.g. (Fink and Zimbelman, 1986; Hulme, 1974; Kilburn and Lopes, 1991; Moore, 1987). However, these methods are only able to provide spatially and temporally integrated values of the flow as a whole, averaging viscosity gradient across the flow (e.g. effect of cooler surface, base and sides) and viscosity variations with time. In chapter 2, I also show that laboratory viscometry has also been largely used and recognized to provides unique information and parameterization of silicate melt and lava suspensions viscosity, key for understanding the lava flow dynamics. However, it has proven difficult, if not impossible, to reproduce natural conditions in the laboratory, in particular in terms of redox state, crystal- and bubble-contents, sizes, shapes and their respective distributions (see Kolzenburg et al., 2022; Mader et al., 2013 for reviews on the topic). While our understanding of lava rheology has advanced significantly over the past decades, two core limitations have always remained in the laboratory: 1) the inability to maintain three-phase suspensions (bubbles escape on experimental timescale, limiting measurements to two-phase crystal-melt suspensions); 2) accurate reproduction of natural emplacement conditions (scale, textures, fO_2).

The only way to directly establish lava rheology in the field is to measure it by inserting a viscometer into the flowing molten rock. Such *in situ* measurements of lava viscosity can capture the rheological flow curve of the lava in its natural state, including all intrinsic and extrinsic dynamics such as crystal and bubble content, temperature, fO_2 etc. If this technique is applied down an active channel and is combined with simultaneous temperature measurement and sampling, it is possible to capture the evolution of lava rheology as a function of cooling, degassing and crystallization. With the detailed textural analyses of the samples, this method holds the power to provide a holistic assessment and parameterization of three-phase suspension rheology at natural conditions (Chevrel et al., 2018b). However, field rheology need dedicated instrumentation and due to the challenges associated with the development and deployment of this specialized instrumentation and the intrinsic hazards of work on active volcanoes, field rheology data remain very scarce (Chevrel et al., 2019b).

In over 60 years (1948 to 2023), I counted only twelve studies on field lava rheology measurements (Belousov and Belousova, 2018; Chevrel et al., 2018b; Einarsson, 1949, 1966; Gauthier, 1971, 1973; Keszthelyi, 1994; Norton and Pinkerton, 1997; Panov et al., 1988; Pinkerton et al., 1995a; Pinkerton and Norton, 1995; Shaw et al., 1968). Two types of instruments have been used and both are derived from methodologies applied in laboratory rheometry (here I am not mentioning the falling sphere method used only once by Shaw et al., 1968):

1) penetrometers, where a penetrating metal rod is pushed into or onto the lava by applying an axial force; this method is commonly used for relatively high viscosity lavas (>10^3 Pa·s).

2) rotational viscometers, analogous to the laboratory concentric cylinder method, where a measurement vane is inserted into the lava and then rotated; this method is commonly used for lower viscosity lavas (<10^4 Pa·s).

Low carbon stainless steel alloys have proven most suitable for construction of both types of field rheometers because they are highly resistant to both mechanical stress and thermal exposure, readily available, and reasonably cost-effective. Although the use of steel may potentially cause iron contamination of the lava, the degree of contamination is considered to be insignificant due to the much shorter timescale of the measurements with respect to the diffusion speed of iron in silicate melts.

Penetrometers

Penetrometers have been employed from the first published measurement realized in Iceland by (Einarsson, 1949) until recently in 2012 at Tolbachik (Belousov and Belousova, 2018). This type of instrument is advantageous because it is easy to build (the simplest versions consist of a rod equipped with a force gauge), light, easily transportable to the field, and permits quick measurements over a wide range of viscosity (10^3 – 10^7 Pa·s). The three kinds of penetrometers have been used to date.

1) The simple penetrometer consisting of a pole with a semi-spherical head that is inserted into lava, and viscosity is estimated from the force used to insert it at a given rate (Belousov and Belousova, 2018; Einarsson, 1949, 1966; Panov et al., 1988; Pinkerton and Sparks, 1978). This method relies on the assumption that the potential effect of lava sticking to the rod is negligible and thus calculates viscous drag based on Stokes' Law (i.e., falling sphere viscometry). Alternatively, viscosity can be obtained from calibration of the relationship between the penetrating force, the speed of penetration and fluid viscosity of a known liquid (Einarsson, 1949, 1966; Pinkerton and Sparks, 1978). The recent study of (Belousov and Belousova, 2018) measured the viscosity profile across small pāhoehoe lobes (Figure 6). To do so, they recorded, using video footage, the speed of penetration under a constant load from the surface to the base of the lobe. This enabled them to document the higher viscosity at the lobe surface, which quickly decreases directly below the skin, reaching a minimum in the interior of the lobe and then increases again toward the base.

2) The ballistic penetrometer was used only once and involves shooting a spear at high-velocity perpendicularly into the lava and measuring its penetration depth (Gauthier, 1971, 1973). The viscosity measurement relies entirely on previous laboratory calibration of the same spear geometry on liquids of different viscosities. The high initial penetration velocity prevents lava advance rates from influencing the measurement and limits cooling of the lava around the spear during penetration. The disadvantage is that the viscosity is an integrated value of the lava properties from the cooler surface of the flow to the hotter core. Thus, this type of penetrometer tends to provide a semi-quantitative measurement of the rheology of the cooler exterior of a flow, and little indication of the rheological characteristics of the hot interior. The measurements are therefore biased by the higher force required to penetrate the more viscous outer layer.

3) The encased spring-loaded, piston-driven device, deployed by Pinkerton and Sparks (1978) to overcome the issue of the cooler crust (Figure 6). The device was preheated

and inserted through the crust before the piston is activated, thereby overcoming the crust-forming limitations of the prior two device types. However, the use of a piston device still encounters issues as the spring does not fully expand all the way each time, which yields inconsistencies in the measurements (Pinkerton, 1978). Additionally, the casing for the piston introduces a large volume of metal within the lava, thus increasing the likelihood of large-scale quenching around the inserted device and thereby influencing the rheological properties in the localized sampling area. Furthermore, the force was dictated by the spring and thus the range of accessible viscosities is predetermined and low. Lastly, the maximum possible piston penetration is ~9 cm, thus limiting the measurement within that restricted depth (Pinkerton, 1978).

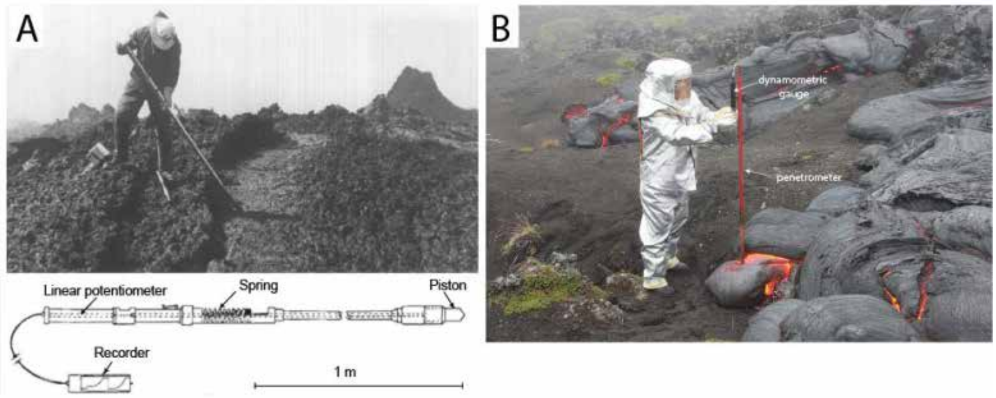

Figure 6: Field penetrometers: A) Photo and sketch of the dynamic penetrometer employed by (Pinkerton and Sparks 1978) on Mt Etna in 197X; B) Video still showing the simple penetrometer with dynamometric gauge in use on Tolbachik volcano (Russia) in 2012 (Belousov and Belousova 2018).

Rotational viscometers

Rotational viscometers, like in the laboratory, involve a rotating spindle immersed into the lava and viscosity is obtained from the wide-gap concentric cylinder theory, where the torque is converted into shear stress and the rotational velocity into strain-rate using Couette theory and the spindle geometry (Dingwell, 1986; Spera et al., 1988). Unlike most laboratory experiments where the immersed spindle is cylindrical, vane geometry (i.e. four orthogonal blades) is favorable for use in the field due to 1) lower weight, 2) ease of penetration, 3) reduced disturbance of lava during insertion, 4) reduced slippage between the edge of the vane and the lava (Shaw et al., 1968). The material between the vanes is trapped, forming a virtual cylinder of sample material whose equivalent diameter is used for calculation. Two types of rotational viscometers have been employed in the field.

1) A fixed rig installed on the frozen surface of a lava lake with a rotating spindle lowered into the molten core and controlled rotation rate by (Shaw et al., 1968). This viscometer was only used in the unique setting where a thick, frozen, stable surface is available for installation. The experimental setup consists of a fixed stand with a rotating shaft and vane attached to its lower end that is lowered vertically into the lava (Shaw et al., 1968).

A wire is spooled to the shaft, passed through a pulley mounted on a tripod and attached to a load. This permits to pull the wire and to rotate the shaft. By changing the load weight, different rotational torques can be applied to the vane. Flow curves are then obtained by measuring the resulting rotational speed.

2) A portable instrument with a speed (strain-rate) controlled spindle inserted into the lava (Chevrel et al., 2018b; Pinkerton, 1994; Pinkerton and Norton, 1995; Pinkerton and Sparks, 1978). The design of portable viscometers has evolved over the years from manually activated to motor-driven (Figure 7). The manually activated shear vane consisted of a stainless-steel vane attached to a torque wrench, which allowed yield stress to be measured by applying torque slowly until the shear vane began to rotate (Pinkerton and Sparks, 1978). This system was also used to measure viscosity over a range of strain rate by monitoring the rotation speeds via an optical tachometer (Pinkerton and Norton, 1995). The first motor-driven rotational viscometer consisted of a rotating steel vane attached to a drill hammer and was built by Prof. Harry Pinkerton in the late 80's (Figure 7). The torques measured at different rotation rates (monitored with optical tachometer) were recorded using a torque meter, mounted coaxially between the drive train and the shear-vane. This device had a relatively low torque limit and was employed on natrocarbonatite lavas at Oldoinyo Lengai (Pinkerton et al., 1995b). In the 90's Pinkerton build the second generation of motor-driven rotational viscometers that was modified for silicate lavas, having higher temperature and higher viscosity than natrocarbonatite lavas (Figure 7). The motor was connected to a reduction gearbox, equipped with a torque limiter (to not break the instrument) and a new, combined, torque-rotation rate sensor. This viscometer has the capacity of varying the rotational speed; and thus, to apply a large range of strain rates (0.2 - 3 s^{-1}) (Pinkerton, 1994; Pinkerton and Norton, 1995). The range of applicable strain rates is limited by the machines torque range (< 2 N) and vane geometry and results in a range of stresses of 100 - 1000 Pa. By changing the torque sensor to a higher torque range of the same instrument, in Chevrel et al. (2018b), we were able to reach higher stresses (up to 2500 Pa) and strain rates (up to 6 s^{-1}) but the lower strain-rate limit was consequently increased to 1 s^{-1} given the lava viscosity and the vane geometry (Figure 7).

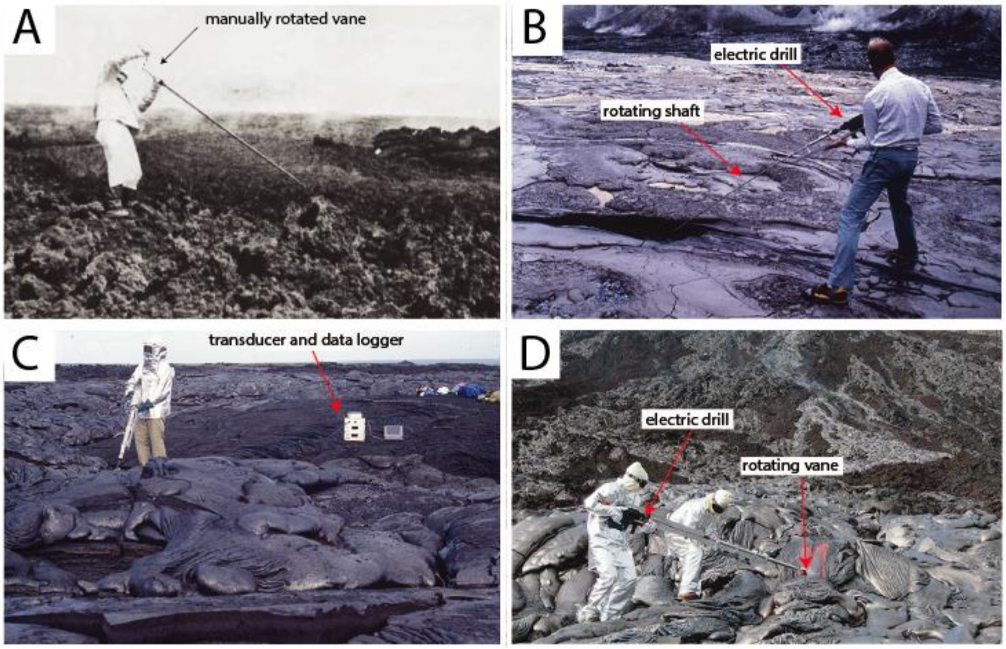

Figure 7: Photographs of all generations of portable rotational viscometers; A) manual rotational viscometer; photo from Chester et al. (2012); B) first motor-driven rotational viscometer employed on natrocarbonatite lavas employed by Pinkerton et al. (1995a); C C) first measurements of the motor-driven rotational viscometer on pāhoehoe lavas by Pinkerton (1994) D) latest measurements using the motor-driven rotational viscometer on pāhoehoe lavas by Chevrel et al. (2018). Figure modified from Chevrel et al. (2019a).

A summary of the viscometry results

Only a few research groups have attempted direct viscosity measurements in the field, on active lava flows. These field data are restricted to five geological setting (as of 2023) and all were performed on basaltic (or carbonatite), low viscosity lavas (< 10^6 Pa·s): Kilauea and Makaopuhi in Hawaii (Chevrel et al., 2018b; Keszthelyi, 1994; Pinkerton et al., 1995a; Shaw et al., 1968), Mt Etna in Italy (Gauthier, 1971, 1973; Pinkerton and Norton, 1995; Sparks and Pinkerton, 1978), Tolbachik and Klyuchevskoy volcanoes in Russia (Belousov and Belousova, 2018; Panov et al., 1988), Surtsey and Hekla in Iceland (Einarsson, 1949, 1966) and Oldoinyo Lengai in Tanzania (Norton and Pinkerton, 1997; Pinkerton et al., 1995b) (Figure 8). Lavas of higher viscosity have not been measured to date because of the extremely challenging conditions of approach. Block lava flows have outer blocky surface that makes it extremely difficult to access the molten interior. Further, the time required to measure high viscosities may expose the operator to risks from falling blocks. Lastly, there are currently no instruments available for measuring at sufficiently high force. Due to this mechanical limitation, the devices employed in the studies reviewed below were so far only able to access a narrow range of flow types (i.e. pahoehoe lobes and stable small lava flow fronts and channels). However, an important limitation even in low viscosity systems is the rapid cooling of the lava surface. The time of the measurement therefore needs to be shorter than crust formation.

In details and focusing only on silicic lavas, these past studies revealed that the viscosity of Hawaiian lavas, measured between 1146 °C and 1130 °C ranges from 1.5×10^3 Pa·s at low strain rates (even 10^4 Pa·s at very low strain rate) to 2.6×10^2 Pa·s at higher strain rates (Figure 8). The strain rate dependency of viscosity was measured by all authors with evidence of a stronger dependency al low strain rate. The similarity between the collected samples and the viscosities obtained at unit strain rate in 1994 (Pinkerton et al., 1995a) and 2016 (Chevrel et al., 2018b), using the same instrument but 22 years apart, is consistent with the fact that temperature, composition and texture (amount of bubbles and crystals) was similar in the two field studies. Although, higher viscosities reported (Shaw et al., 1968) at very low strain rates suggest pseudo-plastic behavior, direct yield strength measurements are lacking. According to laboratory experiments of Hawaiian lavas at subliquidus conditions (Ryerson et al., 1988; Sehlke et al., 2014), yield strength may appear with crystallization but should be < 200 Pa for the crystal content of the lavas measured in the field (< 25 vol. %). Unfortunately, this relatively low yield strength is, to date, difficult, if not impossible, to measure using current field instruments. Further measurements at low shear stresses and low strain rates are needed to determine whether yield strength can develop. Until then a power law model is considered to be the most appropriate model to characterize the behavior of Hawaiian lava at temperatures above 1130 °C (Figure 8).

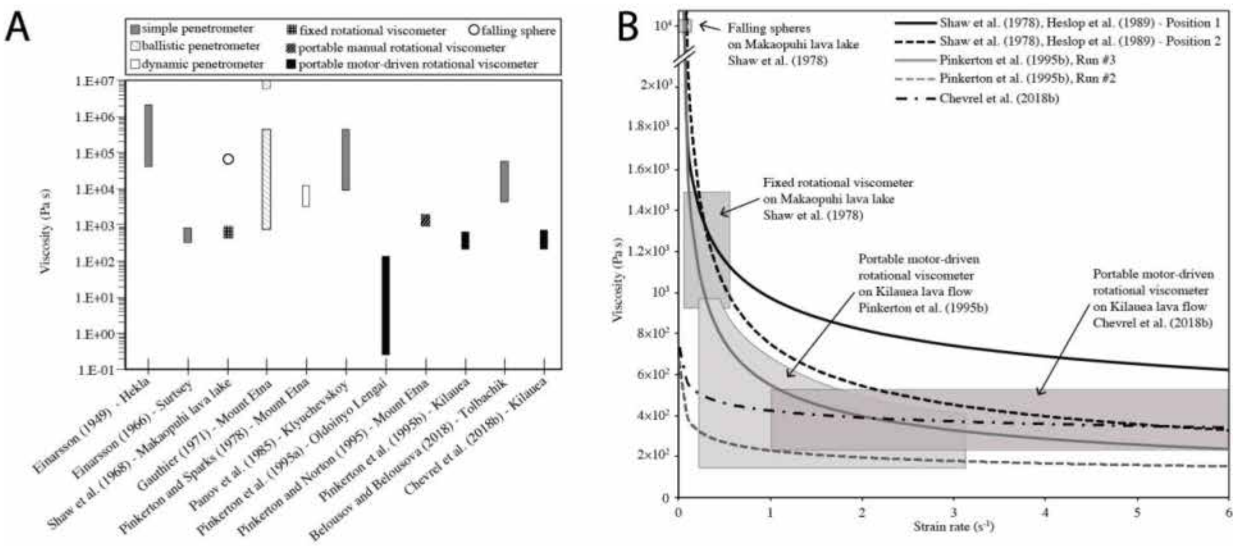

Figure 8: (A) Viscosity range measured during field campaigns. The boxes are grey- shaded according to the type of viscometers. (B) Variation of viscosity with strain rate for Hawaiian lavas as obtained from field viscometry. Boxes represent the measured range of viscosity and strain rate and curves are best fits as given by the different studies.

At Mount Etna, viscosities measured ranged from 10^3 to 10^7 Pa·s, with higher values influenced by cooler crust (Gauthier, 1973). Restricted range from 10^3 to 10^4 Pa·s and presence of yield strength depending on temperature, crystal content, and strain rates were measured by (Pinkerton and Norton, 1995; Pinkerton and Sparks, 1978). Despite well-constrained properties from laboratory measurements (Pinkerton and Norton, 1995; Vona et al., 2011), more field measurements are needed for accurate flow curves of natural lavas.

In Kamchatka, the pāhoehoe lobes measured at Tolbachik in 2012 by (Belousov and Belousova, 2018) have slightly lower viscosities than the ‘a‘ā flow measured 1983 Predskazannyi eruption at Klyuchevskoy volcano by (Panov et al., 1988): 0.5–5 × 10^4 Pa·s and 0.11–3.6 × 10^5 Pa·s, respectively. Note, however, (Belousov and Belousova, 2018) also revealed that during the Tolbachik 2012 eruption the lava traveling within the ‘a‘ā channel was less viscous that the early erupted pāhoehoe lava. This is consistent with some observations at Hawaii, where pāhoehoe flows formed at the rupture of 'a'ā front flow (Hon et al., 2003). Unfortunately, authors did not sample the lava at the moment of the measurements and hence limited interpretation is possible.

In Iceland, (Einarsson, 1949, 1966) measured viscosities at Surtsey as low as 5×10^2 Pa·s and up to 1.5×10^6 Pa·s at Hekla both using the same penetrometer. However, the value at Surtsey was challenging to measure, as the rod sank too quickly under its own weight. Einarsson noticed that this value was lower than expected and he attributed this underestimation to the "foamlike" texture of the lava. At that time, Einarsson, therefore sensed the potential effect of bubbles on lowering lava viscosity. Until 2023, there were no other field measurements to compare with (see section 3.3). This highlights the need for more measurement in order to build flow curves and determine the lava rheological natural behavior.

More details on these previous measurements are reported in the review written in collaboration with Prof. H. Pinkerton (Chevrel et al., 2019b).

Lessons learned

Field viscometry must always be performed in combination with temperature measurements and lava sampling. This is because the subsequent textural and petrographic analyses of these samples and data are key to understanding how crystal and bubble content affect rheology during lava emplacement. The molten lava must be sampled and quenched rapidly to conserve the texture at the location of measurement. In (Chevrel et al., 2018b) we show that volatile and bubble content must be considered if the viscosity of active lava is estimated via combined rheological and petrological models. We stated, that to reproduce the field viscosity measurement using available models, three-phase parameterization with 50 % bubbles and 15% crystals is needed. Good agreement between field measurement and model-based viscosity estimation was obtained when considering elongated crystals and deformed bubbles. Furthermore, we showed that field viscosity measurements could not be readily compared with sub-liquidus equilibrium laboratory measurements on natural lavas. Experiments performed in the laboratory tend to overestimate viscosity at a given temperature because of the shift of crystallization toward higher temperature due to lack of volatiles in the melt and ambient pressure and oxygen fugacity as well as the dynamic thermal and chemical disequilibrium present during lava flow on the surface. To approach parameterization of lava rheology, future studies must combine field rheology with disequilibrium laboratory experiments under constrained oxygen fugacity (see chapter 5).

Reducing errors and increasing precision of field measurements requires accurate sensors as well as meticulous setup and calibration, which is difficult to achieve in the field where conditions are more dynamic and less controlled than in the lab. Field measurements will always be constrained by the balance between measurement machinery and the lava's thermodynamics. To reduce the effects of crust formation during measurements the instruments need to be pre-heated and inserted into fresh, molten lava through emerging breaches in the crust, or at the breaking point of pāhoehoe lobes where little-to-no crust is present. Further, the measurement timescale needs to be shorter than the timescale of cooling and crust formation. Both issues may be minimized by employing a dynamic penetrometer (Pinkerton and Sparks, 1978), which allows triggering the sensor once the lavas isothermal core is reached. These are, however, limited to a specific range of stress – strain-rate conditions (Figure 9).

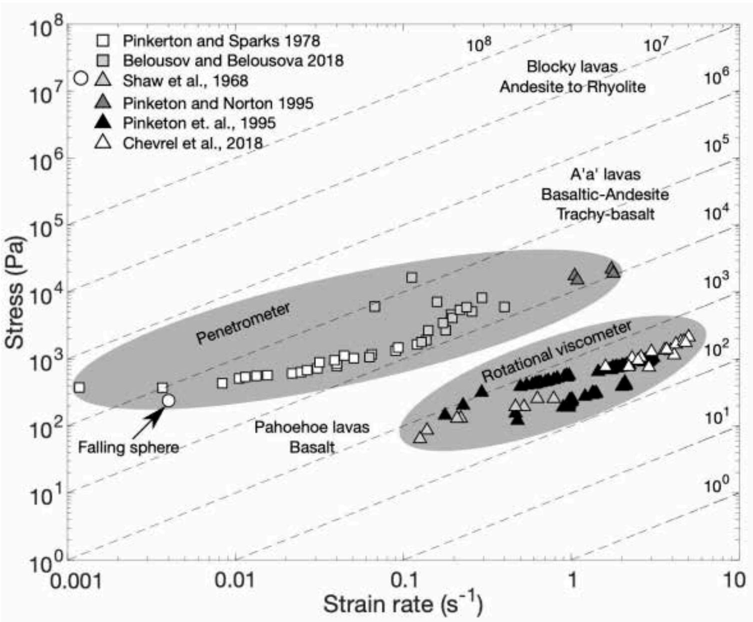

Figure 9: Regime plot of stress vs strain rate, mapping the measurement capacities of field rheometers. The plot shows the domains where lava viscosity has been measured with current hardware (shaded areas). It is important to state that neither method (rotational or penetration) is superior to the other but instead, they are to be regarded as complementary and employed depending on the viscosity regime that is encountered in the field. Dashed lines are iso-viscous conditions, squares and triangles represent data acquired with penetrometers and rotational viscometers, respectively. The highlighted circle represents the only data acquired by falling sphere method (figure from Kolzenburg, Chevrel, Dinwgell 2022)

Figure 9 further highlights the current gaps in achievable field measurement conditions. The development of the next generation of field rheometers thus needs to address several core issues. They need to be robust, light enough to be carried over rough ground and to remote locations, easily mounted and easy to handle (ideally by one person). Additionally, in order to capture the full rheological behavior of lava, field rheometers need to be able to apply a range of stress – strain-rate combinations. Current limitations include low strain rates (< 1 s^{-1}) and low shear stresses (< 200 Pa). The aforementioned issues place high demands on the dimensions of sensor capability and power. The technological advances since the early measurements (e.g. manual to electronically controlled motors and sensors) make possible the development of a new generation of viscometer for future measurements on active lavas (see section 3.3). Overall, the rotational viscometers have been used in low-viscosity ranges (~10^2-10^4 Pa·s) whereas the prior penetrometers are effective at higher viscosities (10^3-10^6 Pa·s). Combination of both methods is the most promising approach to recover a more complete rheological map and to describe the full flow curves for natural lavas. Finally, all previous studies presented only punctual data. In order to use field rheometry to its full potential for mapping of lava flow rheology, future field campaigns should perform various measurements along the flow, from the vent to the front. This likely also requires multiple field rheometers to be deployed synchronously in order to resolve the lava flows' rheology in 4D (see chapter 5).

3.3 Recent advances

A new rotational viscometer (Chevrel et al., 2023a)

Following the measurements performed in 2016 (Chevrel et al., 2018b), it became obvious that it was necessary to build a new, more versatile, lighter, and more modern rotational viscometer. Indeed, Pinkerton's prototype had a total length of the assembled apparatus was 2.7 m, with a weight of about 15 kg (without the analogue transducer). It required at least 2 people to carry it during measurement and one other to monitor the recording, which was not practical and prevented further investigation. A viscometer that is aimed to be used for measuring the viscosity of flowing lava on volcano flanks involves some specific requirements. The device needs to be portable to access remote places. It has to be autonomous in energy for a time long enough to ensure several measurements. It has to be handled and operated by one person so one can easily move around on uneven terrain to approach the active lava stream. This means that in terms of weight it has to be light enough to be held only by hands and to be directed and placed into the molten lava. The part that is to be immersed must be resistant to the high temperature of around 1200 °C (maximum temperature of currently erupting lava on Earth). The rest of the device does not need to be as resistant, as it can be easily protected by a thermic shield that would cut the radiative heat. However, the device needs to be durable to undergo transport across rough terrains. Additionally, the device must have a security system in place that can easily free the immersed sensor from the rest of the instrument in the event that cooling lava entraps it. Finally, in the case of rotational viscometer, the instrument must be able to work over a large range of rotational speeds and torques to explore the non-Newtonian behavior of lava.

In (Chevrel et al., 2023a), we presented a new rotational viscometer that was built over few years (2017-2021) in collaboration with engineers from various French institutes. This prototype is 11 kg (8 kg in hands and 3 kg in the back) and is held via two handles, one placed at the front to direct the propeller and the other at the back (Figure 10). Batteries and electronics are linked via cables and placed in a small backpack. It is very easy to deploy and can be handled and operated by a single person. A thermal shield can be placed in front of the forward hand to stop radiative heat if necessary. The entire system is controlled by a single board computer Raspberry PI3 that communicates with the various components. The main components include a motor with its controller, a torque and a temperature sensor, power supplied and acquisition system. The orders are sent through the inputs/outputs of the raspberry so that the software can process the information and carry out the corresponding actions. The centralized-on board computer simultaneously records the three fundamental parameters to determine the viscosity of the lava that are the rotation speed, the torque, and the temperature. The stress, strain-rate, and ultimately the viscosity are calculated afterward. To explore a large viscosity range, a set of shear vanes with various sizes (equivalent diameter and length) have been also prepared. One of the main advantages of this instrument, thanks in part to improved wireless transmission and an acquisition speed of 100 ms, are synchronized measurements of temperature, torque, and rotational velocity. This was not the case in the previous version. This field rotational viscometer has been designed for volcanology, yet, it is adapted to measuring large volumes of high temperature material (<1350°C) and hence could be operated in different contexts such as industrial processes, including in the glass industry, as well as viscosity measurements of molten rock.

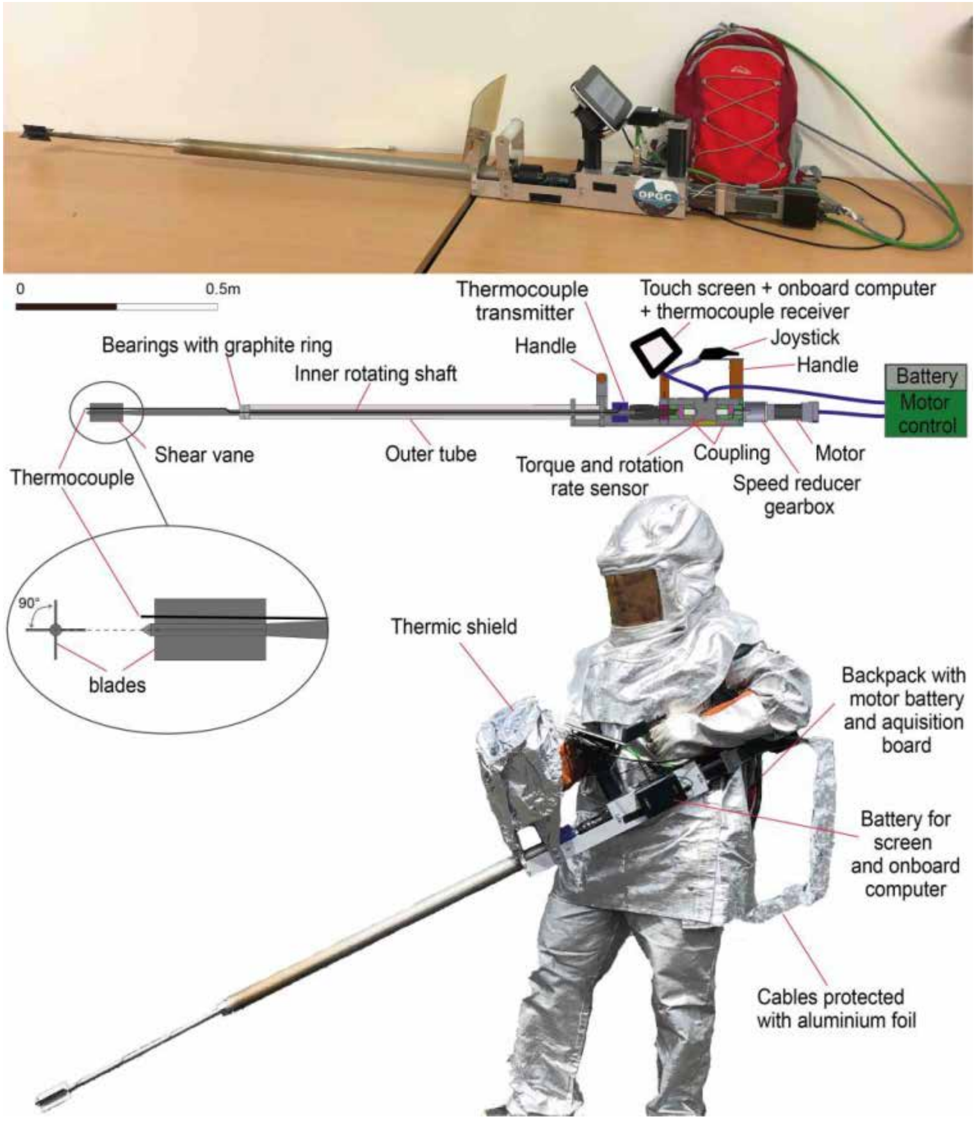

Figure 10: Overview of the rotational viscometer. Up: photo of the device with the backpack carrying the battery and motor microchip board. Middle: sketch highlighting the main elements (see also exploded view in supplementary information 2). Bottom: operator wearing a fire suit and holding the instrument in the field

The viscometer was calibrated using calibrated standard oils (N 190000 and N15000) to the limited viscosity range from 10 to 650 Pa·s with accuracy of 10 Pa·s. Tests at lower viscosity (e.g. using the calibration standard N15000 at 48°C) showed that the instrument retrieved a viscosity that falls within 10 Pa·s but with a deviation from the calibrated viscosity of up to 40 % (Chevrel et al., 2023a). This large deviation is mainly due to the torque sensor accuracy (> 5 mN.m) and the ambient noise due to mechanical assembly that limits accurate measurements below 10 Pa·s. Given the current torque sensor range (up to 2500mN.m), the speed range (0.5 to 100 RPM) and the adaptable vane geometry, the maximum viscosity that could potentially be measured is as high as 7.10^4 Pa·s.

Recently, new calibration was performed and confirmed that viscosity as high as 4300 Pa can be measured. The new rotation viscometer was deployed during the 2023 Litli-Hrútur eruption in Iceland and successfully measured viscosity of pahoehoe lobe of the order of 3.7 10^2 Pa·s (Harris et al., 2024a; see chapter 5).

A new penetrometer (Harris et al., 2024b)

Penetrometers, although more simple than rotational viscometer are easier to deploy an only required to record the force and time needed to push a defined geometric shape into the lava. Within his PhD project, Martin Harris build a new penetrometer (Harris et al., 2024b). This device consists of a stainless-steel pipe with an engineered rounded tip capable of withstanding high temperatures for moderate timescales (*i.e.*, minutes) fixed to a load cell that records axial force when pushed into a material, while simultaneously measuring the penetration depth via a free-moving tube that is pushed backward along the penetration tube (Figure 11). The device uses a commercial hand-held size force gauge that is interchangeable and must be selected based on the expected viscosity range (*e.g.*, the 1000 N gauge for ‘a‘ā lava and the 100 N gauge for pāhoehoe lobes). One of the novelties of this new penetrometer is that the displacement rate of penetration is measured by a laser time-of-flight distance sensor. This sensor is fixed to the handle of the force gauge and pointed at a target at the end of a separate smaller tube attached via linear bearings to the stainless tube inserted into the lava. As one tube is pushed into the lava, the adjacent tube is pushed back up and the distance sensor registers that simultaneous displacement. The force gauge and the laser are wired to a Raspberry Pi (or equivalent single board) computer that executes a Python code written for digital data acquisition. The entire suite of electronic sensors is powered with a portable power bank fixed to the penetrometer handlebar. The device is portable by one person (1.5 meters long, 5.5 kg in weight), and uses a single-board computer for data acquisition (Figure 11). The penetrometer has undergone testing in three analog materials. All three materials were measured with a well-calibrated laboratory Anton Paar concentric cylinder rheometer equipped with a water bath casing that allows for temperature-controlled analog measurements between 2 and 70 °C. Using the known temperature-dependent viscosities for each of the three analog materials, (Harris et al., 2024b) built a calibration procedure using the ratio of force to penetration speed (N/(m/s)). This procedure takes the instrumental outputs (*e.g.*, force, displacement, and time) and calculates the viscosity based on the known viscosity of analog materials at the same force/speed ratio. This calibration moves away from Stoke’s Law (geometrical method) and therefore more precise viscosity is obtained with the calibration based on instrumental sensitivity of the force gauge and distance sensor. The penetrometer has an operational range from 2.5×10^2 to 2.1×10^5 Pa·s and was calibrated for viscosities ranging from 5.0×10^2 to 1.6×10^5 Pa·s (Harris et al., 2024b).

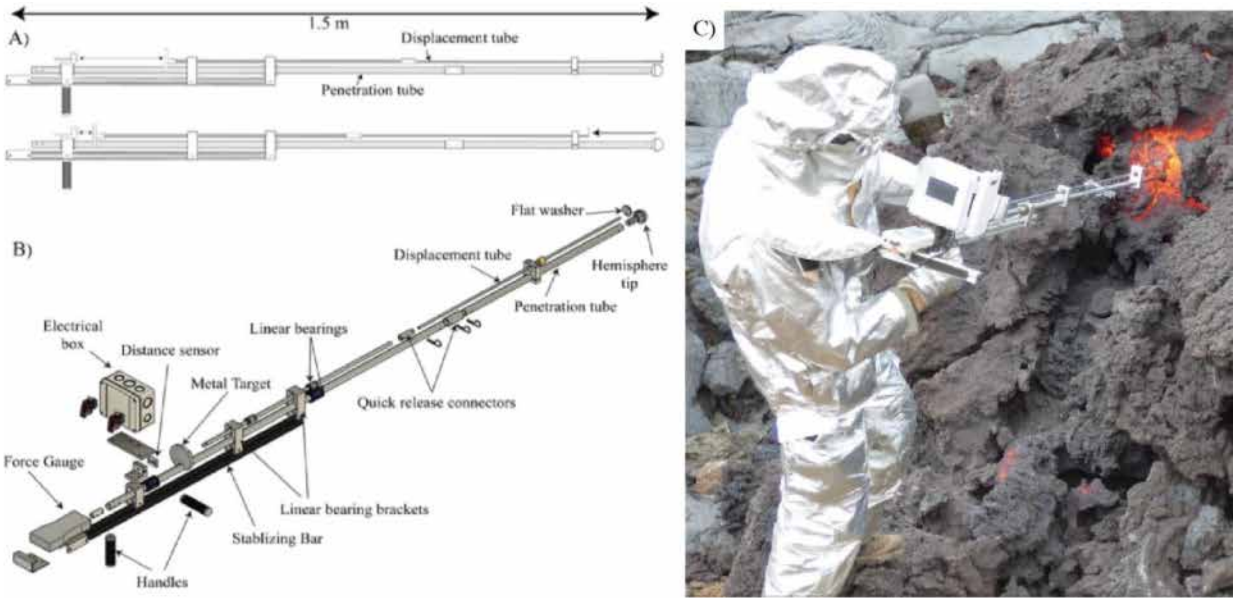

Figure 11 (A) Simple profile views that highlight the two main components of the penetrometer, 1) the penetration tube and 2) the displacement tube, with the relative motion of the displacement tube shown. B) An exploded view of the major components of the penetrometer. Drawings of all individual custom machined parts with detailed specifications can be found within (C) Field usage of the penetrometer, the operator is 1.88 meters tall for scale. From M. Harris et al. 2024a.

An initial version of the penetrometer was equipped with a thermocouple (K-type) fed through the stainless-steel tube and extend through the tip of the rounded end, with connections to the Raspberry Pi. However, during testing, it has become clear that the duration of a penetrometer measurement (~1-10 seconds) is not enough time for a thermocouple to homogenize with the material. Thus, moving forward, a separate thermal probe will be developed for simultaneous temperature readings in the material (or area) that the penetrometer is used.

This penetrometer was deployed during the 2023 Litli-Hrútur eruption in Iceland where in-situ viscosity measurement of a ‘a‘ā flow front revealed 1.2×10^4 to 3.4×10^4 Pa·s at temperatures from 1148-1152 ° C (Harris et al., 2024b). The penetrometer was used in tandem with the new rotational viscometer (Chevrel et al., 2023a) on the same lava flow, providing for the first time a rheological transect measured *in situ* along a lava flow (Harris et al., 2024b; see chapter 5).

4. Response to volcanic effusive eruptions

4.1 Introduction

Observatories remain the core of volcanic activity monitoring. The link between academic researchers in universities and observatories must be strong to enhance our understanding of volcanic phenomena. Academics provide answers to fundamental issues that observatories can effectively use to respond to societal and environmental emergencies. Within the framework of the ANR LAVA project (PI Andrew Harris; 2016-2021), I participated in mounting a protocol that allows for a rapid response in modeling the advance of lava flows at Piton de la Fournaise. This protocol combines several data acquisition methods (thermal and deformation satellite images and field observations) and numerical modeling of the inundation zone and the thermo-rheological properties of lava. This protocol has been highly valued by the Observatoire Volcanlogique du Piton de la Fournaise (OVPF) because it provides a wealth of organized information useful for monitoring the ongoing eruption without adding extra workload to observatory staff.

In this chapter, I will present the state of the art before I started to work on the subject and where I have brought this investigation, to the point that the delivered product is now indispensable and valuable for responding to effusive eruption at Piton de la Fournaise.

Most of the following comes from my most recent article on the subject:

Chevrel MO, Harris A, Peltier A, Villeneuve N, Coppola D, Gouhier M, Drenne S. **(2022)** Volcanic crisis management supported by near real time lava flow hazard assessment at Piton de la Fournaise, *Volcanica* 5(2), pp. 313–334. https://doi.org/10.30909/vol.05.02.313334

and other relevant publications on the subject:

Chevrel MO, Villeneuve N, Grandin R, Froger JL, Coppola D, Massimetti F, Campus A, Hrysiewicz A, Peltier A, (2023) Report on the lava flow daily monitoring of the 19 September – 05 October 2022 eruption at Piton de la Fournaise. *Volcanica 6(2): 391–404. https://doi.org/10.30909/vol.06.02.391404*

Peltier A, **Chevrel MO**, Villeneuve N, Harris A (2022) Reappraisal of gap analysis for effusive crises at Piton de la Fournaise. *Journal of Applied Volcanology* 11, 2. https://doi.org/10.1186/s13617-021-00111-w

Chevrel MO, Favalli M, Villeneuve N, Harris A, Fornaciai A, Richter N. Derrien A, Boissier P, Di Muro A, Peltier A (2021) Lava flow hazard map of Piton de la Fournaise volcano. *Natural Hazards in Earth System Sciences,* 21, 1–22, 2021 https://doi.org/10.5194/nhess-21-2355-2021

Harris AJL, **Chevrel MO**, Coppola D, Ramsey MS, Hrysiewicz A, Thivet S, Villeneuve, N Favalli M., Peltier A., Kowalski P, Di Muro A, Froger J.-L, Gurioli L. (2019) Validation of an Integrated Satellite-data-driven Response to an Effusive Crisis: The April–May 2018 Eruption of Piton de La Fournaise. *Annals of Geophysics,* Vol.62,2, VO30. https://doi.org/10.4401/ag-7972

Peltier A, Ferrazzini V Di Muro A., Kowalski P, Villeneuve N, Richter N, **Chevrel MO**, Froger J-L, and Hrysiewicz A, Gouhier M, Coppola D, Retailleau L, Beauducel F, Boissier P,

Brunet C, Catherine P, Fontaine F, Lauret F, Garavaglia L, Lebreton J, Canjamale K, Desfete N, Griot C, Harris A, Arellano S, Liuzzo M, Gurrieri S, Ramsey M (2020) Volcano crisis management during COVID-19 lockdown at Piton de la Fournaise (La Réunion). *Seismological Research Letters*, Vol. 92 (1): 38–52. https://doi.org/10.1785/0220200212

4.2 Background: model-based lava flow hazard responses upon eruptions as of 2018

By far the greatest problem facing a community in the path of a lava flow is the destruction of structures by burning, flooding, and/or burial (Blong, 1984). Any unmovable structure, and its contents, will be destroyed. Destruction of all of these essential elements of a community have lasting repercussions on social fabric, mental health, and local economies (Harris, 2015). For example, after the 2002 Nyiragongo eruption, about 120,000 people were left homeless, and 15 % of the city and a third of the airport runway were completely buried by lava (Tedesco et al., 2007). Following the 2021 Nyiragongo eruption, 3600 houses were destroyed and more than 400,000 people were affected either by water supply difficulties or displacement (UNOCHA report of 5 June, 2021). In June 2018, the effusive eruption of Kīlauea in the Puna region of HawaiʻI destroyed more than 700 structures and caused economic losses estimated at more than 800 million US dollars (Meredith et al., 2022). More recently, the eruption of La Palma (Canaries), which began in September 2021 and ended in January 2022, "swept away over 2800 buildings, leaving over 350 hectares of productive farmland (banana plantations, avocado plantations, vineyards) covered by lava, and buried over 70 km of vital roads, including the main North South connection" (Carracedo et al., 2022).

To better assess lava flow hazard, run real-time appraisals of potential lava flow inundation areas and, thus, respond to an effusive crisis in an effective manner. For this scientists and civil protection agents must work together closely to test and validate operational tools before an event occurs.

Example of lava flow hazard assessment responses at Hawaii and Etna

Since 2007, the Hawaiian Volcano Observatory (HVO) has been evaluating the short-term threat to communities posed by lava flows through frequent airborne and satellite map- ping of lava flow fields and assessing steepest descent paths (Kauahikaua, 2007). These techniques have regularly been used during effusive activity at Kīlauea to build hazard maps including likely lava flow paths, and routes for communication with emergency managers and the public have been well- developed (Brantley et al., 2019; Kauahikaua et al., 2017). In 2014, during the lava flow crisis in the vicinity of the town of Pāhoa, scientists from the HVO measured lava flow advance rates and provided a range of potential arrival times that were used to build emergency plans (Poland et al., 2016). During the 2018 eruption in the Puna district, HVO rapidly produced preliminary lava flow path forecasts using the DOWNFLOW model of (Favalli et al., 2005), a commonly used stochastic model that computes the line of steepest descent (LoSD) and probable lava flow inundation area. Throughout the eruption, lava flow path simulations were run on regularly updated topography, and from active flow fronts, new fissures, and channel overflow locations, to yield maps of likely future flow directions and inundation areas (Neal et al., 2019). These maps facilitated communication of up-to-date hazard information to emergency managers and provided situation awareness for eruption response field crews. Since 2022, HVO also utilizes a new physics-based lava flow model (lava2d) developed by (Hyman et al., 2022).

On Mount Etna (Italy), the Istituto Nazionale di Geofisica e Vulcanologia (INGV) at the Etna Observatory (EO) models and tracks lava flow emplacement using a combination of satellite-derived discharge rate estimates and numerical models (Vicari et al., 2011). INGV-EO employs the HOTSAT satellite monitoring system to convert infrared data from both MODIS and SEVIRI sensors into TADR that is then input in the numerical model GPUFLOW. GPUFLOW, an evolution of MAGFLOW, is based on a cellular automaton, physics-based model which can reproduce, spatially and temporally, the likely lava flow propagation (Bilotta et al., 2014; Ganci et al., 2012; Del Negro et al., 2013). The combination of HOTSAT and GPUFLOW is integrated into a web-GIS system, LAV@HAZARD, that produces real-time hazard assessment by providing time of propagation of lava flow fronts, maximum runout distance, and area of inundation (Vicari et al., 2011). This operational tool was described and validated using a retrospective analysis of Etna's 2008–2009 flank eruption by (Ganci et al., 2012). It has since been operational by providing automatic reports including the radiant heat flux, TADRs, and a short-term hazard map. These products are communicated to INGV and local civil protection through periodic bulletins. Although the monitoring strategy implemented in LAV@HAZARD was designed for Etna, it has been adapted and employed during volcanic crises at other sites, such as Fogo at Cabo Verde (Cappello et al., 2015) and Nabro in Eritrea (Ganci et al., 2020).

Short-term lava flow hazard assessment responses at Piton de la Fournaise before 2018

Forecasting lava flow paths and runout using near-real time modelling began at Piton de la Fournaise with the eruption of June 2014 (Harris et al., 2017), the first eruption after 4 years of quiescence. Between 2014 and 2018, the chain of tasks involved multinational partners and each step was operated by a different institute in a different country and was collated on a centralized reporting page (Harris et al., 2019b). Five sequential actions were executed:

Action 1) At the start of an eruption, OVPF communicated the vent or fissure coordinates to INGV in Pisa (Italy) where the lava flow inundation area and the line of steepest descent (LoSD) were estimated using DOWNFLOW (Favalli et al., 2005) on the most recent available Digital Elevation Model (DEM).

Action 2) The DOWNFLOW-derived LoSD was sent to the Laboratoire Magmas et Volcans (LMV, UCA, France) where the FLOWGO model (Harris and Rowland, 2001) was run to estimate the maximum the lava flow runout distance from the vent for a given discharge rate. FLOWGO having been initialized and validated for channel-fed flow at Piton de la Fournaise (Harris et al., 2015). This DOWNFLOW + FLOWGO association was actually first presented by (Wright et al., 2008) on Mt Etna but was never used as an operational tool.

Action 3) In parallel, the time average discharge rate (TADR) rate was derived from satellite-based thermal infrared images with the MIROVA platform at the Universita di Torino in Italy (Coppola et al., 2016) and communicated to LMV for FLOWGO modelling. The cumulative volume was also be calculated by integrating TADR values over the period of time in between two satellite images.

Action 4) The resulting lava flow area coverage obtained via Action 1, and the lava flow runout maximum distance obtained for the given discharge rate (Actions 2 and 3) was represented as a graph of lava velocity versus distance from the vent to the flow front and communicated to OVPF via email exchange (Harris et al., 2017).

Action 5) In parallel the evolution of the lava flow field (vent location, channel dimension, covered area, flow outline) was obtained either from (i) airborne photogrammetry acquired by OVPF, (ii) interferograms and coherence maps derived from InSAR via the OI2 platform developed at the OPGC, UCA and (iii) satellite infrared and visible imagery, as acquired by the ASTER Urgent Request Protocol (Ramsey et al., 2016). These products were also used to close the loop by up-dating and cross-checking the performance of DOWNFLOW and FLOWGO (Harris et al., 2019b).

This protocol was triggered in real time at the start of any given eruption through release of an email from the director of OVPF with vent coordinates and was designed so that it could be repeated and updated as the eruption conditions evolved (e.g. new vents opening, extension of tubes, change in TADR). Between 2014 and 2018, the products shared with OVPF comprised a map with the DOWNFLOW results (showing the area covered by the probable lava flow paths) and the results of FLOWGO (presented as a graph showing the lava velocity versus distance from the vent to the flow front for the range of MIROVA-given TADR) (Harris et al., 2017). The OVPF director could then inform the local civil protection (État-Major de Zone et de Protection Civile de l'Océan Indien; EMZPCOI) by phone call but no document was exchanged. Through those years, the response protocol was reviewed and updated throughout each eruption. In 2018, I took over development of this protocol until it became fully operational (Harris et al., 2019b). Since then, I have run the modelling-base response protocol for every eruption (16 to date) and have implemented an operational tool that can be run as a desktop module at OVPF, as presented and discussed herein.

4.3 Near real-time lava flow simulation since 2018 at Piton de La Fournaise

Improving the protocol

Since 2018, my objective has been to centralize the protocol, to improve its efficiency and implement it at OVPF. First, the execution of DOWNFLOW and FLOWGO was combined into a single code triggering both models, renamed DOWNFLOWGO (Harris et al., 2019b; Peltier et al., 2021), thereby merging Actions 1 and 2. Action 3 was also streamlined because the original process required a new simulation to generate the flow runout projection with each change in the TADR, which was time-consuming and inefficient. Simulations are now run for a range of likely effusion rates (typically between 5 and 50 m^3/s at increments of 5 m^3/s). This improvement was possible thanks to the development of PyFLOWGO (see section 2.4 and Chevrel et al. 2018). In essence, once the vent coordinates are entered in the code line, a raster of the most probable area to be covered and the line of steepest descent (LoSD) are computed with DOWNFLOW using the new calibration obtained in Chevrel et al. (2021b; see also section 4.4). Then, in sequence, PyFLOWGO is ran x times for x effusion rates to provide runout locations (coordinates and elevation) down the LoSD. This is done at 10 m steps down the LoSD, with this step size having been defined as the ideal iteration step to ensure numerical convergence to give the runout points (Chevrel et al. 2018). The complete computing time is then now less than two minutes for the Enclos area (130 × 10^6 m^2) on a 5 m resolution DEM.

Subsequently, this protocol has been implemented as a standalone software package that delivers the modelling outputs ready to be imported into any Geographic Information System (GIS) allowing production of a short-term hazard maps within the first minutes to hours after the start of an eruption. A first example of such map is shown in Peltier et al. (2021). Maps are a common way of communicating comprehensive hazard information allowing the spatial extent of the hazard, as well as information as to key infrastructure and land type at risk, to be quickly assessed by emergency managers (Pareschi et al., 2000; Thompson et al., 2015). For efficiency, a GIS template was prepared with all the needed layers, including locations of the OVPF monitoring network and all features required by civil protection (see below *Improving the delivered hazard map*). The delivered short-term hazard, hence contains the following DOWNFLOWGO outputs (Chevrel et al., 2022):

1) The line of steepest descent from the main vent location (in case of multiple vents along a fissure, several simulations may be run);

2) The probable area of lava flow coverage (i.e. the probability that a pixel will be hit by lava);

3) The runout distances (i.e. where the lava should stop) for the pre-defined effusion rates along the LoSD.

The map is then used as a guide to assess the probable runout given current TADR obtained from the satellite detection systems such as MIROVA (Coppola et al., 2016) and HOTVOLC, a platform of volcanic hotspot detection systems from the *Observatoire de physique du globe de Clermont-Ferrand* (OPGC) at UCA (Gouhier et al., 2016). Actions 3 and 5 are still implemented through email exchange and/or consultation of these dedicated websites. The update of TADR allows the look-up-based assessment to be revised, and provision of lava flow outline, field observations, visible or infrared satellite images and InSAR coherence maps allow on-the-fly validation of the hazard map and possible update.

Once the map has been produced, it is first reviewed and approved by the OVPF director, who is then responsible for transmitting the map to the local civil protection. By common agreement, the maps are not open to the general public during an eruption. This is to avoid misinterpretation from untrained operators and the spread of false information. However, following any given eruption, the maps are published in the OVPF monthly bulletin (Chevrel et al., 2022).

Over the last year (2023), I further improved the protocol. The DOWNFLOWGO has been compiled in a python package which includes a Graphical User Interface and produce the map without the use of GIS. This all-in-one package is openly available: https://github.com/oryalava/DOWNFLOWGO. The package has been recently installed on the OVPF operating system. As of today, any staff member from OVPF can run the code by simply entering the vent coordinate and updated DEM, and thereby obtain the resulting map (Figure 12).

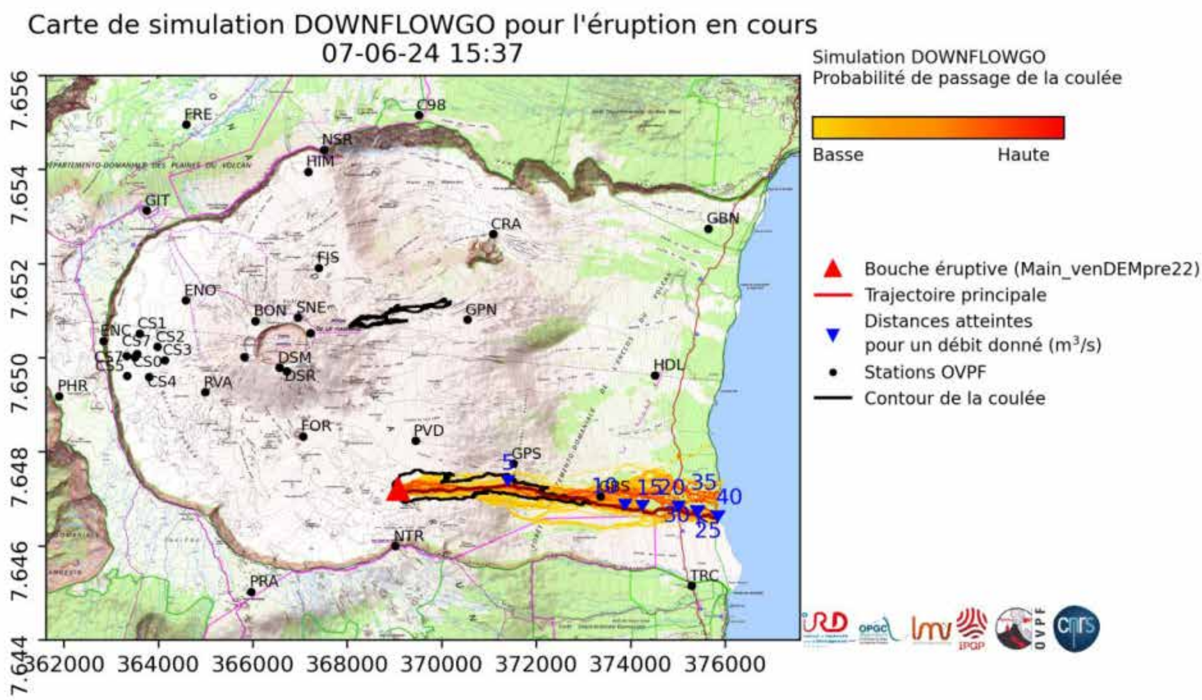

Figure 12: Example of a map produced with the all-included DOWNFLOWGO code for the July 2023 eruption showing the lava flow inundation area (probability obtained via DOWNFLOW increases from yellow to red; Δh = 2 and N = 10,000) and runout distances (blue arrows) obtain via FLOWGO for given discharge rate (numbers are in m³/s) along the LoSD (red line). The background is the BD TOPO IGN® from IGN. The map was produced for the purpose of this dissertation in June 2024.

Improving the delivered hazard map through exchange with civil protection

Between 2014 and 2018, the OVPF director informed the local civil protection (EMZPCOI) of the lava flow location and probable path and runouts, but no physical product was shared. The primary format of communication was a telephone exchange between the OVPF and EMZPCOI, supported by information from visual observations made during flight surveys and/or field crews. Because the communication lacked product support, officers in charge of civil protection actions took much caution by, for example, over-estimating the zone at risk in their assessments areas to be closed. The belt road to the east of the Enclos would also be closed when lava flows arrived in the Grandes Pentes area at a distance of 3 km from the road. The other difficulty with this communication format was, without a hazard map, assessment of the situation consisted of simply pointing to the potentially affected area on a topographic map without precision of the probability distribution of lava flow paths (Chevrel et al., 2022)

A first short-term hazard map was built for the April 2018 eruption (Figure 13A; Harris et al., 2019b) but the first time a short-term hazard map was shared with EMPZCOI was for the August 2019 eruption. Since then, maps have been generated and shared for all eruptions, with maps being sent to EMZPCOI within the first minutes to a few hours of eruption onset. Some examples are given and discussed in Chevrel et al. (2022). These dedicated hazard maps have allowed EMZPCOI to have a better sense of the likely flow inundation area, front position and advance of the lava flow with discharge rate. Most importantly, the maps have allowed EMZPCOI to plan their response actions with higher degrees of confidence (e.g. to decide when and where to close the road, where to deploy wildfire countermeasures, or even when and where to evacuate populations, including hikers, and/or to close tourist overlooks that are identified as potential fire traps).

Between 2018 and 2020, the maps have been improved after each eruption upon specific requests from the EMPZCOI. To ensure that the maps are as useful as possible in aiding EMZPCOI in improved crises management and that communication within EMZPCOI as well as with OVPF was fully informed, several exchanges and meetings were organized between EMZPCOI and OVPF, as well as LMV-OPGC. These exchanges served as a means of training for the emergency managers, so that EMZPCOI fully understood the scientific approach behind the modeling, including uncertainties in models. In return, it allowed the scientific group to understand the needs of the emergency managers. This work focused on improving the maps in terms of graphical representation following constructive comment from EMZPCOI. As a result, there is a great deal of difference between the first map produced for the April 2018 eruption and the maps generated after these exchanges, since April 2021 eruption (Figure 13). Map changes as a result of user needs include:

1) A yellow-to-red sequential color scheme with increasing the probability of inundation, have replaced the blue shades for lava inundation, to avoid confusion with water.

2) A line showing the boundaries of the two municipalities that shares the Enclos (Sainte-Rose to the north and Saint-Philippe to the south) was requested so that the right municipality could be quickly inform if needed. This is fundamental in cases where the lava flow reaches the road, as Sainte-Rose is responsible for closure, diversion and replacement/repair to the north, and Saint-Philippe to the south. It also helps the two municipalities to prepare for losses.

3) Including the vegetated areas was requested to visualize where potential wildfires could start. This allows civil protection to alert the local fire department(s) so they could intervene in time to stop fires igniting or spreading. This could also of use to the French National Forestry Office in case any endemic flora and fauna at risk could be saved.

4) To improve easy geographical location of the potential lava flow impact, the map needed to include well-known features, such as trails, past lava flows, and well-known scoria cones. The anonymous shaded-relief back- ground which is suitable for scientific purposes and model testing, turn out to not be appropriated for outreach and communication purposes.

To comply with requests 2 to 4, we therefore finally came into the conclusion that the most meaningful and usable background for EMZPCOI was the commonly used map of the sector from the *Institut national de l'information geographique et forestiere* (IGN) (Figure 13B). This provides real added value to the product for response purposes and allows for rapid decision-making by the authorities.

5) The EMZPCOI wanted the possibility to see specific items on the maps as organized into operational, strategic, and human resources. Operational resources include vital centers (rescue centers, hospitals and clinics, military camps, town halls, etc.) and strategic sites (airport, water reserves, gas stations, etc.). Strategic resources are roads, some specific sites and establishments such as schools and retirement homes, as well as electricity, phone, and internet networks. Human resources comprise homes, schools and colleges, as well as commercial or industrial areas. EMZPCOI therefore provided these layers as GIS-compatible

format so that they could be implemented and activated within our map template, upon request.

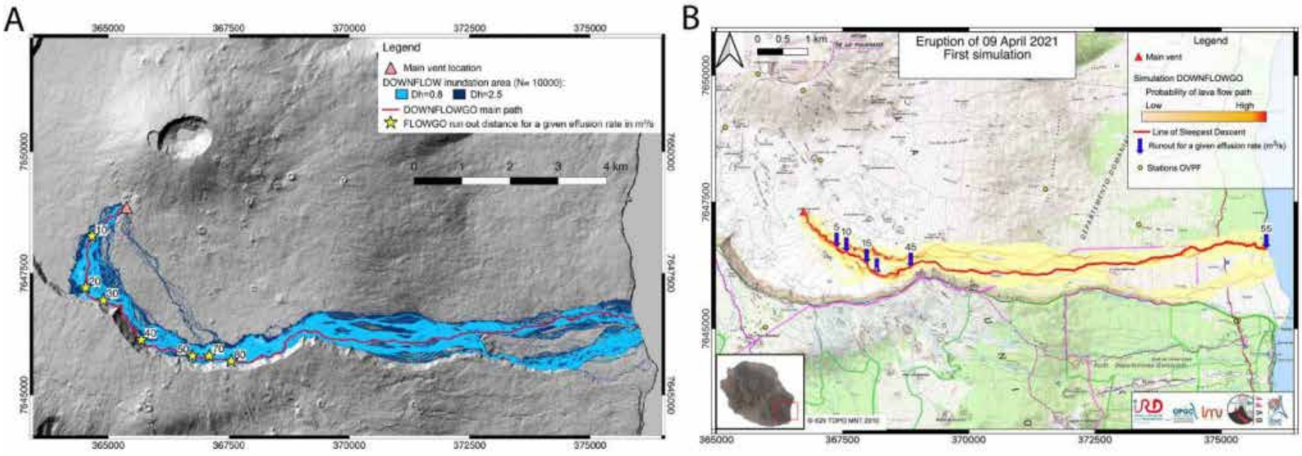

Figure 13: (A) The first map produced during the April 2018 eruption showing the lava flow inundation area (simulation with Δh = 0.8 in light blue and Δh = 2.5 in dark blue) and run out distances (yellow stars) for a given TADRs (numbers are in m3 s−1) along the LoSD descent (red line). The background is the hill-shaded 2010 LiDAR DEM produced by Institut national de l'information géographique et forestière (IGN). (B) Map produced during the April 2021 eruption showing the lava flow inundation area (probability increases from yellow to red; Δh = 2 and N = 10,000) and runout distances (blue arrows) for given discharge rate (numbers are in m3 s−1) along the LoSD (red line). The background is the BD TOPO IGN® from IGN.

The maps will certainly continue to be improved in the future. Indeed, some requests have been made but have not yet been fulfilled. For example, a critical tool for civil protection issues would be to automatically assess the number and location of people and buildings likely to be affected by the eruption, and therefore allow improved evacuation planning and loss preparation. This could potentially be done by adding the information of the map or providing a separate map where expected losses could be highlighted. Because (since the production of the maps) inhabited areas have not been threatened, this has not yet been implemented. Another request from the EMZPCOI is to include an assessment of the time before the lava flow front would reach critical morphological features (such as the caldera wall, the Grandes Pentes, or the coast) or infrastructure (such as the road and inhabited areas). This relates to the improvement of the numerical model itself, rather than just the map; accordingly, this has not yet been provided.

Uncertainties for runout distances were shown to be in the order of 30 % (see detailed analyses in Chevrel et al., 2022) while uncertainties on the satellite-derived TADRs are of the order of 50 % for HOTVOLC and 35 % for MIROVA (Coppola et al., 2016). Due to difficulties of representation, uncertainties are not represented on the maps but known by all actors. For this, regular explanation of the modeling is done during meetings with civil protection. This is essential to ensure that all duty staff know that these maps are a first-order estimation of the area to be covered and that the lava can always take another direction or go further than predicted.

There is still room for improvement of both the physical modelling, including refinement of the rheological models, and protocol executable actions such as automatic maps production (see chapter 5). This protocol could be exported to any other mafic effusive volcano with some modification including in initialization, calibration and validation (see chapter 5). Ultimately and importantly, engagement with end-users (local authorities) is required to refine any resulting maps to the local area and agency needs; this is the best way to ensure that the short-term hazard maps are well understood and are useful for preparedness and reducing potential risks.

4.4 Long-term lava flow hazard assessment at Piton de La Fournaise

Long-term lava flow hazard assessment consists on providing information on the spatial distribution probability of future lava flow invasion (years to decades). Such information is important for planning actions implemented by local authorities and in building resilience to future eruptions. At Piton de la Fournaise, the long-term impact of lava flow hazard was previously studied (Davoine and Saint-Marc, 2016; Villeneuve, 2000), and an initial lava flow hazard map was published in a national report in 2012 (Di Muro et al., 2012; Nave et al., 2016). However, given the high eruptions frequency at Piton de la Fournaise and a constantly changing topography - between the publication of the national report in 2012 and the end of 2019 - 18 eruptions occurred and approximately 19 km^2 of land was covered by lava - regular reassessments of lava flow hazard is needed.

In Chevrel et al. (2021a), we describe the methodology and present the up-to-date lava flow hazard map for Piton de la Fournaise (Figure 14). The series of actions to build such hazard map involved inventory of all the eruptions to define (1) the vents distribution, (2) the lava flow recurrence times and (3) the statistical lava flow lengths and then simulations with DOWNFLOW (Favalli et al., 2005) to model the lava flow paths. The inventory comprises more than 200 individual lava flows emplaced within the Enclos since 1931 to date, about 15 lava flows emplaced outside of the Enclos since 1708, and more than 700 vents over the entire edifice.

The DOWNFLOW stochastic approach computes lava flow inundation area by summing N lava flow paths for a given random vertical perturbation (Dh) added to the DEM. The calibration therefore requires setting of best-fit values for these two main parameters. For this, we applied ranges of Dh (0 to 5 m) and N (100 to 10 000) to 11 selected flows emplaced between 2010–2019. We found best fit of Dh = 2 m and N > 5000. Following Tarquini and Favalli (2013), a safe choice for N to ensure statistically robust simulations and ensure model (and output map) robustness is 10 000 in all cases. These best-fit parameters are also employed to feed the DOWNFLOWGO protocol presented in section 4.3.

The resulting lava flow hazard map (Figure 14) highlights the spatial distribution probability of future lava flow invasion for the medium to long term (years to decades) at Piton de la Fournaise (Chevrel et al., 2021a). For example, this map shows that half of the island belt road that crosses the Enclos is in an intermediate probability (> 0.5 %) zone in terms of lava inundation. This maps also highlights that even if the probability is low, the probability of lava flow invasion is not negligible for several municipalities located beyond the Enclos on the northeast and southeast flanks of the volcano (i.e., Saint-Philippe and Sainte-Rose).

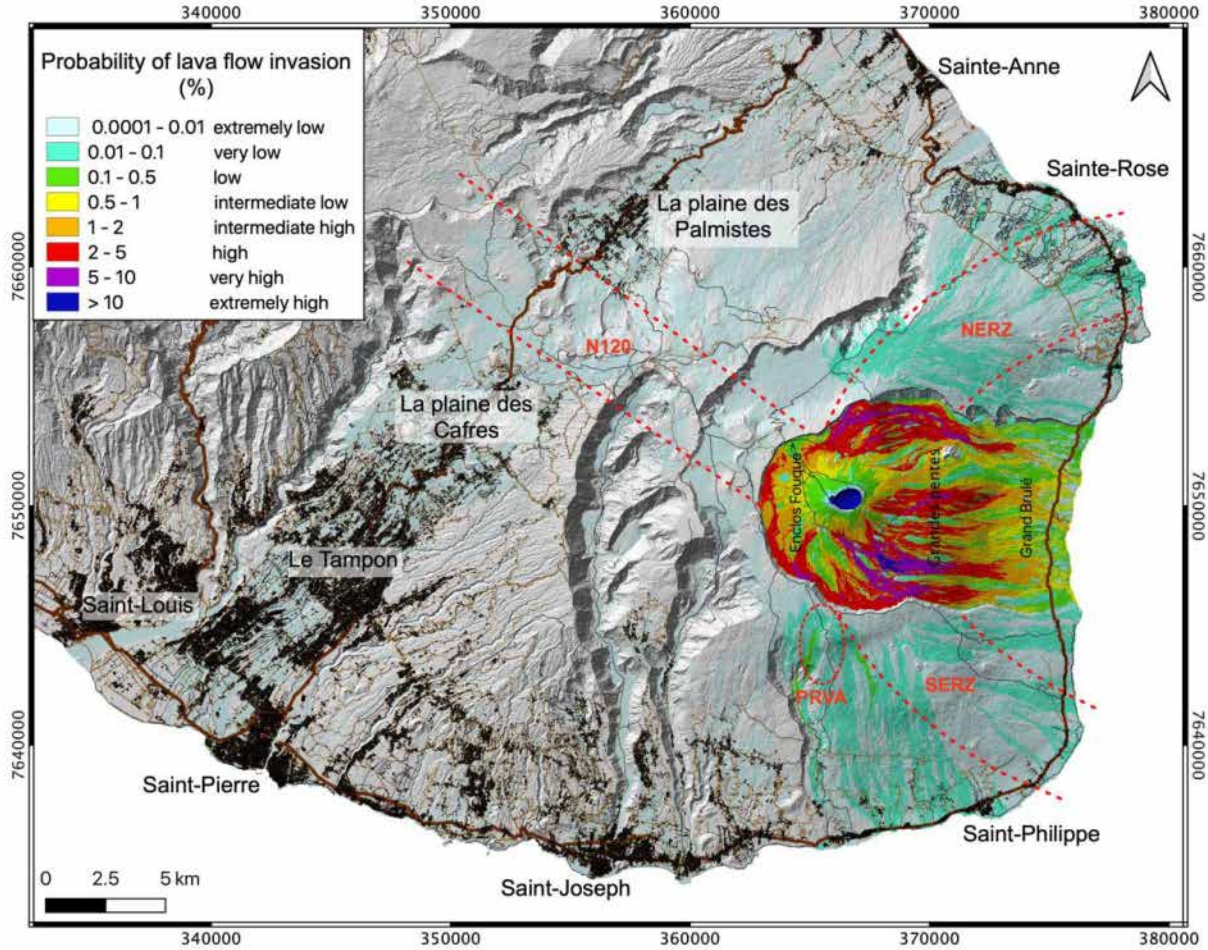

Figure 14: Lava flow hazard map of Piton de la Fournaise. Probability of lava flow invasion is given as percentages. Buildings are represented as black polygons, the main roads are in brown (in bold is the RN2 national road), and tourist trails are the thin black lines (data from BD TOPO® IGN). The dashed red lines outline the rift zones to 120N (N120), to the northeast (NERZ), and to the southeast (SERZ) as well as the Puy Raymond volcanic alignment (PRVA). The background is the hill shade of the lidar DEM from IGN – released in 2010. This is Figure 6 from Chevrel et al. (2021a).

The map applies to the frequent typical effusive events, where the less frequent high-volume events actually characterize the lowest-probability areas. Dedicated studies for probability occurrence of such high-volume events thus need to be conducted to complete the hazard assessment. This lava flow hazard map production methodology is, though, intended as a flexible approach that can be applied to frequently active effusive centers, producing up-to-date maps based on a continually evolving database that can be updated as eruption conditions evolve.

In the case of an imminent eruption, this hazard map will complement the near real-time information provided by the in-place protocol that is shared with civil protection (Section 4.3). It can be used to identify potential locations from where people may need to be evacuated and road sections that need to be closed in the event of an eruption. The presented map is thus also intended to aid and guide stake-holders in developing effective mitigation and land use plans considering the main volcanic hazard, with the caveat that our maps are for a “typical” effusive event. The data produced (and openly accessible) have recently been included in the departmental file of major risks of La Réunion: https://ddrm-reunion.re/volcanique/.

5. Research perspectives

5.1 Preamble

Given the current global situation, it is hard, if not impossible, to ignore our duty as researchers to concentrate our efforts keeping our lives on this planet sustainable. As volcanologists and geologists, we see the planet differently, through the lens of volcanoes and rocks, often detached from the immediate concerns of climate and life. What is a million years but a second in the story of our solar system? Yet, as human beings and scientists, the changes that the biosphere and human civilization have undergone in the past 50 to 100 years are a frightening reality. It is time to stop looking away and instead to use our intellect to aid society and biodiversity. For this, I believe to the empowerment of those who need it most and I therefore want to share and transfer scientific knowledge as much as I can. I want to keep fighting for free and open-access science. I am eager favor sustainable science through inter and transdisciplinary project.

In the coming years, I will continue developing field rheology. I want to develop instrumentation to a point where it can become a routine technique for implementing models of natural lavas and parameterization the still poorly understood role of bubbles. I am convinced that integrating field rheology in volcano observatory workflows will improve lava flow forecasting models used by institutions tasked with the science response to effusive eruptions.

I will keep working with volcano observatories to improve their response systems to volcanic eruptions. The operational protocol I have been using at Piton de la Fournaise can be adapted to other locations. For this I aim at developing collaborations to gather suitable input parameters for accurately describing and modeling eruptions, while keeping the operational tools free and open access.

Finally, I would like to contribute to initiatives aimed at strengthening resilience against volcanic hazards, preserving the memory of geological events, enhancing scientific research, and promoting sustainable development. I would like to engage projects with local communities via co-construction processes and the exchange of knowledge across various disciplines, such as physical volcanology, environmental sciences, and social and human science.

5.2 Future for field rheology

Initial attempts to measure the viscosity of lava used crude instruments (such as forcing a rod by hand into flowing lava), and even the latest instruments (motor-driven rotational viscometer) are significantly less refined than those one would encounter in a well-equipped laboratory. The great advancement over the past couple of years (see chapter 3), and my position as volunteer research assistant professor at UB, where a lava rheology dedicated laboratory is in place, have open new perspectives for this research activity (an NSF grant # 2420723 “Tackling Multiphase Lava Rheology at its Origins” has just been awarded). Now that two instruments are fully operational (Chevrel et al., 2023b; Harris et al., 2024a; see chapter 3), they can be deployed in tandem in the field in order to map the rheological evolution of a lava flow. Recently, we conducted a field mission at the 2023 Litli-Hrútur eruption in Iceland where we deployed both rheometers. Viscosity measurements were combined with temperature measurement and sampling for textural characterization. Result showed the exponential increase of viscosity along the extend of the flow for the first time measured directly in the lava (Harris et al., 2024a). This deployment also highlighted the need for instrumental improvements to make field operations more accurate, faster, easier, and safer.

Future plans hence involve continuing to improve the instruments and conducting more field viscometry, combined with temperature measurements and lava sampling, on other volcanoes. Where possible we will hence map lava rheology in 4D (i.e. with distance from the vent and through time). Such results will serve to validate the rheological trends observed through experimental or channel morphology approaches. The aim is to provide continuous near real time viscosity data to benchmark lava flow models and make use of field rheology data to its full potential. The success of field rheology campaigns is fundamentally controlled by the eruptive dynamics of the volcano, accessibility of the flow, and external conditions (e.g., weather). While an eruption may be in progress and the necessary infrastructure available, field measurements are not always possible, as they require direct approach to and contact with active lava. Additionally, working in a dynamic environment like active lava means that the lava is continuously changing (e.g., cooling, crystallization, outgassing), making stable conditions rare. All these factors must be favorable to perform accurate and reproducible field rheometry. Thus, this research activity is a long-term effort. To this end, collaborations have been established to facilitate rapid deployment with an international network including University of Iceland, Etna volcano observatory of the Istituto Nazionale di Geofisica e Vulcanologia, the Hawaiian Volcano Observatory and the OVPF.

The continued use of these instruments at future eruptions will provide the necessary data that is currently lacking to better understand the rheology of natural multiphase lava. To completely understanding multiphase (melt+crystals+bubbles) rheology, *in situ* measurements must be combined with laboratory experiments at similar natural conditions. As mentioned in chapter 2, laboratory viscometry of silicate melts or analogue suspensions, describe the two-phase suspensions reasonably well. However, there is still a lack of three phases rheology understanding. We anticipate that association of rheological field data with temperature measurement, detailed textural analyses, and dedicated experimentation in the laboratory is needed to provide a holistic assessment and parameterization of three-phase suspension rheology at natural conditions. Such multipronged analyses have not been performed to date (the available data only provide snapshots of the story). Future actions must therefore be to carry out laboratory experiments at the same conditions as in the field (cooling rate, strain rate, fO_2) to identify the role of each phase and their interaction and their variability and evolution over the range of conditions expected during lava emplacement. This requires combination of sub-liquidus viscosity measurements at both thermal equilibrium and disequilibrium conditions (see chapter 2) as well as over a wide temperature range and relevant fO_2. In a first stage, the laboratory experiments will be performed at LAVAP-UB but in the future such facilities are planned for installation at the LMV, UCA. For this, I plan to led a project that will include building a high temperature rheology laboratory at LMV equipped with a concentric cylinder to measure the viscosity at super and sub-liquidus conditions, a creep-apparatus or micro-penetration device as well as a scanning calorimeter to constrain the viscosity near the glass transition. These instruments will all be equipped with gas lines to constrain the fO_2. I foresee that this equipment will serve for several researchers at LMV and in France for studying magma properties and in particular the role of volatiles under specific reduced conditions.

5.3 Response to effusive crises: improvement and applications to other volcanoes

Responding to effusive crises in an efficient manner include well-calibrated and validated modelling, short-time scales and healthy communication with authorities. The protocol in place at OVPF for responding to Piton de la Fournaise effusive eruption can be always improved and may serve as an example for application at other volcanoes.

Improvements of the current protocol

Future improvements of the protocol itself is multifaced but have a common goal that is to improve our efficiency and accuracy in responding to effusive eruptions. These includes:

1) the never-ending effort to improve the physical model to improve our ability to model lava flow emplacement while reducing uncertainties. For this, both the deterministic FLOWGO approach and DOWNFLOW model can be improved by implementing them with field-based data. At Piton de la Fournaise, the volcanic activity follows cycles that cause the location, erupted lava volume, effusion rate, and flow dimensions to evolve with time (Chevrel et al., 2021a). Both the maps and the parameters used for modeling hence are cycle-dependent. for now the model is mainly based on the 2010 and the 2018 eruptions (Harris et al., 2015, 2019b). There is hence a need for a retrospective study on the rheological properties of the lava through the years. This work will allow to constrain the variability of the lava rheology and its effect on modelling. For this, data such as the one acquired by the DynVolc database will be exploited as input for FLOWGO modelling. Furthermore, when field viscosity measurements will be acquired at Piton de la Fournaise, they will then be used to validate the model and hopefully improve it.

2) DOWNFLOW is unable to simulate levées, breakouts, overflows, lobes, tubes, bifurcation, etc. and FLOWGO assumes that the lava flow is channelized and cooling-limited. This means that complex lava flow fields, volume-limited lava flows, and long duration flows cannot be modeled accurately because syn-eruptive topography changes that would influence the flow are not captured on the DEM. At Piton de la Fournaise, effusive events are of relatively short duration, thus DOWNFLOWGO is, so far, the best option to rapidly build short-term hazard maps that show the most probable inundation area and the runout length for the given discharge rate at the beginning of an eruption when flow is in a well-defined channel. In the event of a long-duration flow, update of the DOWNFLOWGO modeling can be operated at the site of breakouts (Harris et al., 2019a) and insulation condition changes from open channel to tubes can also be modeled. Future options to better incorporate syn-eruptive lava flow morphology and flow front propagation could include use of a physics-based model which can spatially and temporally reproduce lava flow propagation (Bilotta et al., 2015; Hyman et al., 2022). At Piton de la Fournaise, a couple of studies have tested such models on previous eruptions - for example Rheolef (Bernabeu et al., 2018), and VOLCFLOW

(Kelfoun and Vargas, 2016; Lemaire master thesis 2022). But further work is needed to validate their use during an eruption crisis and to ensure that they can be implemented in a timely fashion. Such implementation would also answer to the frequent request from the civil protection, that is the assessment of lava flow front advance rate and time to reach an important morphological feature or infrastructure.

3) The time constraint for delivery of the map within the current protocol mostly depends on the time between the start of the eruption and the confirmation of vent location. This may take from several minutes to a few hours and depends on the location of the eruptions, the weather conditions, the availability of the observatory staff and helicopter in case of eruptions in remote places. Future effort will concentrate on reducing this time constrains. This could be done by automatic implementation of the vent location obtained from (i) tremor maps or (ii) by automatic pixel detection on thermal or visual satellite images. (i) At Piton de la Fournaise, the center of the tremor location is obtained by a triangulation method, which locates the source of the tremor, interpreted as the main fissure, with an error of hundreds of meters (Battaglia and Aki, 2003). Tremor maps are produced every 15 minutes by the OVPF (Beauducel et al., 2020). This implementation into the protocol is a short-term work. (ii) Vent location may also be improved with the increase of satellite sensor's spatial and temporal resolution that would enhance our ability to locate the vent and hence to quickly respond to an emergency crisis. Satellite missions specifically for volcanology could revolutionize event monitoring, potentially allowing for near-instantaneous data acquisition (Ramsey et al., 2022). Meanwhile efforts are ongoing to use existing sensors such as for example VIIRS (Visible Infrared Imaging Radiometer Suite) that has 750m resolution and revisit time of about 12 hours (Campus et al., 2022). Through a pixel detection system of the satellite images, the most probable vent location will be directly be implemented into DOWNFLOWGO to generate the hazard maps. The probability distribution of the vent location could also be implemented and translated into the hazard map.

Additionally, combination of various available satellites sensors offers the opportunity to map the flow with unprecedented frequency (Chevrel et al., 2023b). Future efforts hence are to be implement this into the protocol to ensure cross-checking the performance of the model.

Exporting the protocol to other volcanoes

This protocol has been designed to be exported to any other mafic effusive volcano. The computational simplicity and rapid turnaround that offer the modelling procedure are important for syn-eruptive monitoring and hazard-mitigation, but its transferability to other volcanoes remains to be tested. For export, some modifications are required. First, the FLOWGO runout and TADR conversion routine needs to be calibrated and validated for the new site. This has, to an extent, already be done in many cases and a well-tested methodology exists for model initialization (e.g. Harris et al., 2007; Harris and Rowland, 2001; Ramsey et al., 2019). As a second step, an up-to-date DEM is required to calibrate DOWNFLOW. This, also, already exists at a number of effusive centers including Nyiragongo, Mont Cameroun and Capo Verde (Favalli et al., 2009, 2012; Richter et al., 2016) and the methodology for model initialization is also well developed (Chevrel et al., 2021a).

I started a first effort to adapt this protocol to the Nyiragongo volcano during the 2021 eruption. At this time, I attempted to produce a preliminary map (Figure 15), but this was without validation and calibration of the model. To this end, I am collaborating on an ongoing project with UB and University of Torino (NSF grant #2223098 PI: Dr. Stephan Kolzenburg, collaborator Prof. Diego Coppola) that is dedicated to fulfil this request. The samples textural characteristic and their rheological evolution as cooling occur are being established and soon to be implemented into DOWNFLOWGO (masters project of Jenna Diamico, UB).

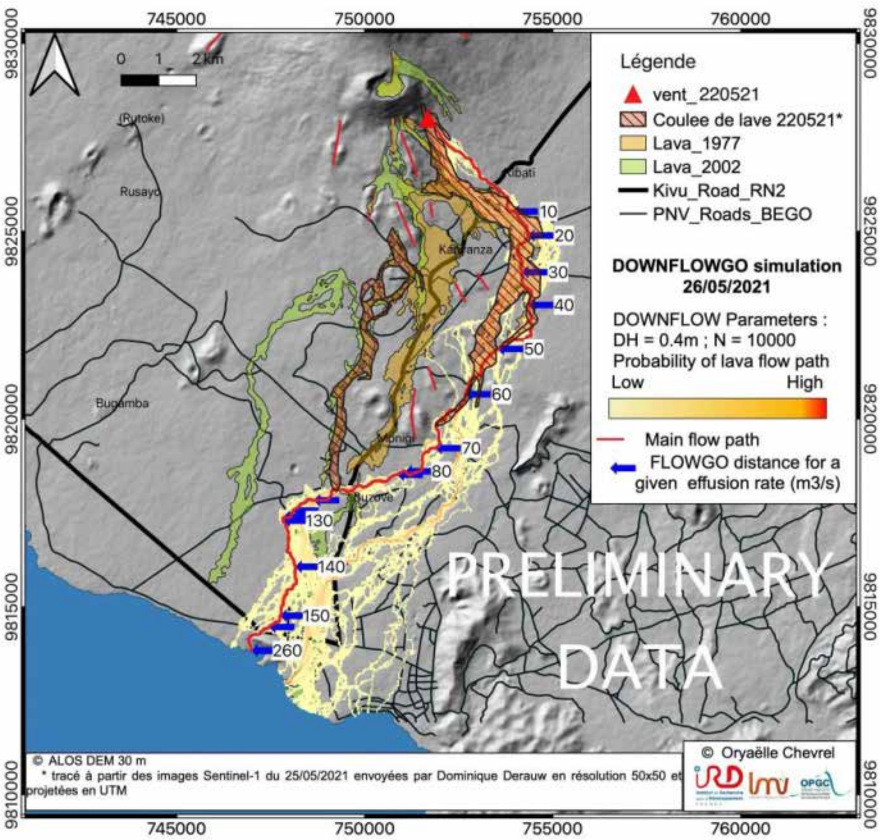

Figure 15: Preliminary data from DOWNFLOWGO using non-validated flow parameters. The results do not reproduce the May 2021 lava flow paths or runout distances well, highlighting the need for optimization.

Another place where I started to work in collaboration with IG-EPN (Henry Calderon's and Evelyn Rodriguez's undergraduate projects) are the volcanoes of the Galapagos archipelago in Ecuador. There, we conducted field mapping and sampling. Rheological constrains are under the making and will serve as input for future modelling. Other potential volcanoes to focus on are where effusive activity is less common but where assessment and constrains on lava flow dynamics are needed such as for example in Nicaragua, Mexico, and Guatemala.

Integration of a lava flow emplacement model, optimized for the specific rheology of the relevant volcano, and informed by near real time satellite monitoring data of volcanic activity has the potential to provide hazard assessment at unprecedented spatial and temporal scales. Once the protocol is initialized, calibrated, validated, and refined so as to be fit-to-purpose, then a rapid response service involving timely pro-vision of lava inundation hazard maps, tailored to the volcano and eruption in hand, should be attainable. Ultimately and importantly, engagement with stakeholders (local authorities) is required to refine any resulting maps to the local area and agency needs; this is the best way to ensure that the short-term hazard maps are well understood and are useful for preparedness and reducing potential risks. This can only be achieved thanks to close collaborations between scientists from observatories and institutes and the local civil protection.

In this context, I co-organized in April 2021 the workshop "International Effusive Crisis Response (Virtual) Workshop" as part of the ANR-LAVA project (2016-2021; PI: A. Harris) in collaboration with the European Volcano Early Warning System project (2018-2021; PI: J. Marti), France. The objective of the workshop was to involve multiple countries to present their response and management protocols in the event of a volcanic crisis. This workshop brought together scientists from academia and volcano observatories, as well as civil protection agents. Participants from several European countries (France, Italy, Iceland, Portugal, Spain) and other continents (Ecuador, United States, D.R. Congo) were present. For each country, both scientists and civil protection agents had the opportunity to share their experiences in responding to effusive crises. Presentations also included societal issues, community expectations and perspectives during volcanic crises. An expert elicitation about scientific response to effusive crises was also conducted (Tadini et al., 2022). Although this workshop was virtual (still under restrictions due to SARS-COV2 pandemic), exchanges were fruitful and it was integrally recorded on the LMV youtube channel. I am committed to participate in organizing similar future gatherings, as they can only improve reactivity and efficiency during the eruptive crisis.

Finally, as mentioned previously, the current protocol is made for lava flow emissions and it cannot currently be applied to other eruption dynamics such as dome formation or pyroclastic flows, as it does not allow for modeling these events. However, such protocol is highly valued by the OVPF because it provides a wealth of organized information useful for monitoring the ongoing eruption without adding extra workload to observatory staff. Therefore, one long term goal is to adapt, improve, or even reinvent this protocol to be effective for all types of eruptions while keeping its efficiency.

5.4 Impacts and benefits of past and present eruptions on populations.

The consequences of an eruption can be dramatic. However, they can also be beneficial by fertilizing soils, or by providing materials for construction or for the production of everyday tools. Furthermore, because people care most about things they know and understand, it is crucial to acquire and share knowledge of our natural heritage, including volcanic events, geology and biodiversity, to get people involved in the preservation of our surroundings. This will strengthen resilience against volcanic hazards, preserving the memory of geological events, enhancing scientific research, and promoting sustainable development. One of my long-term research interests is therefore 1) to explore how societies live through and survived eruptions, and how they utilize volcanic deposits, and 2) to promote scientific knowledge and improve sustainable development through geological heritage. To achieve this, I have established collaborations with various institutes in France and Latin America. Although, this part of my research is still under development, I, here present two main lines of research, which I hope to expand significantly in the coming years.

Living through and surviving eruptions

Over the last years, collaboration with archaeologists has shown me how volcanology and archaeology converge on many themes concerning the impact of volcanic eruptions on civilizations as well as the use of volcanic products (Chevrel et al., 2016b; Hamon et al., 2023, 2024; Ramírez-Uribe et al., 2021; Reyes-Guzmán et al., 2023). Futures plans are to strengthen collaborations with departments of archaeology, geography, and social and human sciences in order to carry out interdisciplinary projects to study the impact of volcanic eruptions, particularly on pre-Hispanic civilizations. In particular, I aim to study how societies experienced and survived eruptions and how they learned to use volcanic products (for agriculture, construction, or their religious rituals). Many sites and volcanic deposits remain to be explored. As volcanologists, we can provide answers regarding the nature of the rocks used for construction or tools, their mechanical properties, date an event, or assess the power of an eruption and the affected distance.

Improving sustainable development through geological heritage

Recently involved in a cross-disciplinary team of volcanologists, biologists, ecologists, and social scientists, I am getting interested in how geological heritage can serve to improve sustainable development and empower people facing global changes. Specifically, I am the correspondent researcher for a submitted proposal (June 2024) to build a “Young Team Associated with IRD” (JEAI) led by Dr. MN Guilbaud from UNAM. The objectives of this project are to focus on specific sites which: 1) are located in active volcanic areas, 2) contain exceptional natural heritage with geological and biological values (geosites, natural reserves) and 3) are emblematic of the various issues that impact sustainable development in the targeted region. Within this framework, I am involved to participate in characterizing the associated geological resources as well as their genesis and vulnerability of the given geosite. In particular, I am involved in a collaborative work on the Xitle volcano lava flow, located in the heart of Mexico City. There we aim at providing all the geological and physical constrains of the lava to provide a hazard assessment for potential future eruption in the vicinity. This work will be used in a larger program to create a network of geosites in the city. Through this type of projects, I want to contribute in developing communication strategies to raise awareness among the population about the benefits of these spaces and the associated volcanic hazards and risks. Interaction with local communities will promote the conservation and restoration of the sites.

Selection of publications

In this last section, I provide a selection of my most significant articles (with links to access them). The first 11 articles were used in the writing of this dissertation, they are given following the chapter orders. Subsequently, I choose 10 other articles to illustrate the diversity of my scientific work.

Chapter 2: Rheological evolution of lava flows

Chevrel MO, Platz T, Hauber E, Baratoux D, Lavallée Y, Dingwell DB (2013) Lava Flow Rheology: A Comparison of Morphological and Petrological Methods. *Earth Planetary Science Letters*, Vol. 384: 102–20. https://doi.org/10.1016/j.epsl.2013.09.022

Chevrel MO, Cimarelli C, DeBiasi L, Hanson JB, Lavallée Y, Arzilli F, Dingwell DB (2015) Viscosity Measurements of Crystallizing Andesite from Tungurahua Volcano (Ecuador). *Geochemistry, Geophysics, Geosystems* Vol. 16 (3): 870–89. https://doi.org/10.1002/2014GC005661

Chevrel MO, Labroquere J, Harris AJL, Rowland SK (2018) PyFLOWGO: An Open-Source Platform for Simulation of Channelized Lava Thermo-Rheological Properties. *Computer Geosciences*. Vol. 111: 167–80 https://doi.org/10.1016/j.cageo.2017.11.009 , https://hal.science/hal-01634842/

Chapter 3: Field rheology

Chevrel MO, Harris AJL, Pinkerton H. (2019) Measuring the viscosity of lava in the field: A review. *Earth-Science Reviews,* Vol. 196 : 1028853. https://doi.org/10.1016/j.earscirev.2019.04.024, https://hal.science/hal-02150640v2

Chevrel MO, Harris A J L, James M R, Calabrò L, Gurioli L, Pinkerton H (2018) The viscosity of pāhoehoe lava: *In situ* syn-eruptive measurements from Kilauea, Hawaii. *Earth and Planetary Science Letters*, Vol. 493: 161-17 https://doi.org/10.1016/j.epsl.2018.04.028, https://hal.science/insu-03708970v1

Chevrel MO, Latchimy T, Batier L, Delpoux R, Harris M, Kolzenburg S (2023) A new portable field rotational viscometer for high-temperature melts *Review of Scientific Instruments: 94, 105116 (2023)* https://doi.org/10.1063/5.0160247, https://hal.science/hal-04262199v2

Harris M, Kolzenburg S, I Sonder, **Chevrel O**. (2024) A new portable penetrometer for measuring the viscosity of active lava. *Review in Scientific Instrument. Vol. 95, 065103* https://doi.org/10.1063/5.0206776 , https://hal.science/hal-04663298

Chapter 4: Response to volcanic effusive eruptions

Chevrel MO, Favalli M, Villeneuve N, Harris A, Fornaciai A, Richter N. Derrien A, Boissier P, Di Muro A, Peltier A (2021) Lava flow hazard map of Piton de la Fournaise volcano. *Natural Hazards in Earth System Sciences,* 21, 1–22, 2021 https://doi.org/10.5194/nhess-21-2355-2021

Chevrel MO, Harris A, Peltier A, Villeneuve N, Coppola D, Gouhier M, Drenne S. (2022) Volcanic crisis management supported by near real time lava flow hazard assessment at Piton de la Fournaise, *Volcanica* 5(2), pp. 313–334. https://doi.org/10.30909/vol.05.02.313334

Selection of supplementary articles (in chronological order):

Flynn ITW, **Chevrel MO**, Ramsey MSR. (2023) Adaptation of a thermorheological lava flow model for Venus conditions. *Journal of Geophysical Research: Planets*, *128*, e2022JE007710. https://doi.org/10.1029/2022JE007710

Verdurme P, Gurioli L, **Chevrel MO**, Médard E, Berthod C, Komorowski JC, Harris A, Paquet F, Cathalot C, Feuillet N, Lebas E, Rinnert E, Donval JP, Thinon I, Deplus C and Bachèlery P. (2024) Magma ascent and lava flow field emplacement during the 2018–2021 Fani Maoré deep-submarine eruption insights from lava vesicle textures. *Earth and Planetary Science Letters. Vol: 636, 118720.* https://doi.org/10.1016/j.epsl.2024.118720 https://uca.hal.science/hal-04555016

Hamon C, Pereira G, **Chevrel MO**, Aubry L, Siebe C, Quesada O, Reyes-Guzmán N. Present Use and Production of Metates and Molcajetes in Turícuaro (Michoacán, Mexico):

Deciphering the Evolution of Food Preparation Practices. (2024) *Ethnoarchaeology. Vol. 15, p. 208-2032* https://doi.org/10.1080/19442890.2023.2280379

Reyes-Guzmán N, Siebe C, **Chevrel MO**, Pereira G, Mahgoub AN, Böhnel H. (2023) Holocene volcanic eruptions of the malpaís de zacapu and its pre-hispanic settlement history. *Ancient Mesoamerica, 1–16.* https://doi.org/10.1017/S095653612100050X

Kolzenburg S, Chevrel MO, Dingwell D. (2022) Magma suspension rheology. *Reviews in Mineralogy and Geochemistry* 87 (1): 639–720. http://dx.doi.org/10.2138/rmg.2022.87.14

Ramírez-Uribe I, Siebe C, **Chevrel MO**, Ferrés D, Salinas S. (2022) The Late Holocene Nealtican lava-flow field from Popocatépetl volcano: Emplacement dynamics and implications for future hazard scenarios and archaeology. *GSA Bulletin. 134 (11-12): 2745–2766.* https://doi.org/10.1130/B36173.1, https://hal.science/hal-03849746.

Harris AJL, **Chevrel MO**, Coppola D, Ramsey MS, Hrysiewicz A, Thivet S, Villeneuve, N Favalli M., Peltier A., Kowalski P, Di Muro A, Froger J.-L, Gurioli L. (2019) Validation of an Integrated Satellite-data-driven Response to an Effusive Crisis: The April–May 2018 Eruption of Piton de La Fournaise. *Annals of Geophysics,* Vol.62,2, VO30. https://doi.org/10.4401/ag-7972

Reyes-Guzmán N, Siebe C, **Chevrel MO**, Guilbaud MN, Salinas S, Layer P (2018) Geology and Radiometric Dating of Quaternary Monogenetic Volcanism in the Western Zacapu Lacustrine Basin (Michoacán, México): Implications for Archeology and Future Hazard Evaluations. *Bulletin of Volcanology*, 80 (18): 1–20. https://doi.org/10.1007/s00445-018-1193-5, https://hal.science/hal-02401449v1

Chevrel MO, Siebe C, Guilbaud MN, Salinas S (2016) The AD 1250 El Metate Shield Volcano (Michoacán): Mexico's Most Voluminous Holocene Eruption and Its Significance for Archaeology and Hazards. *The Holocene,* Vol.26 (3): 471–88. https://doi.org/10.1177/0959683615609757, https://hal.uca.fr/hal-03849772

Chevrel MO, Baratoux D, Hess KU, Dingwell DB (2014) Viscous Flow Behavior of Tholeiitic and Alkaline Fe-Rich Martian Basalts. *Geochemica Cosmochimica Acta,* Vol. 124: 348–65. https://doi.org/10.1016/j.gca.2013.08.026

References

Anderson, S. W., Fink, J. H. and Rose, W. I.: Mount St. Helens and Santiaguito lava domes: The effect of short-term eruption rate on surface texture and degassing processes, J. Volcanol. Geotherm. Res., 69(1–2), 105–116, doi:10.1016/0377-0273(95)00022-4, 1995.

Andrews, G. D. M., Kenderes, S. M., Whittington, A. G., Isom, S. L., Brown, S. R., Pettus, H. D., Cole, B. G. and Gokey, K. J.: The fold illusion: The origins and implications of ogives on silicic lavas, Earth Planet. Sci. Lett., 553, 116643, doi:10.1016/j.epsl.2020.116643, 2021.

Bagdassarov, N. S. and Dingwell, D. B.: A rheological investigation of vesicular rhyolite, J. Volcanol. Geotherm. Res., 50(3), 307–322, doi:10.1016/0377-0273(92)90099-Y, 1992.

Bagdassarov, N. S. and Dingwell, D. B.: Frequency-dependent rheology of vesicular rhyolite, J. Geophys. Res., 98, 6477–6487, doi:10.1029/92JB02690, 1993.

Battaglia, J. and Aki, K.: Location of seismic events and eruptive fissures on the Piton de la Fournaise volcano using seismic amplitudes, J. Geophys. Res. Solid Earth, 108(B8), doi:https://doi.org/10.1029/2002JB002193, 2003.

Beauducel, F., Lafon, D., Béguin, X., Saurel, J. M., Bosson, A., Mallarino, D., Boissier, P., Brunet, C., Lemarchand, A., Anténor-Habazac, C., Nercessian, A. and Fahmi, A. A.: WebObs: The Volcano Observatories Missing Link Between Research and Real-Time Monitoring, Front. Earth Sci., 8(February), 1–22, doi:10.3389/feart.2020.00048, 2020.

Belousov, A. and Belousova, M.: Dynamics and viscosity of ʻaʻā and pāhoehoe lava flows of the 2012-2013 eruption of Tolbachik volcano, Kamchatka (Russia), Bull. Volcanol., 80(6), doi:doi.org/10.1007/s00445-017-1180-2, 2018.

Bernabeu, N., Saramito, P. and Harris, A.: Laminar shallow viscoplastic fluid flowing through an array of vertical obstacles, J. Nonnewton. Fluid Mech., 257, 59–70, doi:https://doi.org/10.1016/j.jnnfm.2018.04.001, 2018.

Bilotta, G., Herault, A., Cappello, A., Ganci, G. and Negro, C. Del: GPUSPH: a Smoothed Particle Hydrodynamics model for the thermal and rheological evolution of lava flows, in Detecting, Modelling and Responding to Effusive Eruptions, vol. 426, edited by A. J. L. Harris, T. De Groeve, F. Garel, and S. A. Carn, pp. 387–408, Geological Society, London., 2014.

Bilotta, G., Cappello, A., He, A., Ganci, G., Negro, C. D. E. L., Nazionale, I., Catania, S. and Etneo, O.: MAGFLOW : a physics-based model for the dynamics of lava-flow emplacement, , doi:10.1144/SP426.16, 2015.

Biren, J., Harris, A. J. L., Tuffen, H., Chevrel, M. O., Gurioli, L., Vlastélic, I., Schiavi, F., Benbakkar, M., Fonquernie, C. and Calabro, L.: Chemical, Textural and Thermal Analyses of Local Interactions Between Lava Flow and a Tree – Case Study From Pāhoa, Hawai'i, Front. Earth

Sci., 8, 233, doi:10.3389/feart.2020.00233, 2020.
Blong, R. J.: Volcanic Hazards, A Sourcebook on the Effects of Eruptions, Academic P., edited by R. J. BLONG, Academic Press, San Diego., 1984.
Brantley, S. R., Kauahikaua, J. P., Babb, J. L., Orr, T. R., Patrick, M. R., Poland, M. P., Trusdell, F. A. and Oliveira, D.: Communication strategy of the U.S. Geological Survey Hawaiian Volcano Observatory during the lava-flow crisis of 2014–2015, Kīlauea Volcano, Hawai'i, edited by M. P. Poland, M. O. Garcia, V. E. Camp, and A. Grunder, F. Volcanol. A Tribut. to Disting. Career Don Swanson, 538, 0, doi:10.1130/2018.2538(16), 2019.
Campus, A., Laiolo, M., Massimetti, F. and Coppola, D.: The Transition from MODIS to VIIRS for Global Volcano Thermal Monitoring, Sensors, 22(5), doi:10.3390/s22051713, 2022.
Cappello, A., Zanon, V., Del Negro, C., Ferreira, T. J. L. and Queiroz, M. G. P. S.: Exploring lava-flow hazards at Pico Island, Azores Archipelago (Portugal), Terra Nov., 27(2), 156–161, doi:10.1111/ter.12143, 2015.
Caricchi, L., Burlini, L., Ulmer, P., Gerya, T., Vassalli, M. and Papale, P.: Non-Newtonian rheology of crystal-bearing magmas and implications for magma ascent dynamics, Earth Planet. Sci. Lett., 264(3–4), 402–419, doi:10.1016/j.epsl.2007.09.032, 2007.
Carracedo, J. C., Troll, V. R., Day, J. M. D., Geiger, H., Aulinas, M., Soler, V., Deegan, F. M., Perez-Torrado, F. J., Gisbert, G., Gazel, E., Rodriguez-Gonzalez, A. and Albert, H.: The 2021 eruption of the Cumbre Vieja volcanic ridge on La Palma, Canary Islands, Geol. Today, 38(3), 94–107, doi:https://doi.org/10.1111/gto.12388, 2022.
Cashman, K. V., Mangan, M. T. and Newman, S.: Surface degassing and modifications to vesicle size distributions in active basalt flows, J. Volcanol. Geotherm. Res., 61(1–2), 45–68, doi:10.1016/0377-0273(94)00015-8, 1994.
Cashman, K. V, Thornber, C. and Kauahikaua, J. P.: Cooling and crystallization of lava in open channels, and the transition of pāhoehoe lava to ʻaʻā, Bull. Volcanol., 61, 306–323, doi:https://doi.org/10.1007/s004450050299, 1999.
Castruccio, A., Rust, A. C. and Sparks, R. S. J.: Rheology and flow of crystal-bearing lavas: Insights from analogue gravity currents, Earth Planet. Sci. Lett., 297, 471–480, doi:10.1016/j.epsl.2010.06.051, 2010.
Castruccio, A., Rust, A. C. and Sparks, R. S. J.: Evolution of crust- and core-dominated lava flows using scaling analysis, Bull. Volcanol., 75, 681, doi:10.1007/s00445-012-0681-2, 2013.
Chevrel, M. O.: Rheology of Martian Lava Flows: An Experimental Approach, Ludwig Maximilians Universitat., 2013.
Chevrel, M. O. and Harris, A. J.: Monitoring Lava Flows, in Modern Volcano Monitoring, vol. Accepted, edited by Z. S. and C. Caudron, Book series Advances in Volcanology., 2024.
Chevrel, M. O., Platz, T., Hauber, E., Baratoux, D., Lavallée, Y. and Dingwell, D. B.: Lava flow rheology: A comparison of morphological and petrological methods, Earth Planet. Sci. Lett., 384, 102–120, doi:10.1016/j.epsl.2013.09.022, 2013a.
Chevrel, M. O., Giordano, D., Potuzak, M., Courtial, P. and Dingwell, D. B.: Physical properties of CaAl2Si2O8-CaMgSi2O6-FeO-Fe2O3 melts: Analogues for extra-terrestrial basalt, Chem. Geol., 346, 93–105, doi:10.1016/j.chemgeo.2012.09.004, 2013b.
Chevrel, M. O., Baratoux, D., Hess, K.-U. and Dingwell, D. B.: Viscous flow behavior of tholeiitic and alkaline Fe-rich martian basalts, Geochim. Cosmochim. Acta, 124, 348–365, doi:10.1016/j.gca.2013.08.026, 2014.
Chevrel, M. O., Cimarelli, C., DeBiasi, L., Hanson, J. B., Lavallée, Y., Arzilli, F. and Dingwell, D. B.: Viscosity measurements of crystallizing andesite from Tungurahua volcano (Ecuador), Geochemistry, Geophys. Geosystems, 16(3), 870–889, doi:10.1002/2014GC005661, 2015.
Chevrel, M. O., Guilbaud, M.-N. and Siebe, C.: The ~AD 1250 effusive eruption of El Metate shield volcano (Michoacán, Mexico): Magma source, crustal storage, eruptive dynamics, and lava rheology, Bull. Volcanol., 78(32), 1–28, doi:10.1007/s00445-016-1020-9, 2016a.
Chevrel, M. O., Siebe, C., Guilbaud, M. and Salinas, S.: The AD 1250 El Metate shield volcano (Michoacán): Mexico's most voluminous Holocene eruption and its significance for archaeology and hazards, The Holocene, 26(3), 471–488, doi:10.1177/0959683615609757, 2016b.
Chevrel, M. O., Labroquere, J., Harris, A. J. L. and Rowland, S. K.: PyFLOWGO: an open-source platform for simulation of channelized lava thermo-rheological properties, Comput. Geosci.,

111, 167–180, doi:10.1016/j.cageo.2017.11.009, 2018a.
Chevrel, M. O., Harris, A. J. L., James, M. R., Calabrò, L., Gurioli, L. and Pinkerton, H.: The viscosity of pāhoehoe lava: In situ syn-eruptive measurements from Kilauea, Hawaii, Earth Planet. Sci. Lett., 493, 161–171, doi:10.1016/j.epsl.2018.04.028, 2018b.
Chevrel, M. O., Harris, A. J. L., Ajas, A., Biren, J., Gurioli, L. and Calabrò, L.: Investigating physical and thermal interactions between lava and trees: the case of Kilauea's July 1974 flow, Bull. Volcanol., 81(2), 1–6, doi:10.1007/s00445-018-1263-8, 2019a.
Chevrel, M. O., Harris, A. J. L. and Pinkerton, H.: Measuring the viscosity of lava in the field: A review, Earth-Science Rev., 196, 102852, doi:https://doi.org/10.1016/j.earscirev.2019.04.024, 2019b.
Chevrel, M. O., Favalli, M., Villeneuve, N., Harris, A. J. L., Fornaciai, A., Richter, N., Derrien, A., Boissier, P., Di Muro, A. and Peltier, A.: Lava flow hazard map of Piton de la Fournaise volcano, Nat. Hazards Earth Syst. Sci., 21(8), 2355–2377, doi:10.5194/nhess-21-2355-2021, 2021a.
Chevrel, M. O., Wadsworth, F., Farquharson, J., Kushnir, A., Heap, M., Williams, R., Delmelle, P. and Kennedy, B.: Publishing a Special Issue of Reports from the volcano observatories in Latin America: Editorial to Special Issue on Volcano Observatories in Latin America, Volcanica, 4(S1), i–vi, doi:10.30909/vol.04.S1.ivi, 2021b.
Chevrel, M. O., Harris, A. J. L., Peltier, A., Villeneuve, N., Coppola, D., Gouhier, M. and Drenne, S.: Volcanic crisis management supported by near real time lava flow hazard assessment at Piton de la Fournaise, La Réunion, Volcanica, 5(2), 313–334, doi:10.30909/vol.05.02.313334, 2022.
Chevrel, M. O., Latchimy, T., Batier, L., Delpoux, R., Harris, M. and Kolzenburg, S.: A new portable field rotational viscometer for high-temperature melts, Rev. Sci. Instrum., 94, 105116, doi:10.1063/5.0160247, 2023a.
Chevrel, M. O., Villeneuve, N., Grandin, R., Froger, J.-L., Coppola, D., Massimetti, F., Campus, A. and Hrysiewicz, A.Peltier, A.: Report on the lava flow daily monitoring of the 19 September–05 October 2022 eruption at Piton de la Fournaise, Volcanica, 6(2), 391–404, doi:10.30909/vol.06.02.391404, 2023b.
Coppola, D., Laiolo, M., Cigolini, C., Delle Donne, D. and Ripepe, M.: Enhanced volcanic hot-spot detection using MODIS IR data: Results from the MIROVA system, in Detecting, Modelling and Responding to Effusive Eruptions, vol. 426, edited by A. J. L. Harris, T. De Groeve, F. Garel, and S. A. Carn, pp. 181–205, The Geological Society Special Publications, London., 2016.
Crisp, J., Cashman, K. v., Bonini, J. A., Hougen, S. B. and Pieri, D. C.: Crystallization history of the 1984 Mauna Loa lava flow, J. Geophys. Res., 99(B4), 7177–7198, doi:10.1029/93JB02973, 1994.
Davoine, P. and Saint-Marc, C.: A Geographical Information System for Mapping Eruption Risk at Piton de la Fournaise., in Active Volcanoes of the Southwest Indian Ocean. Active Volcanoes of the World., edited by P. Bachèlery, J.-F. Lénat, A. Di Muro, and L. Michon, Springer., 2016.
Dietterich, H. R., Downs, D. T., Stelten, M. E. and Zahran, H.: Reconstructing lava flow emplacement histories with rheological and morphological analyses: the Harrat Rahat volcanic field, Kingdom of Saudi Arabia, Bull. Volcanol., 80(12), doi:10.1007/s00445-018-1259-4, 2018.
Dingwell, D. B.: Viscosity-temperature relationships in the system Na2Si2O5-Na4Al2O5, Geochim. Cosmochim. Acta, 50, 1261–1265, doi:10.1016/0016-7037(86)90409-6, 1986.
Dingwell, D. B. and Virgo, D.: The effect of oxidation state on the viscosity of melts in the system Na2O-FeO-Fe2O3-SiO2, Geochim. Cosmochim. Acta, 51, 195–205, doi:10.1016/0016-7037(87)90231-6, 1987.
Dingwell, D. B. and Virgo, D.: Viscosities of melts in the NaO-FeO-Fe2O3-SiO2 system and factors controlling relative viscosities of fully polymerized silicate melts, Geochim. Cosmochim. Acta, 52, 395–403, doi:10.1016/0016-7037(88)90095-6, 1988.
Einarsson, T.: The flowing lava. Studies of its main physical and chemical properties., in The eruption of Hekla 1947-1948, vol. IV, pp. 1–70, Soc Scientiarum Islandica, Reykjavik., 1949.
Einarsson, T.: Studies of temperature, viscosity, density and some types of materials produced in the Surtsey eruption., 1966.
Favalli, M., Pareschi, M. T., Neri, A. and Isola, I.: Forecasting lava flow paths by a stochastic approach, Geophys. Res. Lett., 32(3), 1–4, doi:10.1029/2004GL021718, 2005.
Favalli, M., Chirico, G. D., Papale, P., Pareschi, M. T. and Boschi, E.: Lava flow hazard at Nyiragongo volcano, D.R.C. 1. Model calibration and hazard mapping, Bull. Volcanol., 71(4), 363–374,

doi:10.1007/s00445-008-0233-y, 2009.
Favalli, M., Tarquini, S., Papale, P., Fornaciai, A. and Boschi, E.: Lava flow hazard and risk at Mt. Cameroon volcano, Bull. Volcanol., 74(2), 423–439, doi:10.1007/s00445-011-0540-6, 2012.
Fink, J.: Surface folding and viscosity of rhyolite flows, Geology, 8(5), 250–254, doi:10.1130/0091-7613(1980)8<250:SFAVOR>2.0.CO;2, 1980.
Fink, J. H. and Griffiths, R. W.: A laboratory analog study of the morphology of lava flows extruded from point and line sources, J. Volcanol. Geotherm. Res., 54, 19–32, 1992.
Fink, J. H. and Zimbelman, J. R.: Rheology of the 1983 Royal Gardens basalt flows, Kilauea Volcano, Hawaii, Bull. Volcanol., 48, 87–96, doi:10.1007/BF01046544, 1986.
Di Fiore, F., Vona, A., Kolzenburg, S., Mollo, S. and Romano, C.: An Extended Rheological Map of Pāhoehoe—ʻAʻā Transition, J. Geophys. Res. Solid Earth, 126(7), 1–23, doi:10.1029/2021JB022035, 2021.
Di Fiore, F., Vona, A., Scarani, A., Giordano, G., Romano, C., Giordano, D., Caricchi, L., Martin Lorenzo, A., Rodriguez, F., Coldwell, B., Hernandez, P. and Pankhurst, M.: Experimental Constraints on the Rheology of Lavas From 2021 Cumbre Vieja Eruption (La Palma, Spain), Geophys. Res. Lett., 50(4), doi:10.1029/2022GL100970, 2023.
Flynn, I. T. W., Crown, D. A. and Ramsey, M. S.: Determining Emplacement Conditions and Vent Locations for Channelized Lava Flows Southwest of Arsia Mons, J. Geophys. Res. Planets, 127(11), doi:10.1029/2022JE007467, 2022.
Flynn, I. T. W., Chevrel, M. O. and Ramsey, M. S.: Adaptation of a thermorheological lava flow model for Venus conditions, J. Geophys. Res. Planets, doi:10.1029/2022je007710, 2023a.
Flynn, I. W., Chevrel, M. O. and Ramsey, M. S.: Adaptation of a Thermorheological Lava Flow Model for Venus Conditions, J. Geophys. Res. Planets, 128(7), doi:10.1029/2022je007710, 2023b.
Ganci, G., Vicari, A., Cappello, A. and Del Negro, C.: An emergent strategy for volcano hazard assessment: From thermal satellite monitoring to lava flow modeling, Remote Sens. Environ., 119, 197–207, doi:10.1016/j.rse.2011.12.021, 2012.
Ganci, G., Cappello, A., Bilotta, G. and Del Negro, C.: How the variety of satellite remote sensing data over volcanoes can assist hazard monitoring efforts: The 2011 eruption of Nabro volcano, Remote Sens. Environ., 236(September 2019), 111426, doi:10.1016/j.rse.2019.111426, 2020.
Gauthier, F.: Etude comparative des caractéristiques rhéologiques des laves basaltiques en laboratoire et sur le terrain, PhD, Univ. Paris-Sud, Fac. des Sci. d'Orsay, 1971.
Gauthier, F.: Field and laboratory studies of the rheology of Mount Etna lava, Philos. Trans. R. Soc. London A Math. Phys. Eng. Sci., 274(1238), 83–98, 1973.
Di Genova, D., Hess, K.-U., Chevrel, M. O. and Dingwell, D. B.: Models for the estimation of Fe3+/Fetotratio in terrestrial and extraterrestrial alkali- and iron-rich silicate glasses using Raman spectroscopy, Am. Mineral., 101(4), 943–952, 2016a.
Di Genova, D., Kolzenburg, S., Vona, A., Chevrel, M. O., Hess, K.-U., Neuville, D. R., Ertel-Ingrisch, W., Romano, C. and Dingwell, D. B.: Raman spectra of Martian glass analogues: A tool to approximate their chemical composition, J. Geophys. Res. Planets, 121(5), 740–752, doi:10.1002/2016JE005010, 2016b.
Ghiorso, M. S. and Sack, O.: Chemical mass transfer in magmatic processes IV. A revised and internally consistent thermodynamic model for the interpolation and extrapolation of liquid-solid equilibria in magmatic systems at elevated temperatures and pressures, Contrib. Miner. Pet., 119, 197–212, 1995.
Giordano, D., Polacci, M., Longo, A., Papale, P., Dingwell, D. B., Boschi, E. and Kasereka, M.: Thermo-rheological magma control on the impact of highly fluid lava flows at Mt. Nyiragongo, Geophys. Res. Lett., 34(L06301), 2007.
Glaze, L. S. and Baloga, S. M.: Rheologic inferences from the levees of lava flows on Mars, J. Geophys. Res. E Planets, 111(9), 1–10, doi:10.1029/2005JE002585, 2006.
Gottsmann, J., Giordano, D. and Dingwell, D. B.: Predicting shear viscosity during volcanic processes at the glass transition a calorimetric calibration, Earth Planet. Sci. Lett., 198, 417–427, doi:10.1016/S0012-821X(02)00522-8, 2002.
Gouhier, M., Guéhenneux, Y., Labazuy, P., Cacault, P., Decriem, J. and Rivet, S.: HOTVOLC: A web-based monitoring system for volcanic hot spots, in Detecting, Modelling and Responding to Effusive Eruptions, vol. 426, edited by A. J. L. Harris, T. De Groeve, F. Garel, and S. A. Carn,

pp. 223–241, The Geological Society Special Publications, London., 2016.
Gregg, T. K. P. and Fink, J. H.: Quantification of extraterrestrial lava flow effusion rates through laboratory simulations, J. Geophys. Res., 101(E7), 16891–16900, doi:10.1029/96JE01254, 1996.
Gregg, T. K. P. and Fink, J. H.: A laboratory investigation into the effects of slope on lava flow morphology, J. Volcanol. Geotherm. Res., 96, 145–159, doi:10.1016/S0377-0273(99)00148-1, 2000.
Hamon, C., Pereira, G., Chevrel, M. O., Aubry, L., Siebe, C., Quesada, O. and Reyes-Guzmán, N.: Present Use and Production of Metates and Molcajetes in Turícuaro (Michoacán, Mexico): Deciphering the Evolution of Food Preparation Practices, Ethnoarchaeology, 15(2), 208–232, doi:10.1080/19442890.2023.2280379, 2023.
Hamon, C., Pereira, G., Aubry, L., Chevrel, M. O., Siebe, C., Quezada, O. and Reyes-Guzmán, N.: Quarrying volcanic landscapes: territory and strategies of metate production in Turícuaro (Michoacán, México), Geofis. Int., 63(2), 929–948, doi:10.22201/igeof.2954436xe.2024.63.2.1760, 2024.
Harris, A., Mannini, S., Thivet, S., Chevrel, M. O., Gurioli, L., Villeneuve, N., Di Muro, A. and Peltier, A.: How shear helps lava to flow, Geology, 48(2), 154–158, doi:10.1130/g47110.1, 2020.
Harris, A., Mannini, S., Calabrò, L., Calvari, S., Gurioli, L., Chevrel, M. O., Favalli, M. and Villeneuve, N.: Forest destruction by ‘a‘ā lava flow during Etna’s 2002–03 eruption: Mechanical, thermal, and environmental interactions, J. Volcanol. Geotherm. Res., 429, 107621, doi:10.1016/j.jvolgeores.2022.107621, 2022a.
Harris, A. J. L.: Basaltic Lava Flow Hazard, in Volcanic Hazards, Risks, and Disasters., pp. 17–46., 2015.
Harris, A. J. L. and Allen, J. S.: One-, two- and three-phase viscosity treatments for basaltic lava flows, J. Geophys. Res., 113, B09212, doi:10.1029/2007JB005035, 2008.
Harris, A. J. L. and Rowland, S. K.: FLOWGO: a kinematic thermo-rheological model for lava flowing in a channel, Bull. Volcanol., 63, 20–44, doi:10.1007/s004450000120, 2001.
Harris, A. J. L. and Rowland, S. K.: FLOWGO 2012: An Updated Framework for Thermorheological Simulations of Channel-Contained Lava, Hawaiian Volcanoes From Source to Surface, Geophys. Monogr. 208, Eds, Carey R, Cayol V, Pol. M, Weis D, Am. Geophys. Union, 2015.
Harris, A. J. L., Flynn, L. P., Matias, O., Rose, W. I. and Cornejo, J.: The evolution of an active silicic lava flow field : an ETM + perspective, , 135, 147–168, doi:10.1016/j.jvolgeores.2003.12.011, 2004.
Harris, A. J. L., Favalli, M., Mazzarini, F. and Pareschi, M. T.: Best-fit results from application of a thermo-rheological model for channelized lava flow to high spatial resolution morphological data, Geophys. Res. Lett., 34, L01301, doi:10.1029/2006GL028126, 2007.
Harris, A. J. L., Favalli, M., Wright, R. and Garbeil, H.: Hazard assessment at Mount Etna using a hybrid lava flow inundation model and satellite-based land classification, Nat. Hazards, 58, 1001–1027, doi:10.1007/s11069-010-9709-0, 2011.
Harris, A. J. L., Rhéty, M., Gurioli, L., Villeneuve, N. and Paris, R.: Simulating the thermorheological evolution of channel-contained lava: FLOWGO and its implementation in EXCEL, in Detecting, Modelling and Responding to Effusive Eruptions., vol. 426, edited by A. J. L. Harris, T. De Groeve, F. Garel, and S. A. Carn, Geological Society, London, Special Publications., 2015.
Harris, A. J. L., Villeneuve, N., Di Muro, A., Ferrazzini, V., Peltier, A., Coppola, D., Favalli, M., Bachèlery, P., Froger, J.-L., Gurioli, L., Moune, S., Vlastélic, I., Galle, B. and Arellano, S.: Effusive crises at Piton de la Fournaise 2014-2015: a review of a multi-national response model, J. Appl. Volcanol., 6(1), 11, doi:10.1186/s13617-017-0062-9, 2017.
Harris, A. J. L., Chevrel, M. O., Coppola, D., Ramsey, M. S., Hrysiewicz, A., Thivet, S., Villeneuve, N., Favalli, M., Peltier, A., Kowalski, P., Muro, A. D., Froger, J.-L. and Gurioli, L.: Validation of an integrated satellite-data-driven response to an effusive crisis: The april-may 2018 eruption of piton de la fournaise, Ann. Geophys., 62(2 Special Issue), doi:10.4401/ag-7972, 2019a.
Harris, A. J. L., Chevrel, M. O., Coppola, D., Ramsey, M. S., Hrysiewicz, A., Thivet, S., Villeneuve, N., Favalli, M., Peltier, A., Kowalski, P., DiMuro, A., Froger, J.-L. and Gurioli, L.: Validation of an integrated satellite-data-driven response to an effusive crisis: the April–May 2018 eruption of Piton de la Fournaise., Ann. Geophys., 61, doi:10.4401/ag-7972, 2019b.

Harris, A. J. L., Rowland, S. K. and Chevrel, M. O.: The anatomy of a channel-fed ‘a‘ā lava flow system, Bull. Volcanol., 84(7), doi:10.1007/s00445-022-01578-0, 2022b.
Harris, M., Chevrel, M. O., Parsons, T., Latchimy, T., Thordarson, T., Höskuldsson, A., Moreland, M., Payet-Clerc, M. and Kolzenburg, S.: In-situ viscosity mapping of the 2023 Litli Hrútur lavas, Geology, Under revi, 16–20, 2024a.
Harris, M. A., Kolzenburg, S., Sonder, I. and Chevrel, M. O.: A new portable penetrometer for measuring the viscosity of active lava, Rev. Sci. Instrum., 95(6), 1–14, doi:10.1063/5.0206776, 2024b.
Hess, K.-U., Lavallée, Y., Castro, J., Noll, K., Mueller, S., Dingwell, D. B., Cameron, B. I., Spieler, O. and Fink, J. H.: Rheology of Obsidian Flow: Emplacement Controlled by Final Water Degassing?, EOS Trans. Am. Geophys. Union, 85(52), Fall Meeting Suppl. Abstract V53C-1584, 2005.
Hess, K. and Dingwell, D.: Viscosities of hydrous leucogranitic melts : A non-Arrhenian, Am. Mineral., 81, 1297–1300, doi:10.2138/am-1996-9-1031, 1996.
Hiesinger, H., Head, J. W. and Neukum, G.: Young lava flows on the eastern flank of Ascraeus Mons: Rheological properties derived from High Resolution Stereo Camera (HRSC) images and Mars Orbiter Laser Altimeter (MOLA) data, J. Geophys. Res., 112(E5), doi:10.1029/2006JE002717, 2007.
Hon, K., Gansecki, C. and Kauahikaua, J. P.: The transition from ’a’ā to pāhoehoe crust on flows emplaced during the Pu’u ’Ō’ō-Kūpaianaha eruption., USGS Prof. Pap. 1676, 89–103, doi:10.1016/0003-6870(73)90259-7, 2003.
Hulme, G.: The Interpretation of Lava Flow Morphology, Geophys. J. R. Astron. Soc., 39, 361–383, doi:10.1111/j.1365-246X.1974.tb05460.x, 1974.
Hulme, G., Fielder, G., Massey, H. S. W., Brown, G. M., Eglinton, G., Runcorn, S. K. and Urey, H. C.: Effusion rates and rheology of lunar lavas, Philos. Trans. R. Soc. London. Ser. A, Math. Phys. Sci., 285(1327), 227–234, doi:10.1098/rsta.1977.0059, 1977.
Hyman, D. M. R., Dietterich, H. R. and Patrick, M. R.: Toward Next-Generation Lava Flow Forecasting: Development of a Fast, Physics-Based Lava Propagation Model, J. Geophys. Res. Solid Earth, 127(10), e2022JB024998, doi:https://doi.org/10.1029/2022JB024998, 2022.
Ishibashi, H.: Non-Newtonian behavior of plagioclase- bearing basaltic magma: subliquidus viscosity measurement of the 1707 basalt of Fuji volcano, Japan, J. Volcanol. Geoth. Res., 181, 78–88, doi:10.1016/j.jvolgeores.2009.01.004, 2009.
Ishibashi, H. and Sato, H.: Viscosity measurements of subliquidus magmas: Alkali olivine basalt from the Higashi-Matsuura district, Southwest Japan, J. Volcanol. Geotherm. Res., 160(3–4), 223–238, doi:10.1016/j.jvolgeores.2006.10.001, 2007.
James, M. R., Pinkerton, H. and Robson, S.: Image-based measurement of flux variation in distal regions of active lava flows, Geochemistry, Geophys. Geosystems, 8(3), doi:10.1029/2006GC001448, 2007.
Jeffreys, H.: The flow of water in an inclined channel of rectangular section, Philos. Mag., serie 6, 4, 293,793-807, 1925.
Kauahikaua, J. P.: Lava flow hazard assessment, as of August 2007, for Kilauea east rift zone eruptions, Hawaii island, U.S. Geol. Surv. Open-File Rep. 2007-1264, (August), 9 p [online] Available from: http://www.usgs.gov/pubprod, 2007.
Kauahikaua, J. P., Orr, T., Patrick, M. R. and Trusdell, F.: Steepest-Descent Lines for Kīlauea, Mauna Loa, Hualālai, and Mauna Kea Volcanoes, Hawai‘i, U.S. Geol. Surv. data release, doi:10.5066/F7FJ2DX0, 2017.
Kelfoun, K. and Vargas, S. V.: VolcFlow capabilities and potential development for the simulation of lava flows, in Detecting, Modelling and Responding to Effusive Eruptions, vol. 426, edited by A. J. L. Harris, T. De Groeve, F. Garel, and S. A. Carn, pp. 337–343, Geological Society, London., 2016.
Kerr, R. C. and Lyman, A. W.: Importance of surface crust strength during the flow of the 1988-1990 andesite lava of Lonquimay Volcano, Chile, J. Geophys. Res., 112, B03209, doi:10.1029/2006JB004522, 2007.
Keszthelyi, L.: On the Thermal Budget of Pahoehoe Lava Flows, , 274, 1994.
Kilburn, C. R. J. and Lopes, R. M. C.: General patterns of flow field growth: `A`a and blocky lavas, J.

Geophys. Res., 96(B12), 19721–19732, doi:10.1029/91jb01924, 1991.
Knudson, J. G. and Katz, D. L.: Fluid dynamics, heat transfer, McGraw-Hill, 81–82, 1958.
Kolzenburg, S., Giordano, D., Cimarelli, S. and Dingwell, D. B.: In situ thermal characterization of cooling/crystallizing lavas during rheology measurements and implications for lava flow emplacement, Geochim. Cosmochim. Acta, 195, 244–258, doi:10.1016/j.gca.2016.09.022, 2016.
Kolzenburg, S., Giordano, D., Thordarson, T., Hoskuldsson, A. and Dingwell, D. B.: The rheological evolution of the 2014/2015 eruption at Holuhraun, central Iceland, Bull. Volcanol., 79(45), doi:10.1007/s00445-017-1128-6, 2017.
Kolzenburg, S., Giordano, D., Di Muro, A. and Dingwell, D.: Equilibrium Viscosity and Disequilibrium Rheology of a high Magnesium Basalt from Piton De La Fournaise volcano, La Reunion, Indian Ocean, France, Ann. Geophys., 61(Vol 61 (2018)), AC18, doi:10.4401/ag-7839, 2018a.
Kolzenburg, S., Di Genova, D., Giordano, D., Hess, K.-U. and Dingwell, D. B.: The effect of oxygen fugacity on the rheological evolution of crystallizing basaltic melts, Earth Planet. Sci. Lett., 487, 21–32, doi:10.1016/j.epsl.2018.01.023, 2018b.
Kolzenburg, S., Hess, K. U., Berlo, K. and Dingwell, D. B.: Disequilibrium Rheology and Crystallization Kinetics of Basalts and Implications for the Phlegrean Volcanic District, Front. Earth Sci., 8(June), doi:10.3389/feart.2020.00187, 2020.
Kolzenburg, S., Chevrel, M. O. and Dingwell, D.: Magma suspension rheology, Rev. Mineral. Geochemitry, 87(1), 639–720 [online] Available from: http://dx.doi.org/10.2138/rmg.2020.86.X, 2022.
Krauskopf, K. B.: Lava Mouvemement at Paricutin Volcano, Mexico, Geol. Soc. Am. Bull., 12, 1267–1284, 1948.
Latutrie, B., Harris, A., Médard, E. and Gurioli, L.: Eruption and emplacement dynamics of a thick trachytic lava flow of the Sancy volcano (France), Bull. Volcanol., 79(1), 1–21, doi:10.1007/s00445-016-1084-6, 2017.
Lejeune, A. M., Bottinga, Y., Trull, T. W. and P., R.: Rheology of bubble-bearing magmas, Earth Planet. Sci. Lett. Sci. Lett., 166, 71–84, 1999.
Lev, E. and James, M. R.: The influence of cross-sectional channel geometry on rheology and flux estimates for active lava flows, , doi:10.1007/s00445-014-0829-3, 2014.
Lev, E., Hamilton, C. W., Voigt, J. R. C., Stadermann, A. C., Zhan, Y. and Neish, C. D.: Emplacement conditions of lunar impact melt flows, Icarus, 369(July), 114578, doi:10.1016/j.icarus.2021.114578, 2021.
Lin, J. W. B.: Why Python is the next wave in earth sciences computing, Bull. Am. Meteorol. Soc., 93, 1823–1824, doi:10.1175/BAMS-D-12-00148.1, 2011.
Llewellin, E. W. and Manga, M.: Bubble suspension rheology and implications for conduit flow, J. Volcanol. Geotherm. Res., 143, 205–217, doi:10.1016/j.jvolgeores.2004.09.018, 2005.
Llewellin, E. W., Mader, H. M. and Wilson, S. D. R.: The rheology of a bubbly liquid, Proceding R. Soc. London, 458, 987–1016, doi:10.1098/rspa.2001.0924, 2002.
Lyman, A. W., Koenig, E. and Fink, J. H.: Predicting yield strengths and effusion rates of lava domes from morphology and underlying topography, J. Volcanol. Geotherm. Res., 129(1–3), 125–138, doi:10.1016/S0377-0273(03)00236-1, 2004.
Mader, H. M., Llewellin, E. W. and Mueller, S. P.: The rheology of two-phase magmas: A review and analysis, Bull. Volcanol., 257, 135–158, doi:10.1016/j.jvolgeores.2013.02.014, 2013.
Magnall, N., James, M. R., Tuffen, H. and Vye-Brown, C.: Emplacing a Cooling-Limited Rhyolite Lava Flow: Similarities with Basaltic Lava Flows, Front. Earth Sci., 5(June), doi:10.3389/feart.2017.00044, 2017.
Mahgoub, A. N., Böhnel, H., Siebe, C. and Chevrel, M. O.: Paleomagnetic study of El Metate shield volcano (Michoacán, Mexico) confirms its monogenetic nature and young age (~ 1250 CE), J. Volcanol. Geotherm. Res., 336, 209–218, doi:10.1016/j.jvolgeores.2017.02.024, 2017.
Meredith, E. S., Jenkins, S. F., Hayes, J. L., Deligne, N. I., Lallemant, D., Patrick, M. and Neal, C.: Damage assessment for the 2018 lower East Rift Zone lava flows of Kīlauea volcano, Hawai'i, Bull. Volcanol., 84(7), doi:10.1007/s00445-022-01568-2, 2022.
Moore, H. J.: Preliminary estimates of the rheological properties of 1984 Mauna Loa Lava, U.S. Geol. Surv. Prof. Pap. 1350, 99, 1569–1588, 1987.

Moore, H. J., Arthur, D. W. G. and Schaber, G. G.: Yield strengths of flows on the Earth, Mars, and Moon, Proc. Lunar Planet. Sci. Conf. 9th, 3351–3378, 1978.
Morrison, A., Whittington, A., Smets, B., Kervyn, M. and Sehlke, A.: The rheology of crystallizing basaltic lavas from Nyiragongo and Nyamuragira volcanoes, D.R.C., Volcanica, 3(1), 1–28, doi:10.30909/vol.03.01.0128, 2020.
Morrison, A. A., Zanetti, M., Hamilton, C. W., Lev, E., Neish, C. D. and Whittington, A. G.: Rheological investigation of lunar highland and mare impact melt simulants, Icarus, 317(June 2018), 307–323, doi:10.1016/j.icarus.2018.08.001, 2019.
Mossoux, S., Saey, M., Bartolini, S., S., P., Canters, F. and Kervyn, M.: Q-LAVHA: A flexible GIS plugin to simulate lava flows, Comput. Geosci., 97, 98–109, doi:10.1016/j.cageo.2016.09.003, 2016.
Di Muro, A., Bachèlery, P., Boissier, P., Davoine, P., Fadda, P., Favalli, M., Ferrazzini, V., Finizola, A., Leroi, G., Levieux, G., Mairine, P., Manta, F., Michon, L., Morandi, R., Nave, R., Peltier, A., Principe, C., Ricci, T., Roult, G., Saint-Marc, C., Staudacher, T. and Villeneuve, N.: Evaluation de l'aléa volcanique à La Réunion. [online] Available from: http://www.reunion.developpement-durable.gouv.fr/IMG/pdf/Rapport_1erephase_etude_volcan_web_cle534456.pdf, 2012.
Nave, R., Ricci, T. and Pacilli, M. G.: Perception of Risk for Volcanic Hazard in Indian Ocean: La Réunion Island Case Study, in Active Volcanoes of the Southwest Indian Ocean: Piton de la Fournaise and Karthala, edited by P. Bachelery, J.-F. Lenat, A. Di Muro, and L. Michon, pp. 315–326, Springer Berlin Heidelberg, Berlin, Heidelberg., 2016.
Neal, C. A., Brantley, S. R., Antolik, L., Babb, J. L., Burgess, M., Calles, K., Cappos, M., Chang, J. C., Conway, S., Desmither, L., Dotray, P., Elias, T., Fukunaga, P., Fuke, S., Johanson, I. A., Kamibayashi, K., Kauahikaua, J., Lee, R. L., Pekalib, S., Miklius, A., Million, W., Moniz, C. J., Nadeau, P. A., Okubo, P., Parcheta, C., Patrick, M. R., Shiro, B., Swanson, D. A., Tollett, W., Trusdell, F., Younger, E. F., Zoeller, M. H., Montgomery-Brown, E. K., Anderson, K. R., Poland, M. P., Ball, J. L., Bard, J., Coombs, M., Dietterich, H. R., Kern, C., Thelen, W. A., Cervelli, P. F., Orr, T., Houghton, B. F., Gansecki, C., Hazlett, R., Lundgren, P., Diefenbach, A. K., Lerner, A. H., Waite, G., Kelly, P., Clor, L., Werner, C., Mulliken, K., Fisher, G. and Damby, D.: The 2018 rift eruption and summit collapse of Kīlauea Volcano, Science (80-.)., 363(6425), 367–374, doi:10.1126/science.aav7046, 2019.
Del Negro, C., Cappello, A., Neri, M., Bilotta, G., Herault, A. and Ganci, G.: Lava flow hazards at Mount Etna : constraints imposed by eruptive history and numerical simulations, Scentific Reports, 3(3493), 1–8, doi:10.1038/srep03493, 2013.
Nichols, R. L.: Viscosity of Lava, J. Geol., 47(3), 290–302, 1939.
Norton, G. and Pinkerton, H.: Rheological properties of natrocarbonatite lavas from Oldoinyo Lengai, Tanzania, Eur. J. Mineral., 9, 351–364, doi:10.1127/ejm/9/2/0351, 1997.
Panov, V. K., Slezin, Y. B. and Storcheus, A. V: Mechanical properties of lavas extruded in the 1983 Predskazannyi eruption (Klyuchevskoy volcano), Volcanol. Seismol., 7, 25–37, 1988.
Pareschi, M. T., Cavarra, L., Favalli, M., Giannini, F. and Meriggi, A.: GIS and volcanic risk management, Nat. Hazards, 21(2–3), 361–379, doi:10.1023/a:1008016304797, 2000.
Paterson, M. S. and Olgaard, D. L.: Rock deformation tests to large shear strains in torsion, J. Struct. Geol., 22(9), 1341–1358, doi:10.1016/S0191-8141(00)00042-0, 2000.
Peltier, A., Ferrazzini, V., Di Muro, A., Kowalski, P., Villeneuve, N., Richter, N., Chevrel, M. O., Froger, J.-L., Hrysiewicz, A., Gouhier, M., Coppola, D., Retailleau, L., Beauducel, F., Gurioli, L., Boissier, P., Brunet, C., Catherine, P., Fontaine, F., Lauret, F., Garavaglia, L., Lebreton, J., Canjamale, K., Desfete, N., Griot, C., Harris, A. J. L., Arellano, S., Liuzzo, M., Guerrieri, S. and Ramsey, M. S.: Volcano Crisis Management at Piton de la Fournaise (La Réunion) during the COVID-19 Lockdown, Seismol. Res. Lett., 92(1), 38–52, doi:https://doi.org/10.1785/0220200212, 2021.
Peltier, A., Chevrel, M. O., Harris, A. J. L. and Villeneuve, N.: Reappraisal of gap analysis for effusive crises at Piton de la Fournaise, J. Appl. Volcanol., 11(1), 1–17, doi:10.1186/s13617-021-00111-w, 2022.
Phan-Thien, N. and Pham, D. C.: Differential multiphase models for polydispersed suspensions and particulate solids, J. Nonnewton. Fluid Mech., 72, 305–318, doi:10.1016/S0377-0257(97)90002-1, 1997.

Pinkerton, H.: Methods of Measuring the Rheological Properties of Lava, University of Lancaster., 1978.
Pinkerton, H.: Rheological and related properties of lavas, in Etna: Magma and lava flow modeling and volcanic system definition aimed at hazard assessment., edited by F. Dobran, pp. 76–89, Global Volcanic And Environmental System Simulation., 1994.
Pinkerton, H. and Norton, G.: Rheological properties of basaltic lavas at sub-liquidus temperatures: laboratory and field measurements on lavas from Mount Etna, J. Volcanol. Geotherm. Res., 68, 307–323, doi:10.1016/0377-0273(95)00018-7, 1995.
Pinkerton, H. and Sparks, R. S. J.: The 1975 sub-terminal lavas, mount etna: a case history of the formation of a compound lava field, J. Volcanol. Geotherm. Res., 1, 167–182, doi:10.1016/0377-0273(76)90005-6, 1976.
Pinkerton, H. and Sparks, R. S. J.: Field measurements of the rheology of lava, Nature, 276, 383–385, doi:10.1038/276383a0, 1978.
Pinkerton, H. and Wilson, L.: Factor controlling the lengths of channel-fed lava flows, Bull. Volcanol., 6, 108–120, doi:10.1007/BF00304106, 1994.
Pinkerton, H., Herd, R. A., Kent, R. M. and Wilson, L.: Field measurements of the rheological properties of basaltic lavas, Lunar Planet. Sci., XXVI, 1127–1128, 1995a.
Pinkerton, H., Norton, G. E., Dawson, J. B. and Pyle, D. M.: Field observations and measurements of the physical properties of Oldoinyo Lengai alkali carbonatite lavas, November 1988, in IAVCEI Proceedings in Volcanology 4. Carbonatite volcanism of Oldoinyo Lengai - petrogenesis of natrocarbonatite., edited by K. Bell and J. Keller, pp. 23–36, Springer-Verlag, Berlin., 1995b.
Pistone, M., Caricchi, L., Ulmer, P., Burlini, L., Ardia, P., Reusser, E., Marone, F. and L., A.: Deformation experiments of bubble- and crystal-bearing magmas: Rheological and microstructural analysis, J. Geophys. Res., 117, B05208, doi:10.1029/2011JB008986, 2012.
Polacci, M., Cashman, K. V. and Kauahikaua, J. P.: Textural characterization of the pahoehoe-'a'a transition in Hawaiian basalt, Bull. Volcanol., 60(8), 595–609, doi:10.1007/s004450050254, 1999.
Poland, M., Orr, T. R., Kauahikaua, J. P., Brantley, S. R., Babb, J. L., Patrick, M. R., Neal, C. A., Anderson, K. R., Antolik, L. and Burgess, M.: The 2014–2015 Pāhoa lava flow crisis at Kīlauea Volcano, Hawai 'i: Disaster avoided and lessons learned, GSA Today, 26(2), 4–10, doi:10.1130/GSATG262A.1.4, 2016.
Prival, J.-M., Harris, A. J. L., Zanella, E., Robustelli Test, C., Gurioli, L., Chevrel, M. O. and Biren, J.: Emplacement dynamics of a crystal-rich, highly viscous trachytic flow of the Sancy stratovolcano, France, GSA Bull., doi:10.1130/B36415.1, 2022.
Putirka, K.: Thermometers and Barometers for Volcanic Systems, Putirka, K., Tepley, F. (Eds.), Miner. Inclusions Volcan. Process. Rev. Mineral. Geochemistry, Mineral. Soc. Am., 69, 61–120, 2008.
Ramírez-Uribe, I., Siebe, C., Chevrel, M. O. and Fisher, C. T.: Rancho Seco monogenetic volcano (Michoacán, Mexico): Petrogenesis and lava flow emplacement based on LiDAR images, J. Volcanol. Geotherm. Res., 411, doi:10.1016/j.jvolgeores.2020.107169, 2021.
Ramírez-Uribe, I., Siebe, C., Chevrel, M. O., Ferres, D. and Salinas, S.: The late Holocene Nealtican lava-flow field, Popocatépetl volcano, central Mexico: Emplacement dynamics and future hazards, GSA Bull., 134(11–12), 2745–2766, doi:10.1130/B36173.1, 2022.
Ramsey, M., Chevrel, M. O., Coppola, D. and Harris, A. J. L.: The influence of emissivity on the thermo-rheological modeling of the channelized lava flows at Tolbachik volcano, Ann. Geophys., 61(Vol 61 (2018)), AC69, doi:10.4401/ag-8077, 2019.
Ramsey, M. S., Harris, A. J. L. and Crown, D. A.: What can thermal infrared remote sensing of terrestrial volcanoes tell us about processes past and present on Mars?, J. Volcanol. Geotherm. Res., 311, 198–216, doi:https://doi.org/10.1016/j.jvolgeores.2016.01.012, 2016.
Ramsey, M. S., Harris, A. J. L. and Watson, I. M.: Volcanology 2030: will an orbital volcano observatory finally become a reality?, Bull. Volcanol., 84(1), 1–8, doi:10.1007/s00445-021-01501-z, 2022.
Reyes-Guzmán, N., Siebe, C., Chevrel, M. O., Guilbaud, M. N., Salinas, S. and Layer, P.: Geology and radiometric dating of Quaternary monogenetic volcanism in the western Zacapu lacustrine basin (Michoacán, México): implications for archeology and future hazard evaluations, Bull. Volcanol., 80(18), 1–20, doi:10.1007/s00445-018-1193-5, 2018.

Reyes-Guzmán, N., Siebe, C., Chevrel, M. O. and Pereira, G.: Late Holocene Malpaís de Zacapu (Michoacán, Mexico) andesitic lava flows: rheology and eruption properties based on LiDAR image, Bullettin Volcanol., 83(28), doi:10.1007/s00445-021-01449-0, 2021.
Reyes-Guzmán, N., Siebe, C., Chevrel, M. O., Pereira, G., Mahgoub, A. N. and Böhnel, H.: Holocene volcanic eruptions of the Malpaís de Zacapu and its pre-Hispanic settlement history, Anc. Mesoamerica, 1759(February 1943), 1–16, doi:10.1017/s095653612100050x, 2023.
Rhéty, M., Harris, A. J. L., Villeneuve, N., Gurioli, L., Médard, E., Chevrel, M. O. and Bachèlery, P.: A comparison of cooling-limited and volume-limited flow systems: Examples from channels in the Piton de la Fournaise April 2007 lava-flow field, Geochemistry, Geophys. Geosystems, 18(9), 3270–3291, doi:10.1002/2017GC006839, 2017.
Richter, N., Favalli, M., De Zeeuw-Van Dalfsen, E., Fornaciai, A., Da Silva Fernandes, R. M., Pérez, N. M., Levy, J., Victória, S. S. and Walter, T. R.: Lava flow hazard at Fogo Volcano, Cabo Verde, before and after the 2014-2015 eruption, Nat. Hazards Earth Syst. Sci., 16(8), 1925–1951, doi:10.5194/nhess-16-1925-2016, 2016.
Riker, J. M., Cashman, K. V, Kauahikaua, J. P. and Montierth, C. M.: The length of channelised lava flows: insight from the 1859 eruption of Mauna Loa Volcano, Hawaii, J. Volcanol. Geotherm. Res., 183, 139–156, doi:10.1016/j.jvolgeores.2009.03.002, 2009.
Robert, B., Harris, A., Gurioli, G., Médard, E., Sehlke, A. and Whittington, A.: Textural and rheological evolution of basalt flowing down a lava channel, Bull. Volcanol., 76, 824, doi:10.1007/s00445-014-0824-8, 2014.
Rose, W. I.: Pattern and mechanism of volcanic activity at the Santiaguito Volcanic Dome, Guatemala, Bull. Volcanol., 37(1), 73–94, doi:10.1007/BF02596881, 1973.
Rowland, S. K., Harris, A. J. L., Wooster, M. J., Amelung, F., Garbeil, H., Wilson, L. and Mouginis-Mark, P. J.: Volumetric characteristics of lava flows from interferometric radar and multispectral satellite data: The 1995 Fernandina and 1998 Cerro Azul eruptions in the western Galápagos, Bull. Volcanol., 65(5), 311–330, doi:10.1007/s00445-002-0262-x, 2003.
Rowland, S. K., Harris, A. J. L. and Garbeil, H.: Effects of Martian conditions on numerically modeled, cooling-limited, channelized lava flows, J. Geophys. Res., 109, E100101, doi:doi.org/10.1029/2004JE002288, 2004.
Rowland, S. K., Garbeil, H. and Harris, A. J. L.: Lengths and hazards from channel-fed lava flows on Mauna Loa, Hawaii, determined from thermal and downslope modeling with FLOWGO, Bull. Volcanol., 67, 634–647, doi:https://doi.org/10.1007/s00445-004-0399-x, 2005.
Russell, J. K., Hess, K.-U. and Dingwell, D. B.: Models for Viscosity of Geological Melts, Rev. Mineral. Geochemistry, 87(1), 841–885, doi:10.2138/rmg.2022.87.18, 2022.
Rust, A. C. and Manga, M.: Bubble shapes and orientations in low Re simple shear flow, Jounal Colloid Interface Sci., 249, 476–480, 2002.
Ryerson, F. J., Weed, H. C. and Piwinskii, A. J.: Rheology of subliquidus magmas, 1. Picritic compositions, J. Geophys. Res., v. 93(B5), 3421–3436, doi:10.1029/JB093iB04p03421, 1988.
Sato, H.: Viscosity measurement of subliquidus magmas: 1707 basalt of Fuji volcano, J. Mineral. Petrol. Sci., 100, 133–142, doi:10.2465/jmps.100.133, 2005.
Sehlke, A. and Whittington, A. G.: The viscosity of planetary tholeiitic melts: A configurational entropy model, Geochim. Cosmochim. Acta, 191, 277–299, doi:10.1016/j.gca.2016.07.027, 2016.
Sehlke, A., Whittington, A., Robert, B., Harris, A. J. L., Gurioli, L. and Médard, E.: Pahoehoe to \`a\`a transition of Hawaiian lavas: an experimental study, Bull. Volcanol., 76, 876, doi:10.1007/s00445-014-0876-9, 2014.
Shaw, H. R.: Rheology of basalt in the melting range, J. Petrol., 10, 510–535, 1969.
Shaw, H. R., Wright, T. L., Peck, D. L. and Okamura, R.: The Viscosity of Basaltic Magma: An analysis of Field Measurements in Makaopuhi Lava Lake, Hawaii, Am. J. Sci., 266, 225–264, 1968.
Shea, T., Houghton, B. F., Gurioli, L., Cashman, K. V., Hammer, J. E. and Hobden, B. J.: Textural studies of vesicles in volcanic rocks: An integrated methodology, J. Volcanol. Geotherm. Res., 190(3–4), 271–289, doi:10.1016/j.jvolgeores.2009.12.003, 2010.
Snyder, D.: Cooling of lava flows on Venus: The coupling of radiative and convective heat transfer, J. Geophys. Res. Planets, 107(10), 1–8, doi:10.1029/2001je001501, 2002.
Soldati, A., Sehlke, A., Chigna, G. and Whittington, A.: Field and experimental constraints on the rheology of arc basaltic lavas: the January 2014 Eruption of Pacaya (Guatemala), Bull.

Volcanol., 78(43), doi:10.1007/s00445-016-1031-6, 2014.
Sparks, R. S. J. and Pinkerton, H.: Effect of degassing on rheology of basaltic lava, Nature, 276, 385–386, doi:10.1016/j.earscirev.2012.10.007, 1978.
Spera, F. J., Borgia, A., Strimple, J. and Feigenson, M.: Rheology of melts and magmatic suspensions I. Design and calibration of a concentric cylinder viscometer with application to rhyolitic magma, J. Geophys. Res., 93, 10273–10294, doi:10.1029/JB093iB09p10273, 1988.
Stein, D. J. and Spera, F. J.: Rheology and microstructure of magmatic emulsions: Theory and experiments, J. Volcanol. Geotherm. Res., 49(1–2), 157–174, doi:10.1016/0377-0273(92)90011-2, 1992.
Stein, D. J. and Spera, F. J.: Shear viscosity of rhyolite-vapor emulsions at magmatic temperatures by concentric cylinder rheometry, J. Volcanol. Geotherm. Res., 113, 243–258, doi:10.1016/S0377-0273(01)00260-8, 2002.
Tadini, A., Harris, A., Morin, J., Bevilacqua, A., Peltier, A., Aspinall, W., Ciolli, S., Bachèlery, P., Bernard, B., Biren, J., da Silveira, A., Cayol, V., Chevrel, M. O., Coppola, D., Dietterich, H., Donovan, A., Dorado, O., Drenne, S., Dupéré, O., Gurioli, L., Kolzenburg, S., Komorowski, J. C., Labazuy, P., Mangione, D., Mannini, S., Martel-Asselin, F., Médard, E., Pialot-Bonnétat, S., Rafflin, V., Ramsey, M., Richter, N., Vallejo, S., Villeneuve, N. and Zafrilla, S.: Structures elicitation of expert judgement in real-time eruption scenarios : an exercise for Piton de la Fournaise volcano, La Réunion island, Volcanica, 5, 105–131, doi:10.30909/vol.05.01.105131, 2022.
Tarquini, S. and Favalli, M.: Uncertainties in lava flow hazard maps derived from numerical simulations: The case study of Mount Etna, J. Volcanol. Geotherm. Res., 260, 90–102, doi:https://doi.org/10.1016/j.jvolgeores.2013.04.017, 2013.
Tedesco, D., Vaselli, O., di Geofisica e Vulcanologia, I., Pisa, S., Pisa, , Italia, , Carn, S., Voltaggio, M., Sawyer, G., Volcano Observatory, G., Goma, M., Goma, , and Tassi, F.: January 2002 volcano-tectonic eruption of Nyiragongo volcano, Democratic Republic of Congo, J. Geophys. Res., 112, doi:10.1029/2006JB004762, 2007.
Thompson, J. O. and Ramsey, M. S.: The influence of variable emissivity on lava flow propagation modeling, Bull. Volcanol., 83(6), 1–19, doi:10.1007/s00445-021-01462-3, 2021.
Thompson, M. A., Lindsay, J. M. and Gaillard, J. C.: The influence of probabilistic volcanic hazard map properties on hazard communication, J. Appl. Volcanol., 4(1), doi:10.1186/s13617-015-0023-0, 2015.
Vaucher, J., Baratoux, D., Toplis, M. J., Pinet, P., Mangold, N. and Kurita, K.: The morphologies of volcanic landforms at Central Elysium Planitia: Evidence for recent and fluid lavas on Mars, Icarus, 200(1), 39–51, doi:10.1016/j.icarus.2008.11.005, 2009.
Verdurme, P., Le Losq, C., Chevrel, M. O., Pannefieu, S., Médard, E., Berthod, C., Komorowski, J., Bachèlery, P., Neuville, D. and Gurioli, L.: Viscosity of crystal-free silicate melts from the active submarine volcanic chain of Mayotte, Chem. Geol., 620(January), doi:10.1016/j.chemgeo.2023.121326, 2023.
Verdurme, P., Gurioli, L., Chevrel, M. O., Médard, E., Berthod, C., Komorowski, J. C., Harris, A., Paquet, F., Cathalot, C., Feuillet, N., Lebas, E., Rinnert, E., Donval, J. P., Thinon, I., Deplus, C. and Bachèlery, P.: Magma ascent and lava flow field emplacement during the 2018–2021 Fani Maoré deep-submarine eruption insights from lava vesicle textures, Earth Planet. Sci. Lett., 636(January), doi:10.1016/j.epsl.2024.118720, 2024a.
Verdurme, P., Chevrel, M. O., Gurioli, L., Médard, E., Berthod, C., Komorowski, J.-C. and Bachèrely, P.: Textural and rheological evolution of deep submarine lava flow emplacement at Fani Maoré volcano, J. Geophys. Res. Earth, submitted, doi:10.5194/egusphere-egu23-5594, 2024b.
Vetere, F., Sato, H., Ishibashi, H., De Rosa, R., Donato, P., Ishebashi, H., De Rosa, R. and Donato, P.: Viscosity changes during crystallization of a shoshonitic magma: new insights on lava flow emplacement, J. Mineral. Petrol. Sci., 108(3), 144–160, doi:10.2465/jmps.120724, 2013.
Vetere, F., Rossi, S., Namur, O., Morgavi, D., Misiti, V., Mancinelli, P., Petrelli, M., Pauselli, C. and Perugini, D.: Experimental constraints on the rheology, eruption, and emplacement dynamics of analog lavas comparable to Mercury's northern volcanic plains, J. Geophys. Res. Planets, 122(7), 1522–1538, doi:10.1002/2016JE005181, 2017.
Vetere, F., Mazzeo, A., Perugini, D. and Holtz, F.: Viscosity behaviour of silicate melts during cooling

under variable shear rates, J. Non. Cryst. Solids, 533(January), 119902, doi:10.1016/j.jnoncrysol.2020.119902, 2020.
Vicari, A., Bilotta, G., Bonfiglio, S., Cappello, A., Ganci, G., H??rault, A., Rustico, E., Gallo, G. and Del Negro, C.: Lav@hazard: A web-gis interface for volcanic hazard assessment, Ann. Geophys., 54(5), 662–670, doi:10.4401/ag-5347, 2011.
Villeneuve, N.: Apports multi-sources à une meilleure compréhension de la mise en place des coulées de lave et des risques associés au Piton de la Fournaise: Géomorphologie quantitative en terrain volcanique., Institut de Physique du Globe de Paris., 2000.
Vona, A. and Romano, C.: The effects of undercooling and deformation rates on the crystallization kinetics of Stromboli and Etna basalts, Contrib. to Mineral. Petrol., 166(2), 491–509, doi:10.1007/s00410-013-0887-0, 2013.
Vona, A., Romano, C., Dingwell, D. B. and Giordano, D.: The rheology of crystal-bearing basaltic magmas from Stromboli and Etna, Geochim. Cosmochim. Acta, (75), 3214–3236, 2011.
Walker, D., Kirkpatrick, R. J., Longhi, J. and Hays, J. F.: Crystallization history of lunar picritic basalt sample 12002: Phase-equilibria and cooling-rate studies, GSA Bull., 87(5), 646–656, doi:10.1130/0016-7606(1976)87<646:CHOLPB>2.0.CO;2, 1976.
Walker, G. P. L.: Lengths of lava flows, Philos. Trans. R. Soc. London, 274, 107–118, 1973.
Wantim, M. N., Kervyn, M., Ernst, G. G. J., del Marmol, M. A., Suh, C. E. and Jacobs, P.: Numerical experiments on the dynamics of channelised lava flows at Mount Cameroon volcano with the FLOWGO thermo-rheological model, J. Volcanol. Geotherm. Res., 253, 35–53, doi:10.1016/j.jvolgeores.2012.12.003, 2013.
Wilson, L. and Head, J. W.: Mars Review and Analysis of Volcanic eruption theory and relationships to observed landforms, Rev. Geophys., 32(3), 221–263, doi:10.1029/94RG01113, 1994.
Wilson, L., Pinkerton, H. and Macdonald, R.: Physical processes in volcanic eruptions, Annu. Rev. Earth Planet. Sci., 15, 73–95, doi:10.1146/annurev.ea.15.050187.000445, 1987.
Wilson, L., Mouginis-Mark, P. J., Tyson, S., Mackown, J. and Garbeil, H.: Fissure eruptions in Tharsis, Mars Implications for eruption conditions and magma sources, J. Volcanol. Geotherm. Res., 185, 28–46, 2009.
Wright, R., Garbeil, H. and Harris, A. J. L.: Using infrared satellite data to drive a thermo-rheological/stochastic lava flow emplacement model: A method for near-real-time volcanic hazard assessment, Geophys. Res. Lett., 35(19), 1–5, doi:10.1029/2008GL035228, 2008.
Zimbelman, J. R.: Estimates od rheologic Properties for Flows on the Martian Volcano Ascraeus Mons, J. Geophys. Res., 90, D157, D162, doi:10.1029/JB090iS01p00157, 1985.
Zimbelman, J. R.: Emplacement of long lava flows on planetary surfaces, J. Geophys. Res., 103(B11), 27,503-527,516, doi:10.1029/98JB01123, 1998.

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