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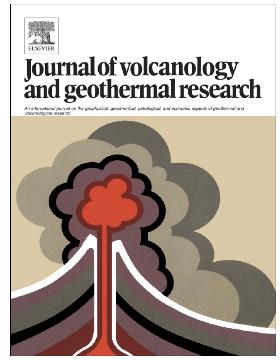


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# Dating young (<1000 yrs) lava flow eruptions of Piton de la Fournaise volcano from size distribution of long-lived pioneer trees

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## Abstract

Dating recent lava flows is a critical issue to assess the volcanic hazards for nearby human populations, but traditional methods such as radiocarbon dating are often not applicable. We propose here a simple statistical method that relates the age of lava flows of the Piton de la Fournaise volcano (PdF) to the size of *Agarista salicifolia* (Ericaceae), a long-lived pioneer tree that quickly establishes after eruption and able to live more than 600 years. We measured the diameter at base of 711 trees on 20 dated lava flows (between 1401 CE and 2007 CE). We used a log-log linear model to assess the relationship between maximum diameter at base of *Agarista salicifolia* and the age of lava flows, and. showed a very strong correlation ($R^2$= 0.987, p< 2.2e-16). We then used this calibrated model to estimate the age of 11 lava flows between 1447 CE (CI: 1349-1531) and 1823 CE (CI: 1806-1839). These new ages, combined with existing radiocarbon ages and historical records, indicate three clusters of eruptions (1460-1630, 1690-1840, since 1970 CE) affecting both the caldera and the flanks of PdF. We interpret such discontinuous dynamics made of periods of intense and low activity as evidencing pulses of high magma supply since at least the 11th century. Overall, our work shows that dating lava flow with calibration based on the size distribution of long-lived pioneer trees represents an accurate alternative method to redefine the hazard map of lava flow inundation. The existence of long-lived pioneer trees in several volcanic areas provides the opportunity to use the same framework in order to better understand eruption recurrence patterns.



## Highlights

- We develop an original method to date young lava flows (<1000 yrs) in the Tropics
- Pioneer tree diameters are used to date lava flows of PdF over the last 700 years
- PdF experienced two volcanic pulses shortly before human settlement on Réunion

## Key words

*Agarista salicifolia*; Ecological succession; Effusive volcano; Eruption recurrence pattern; Réunion island; Volcanic hazard

## 1 Introduction

Dating recent lava flows is a critical issue to characterize the eruption recurrence pattern and subsequently to assess the volcanic hazards for nearby human populations (Trusdell 1995, Le

Pennec et al. 2008, Negro et al. 2013). Historical archives can provide reliable sources used for reconstructing the recent geological history of volcanoes. However, such written sources may be scarce or inaccurate especially in volcanic areas where human settlement was late or infrequent (Neri et al. 2011, Michon et al. 2013). Therefore, several methods are commonly used in order to date recent (<1000 years) lava flows. First, radiocarbon dating on sampled charcoals coming from trees burned by lava flows is frequently applied (Rubin et al. 1987, Madeira et al. 1995). Yet, charcoal often remains inaccessible, particularly in areas where lava flows are numerous and/or thick, and where erosive processes are too young or insufficient to totally incise the lava flows and excavate the underlying paleo-soils. Second, secular variations of the Earth's magnetic field can also be used to date recent lava flows (Holcomb et al. 1986, Tanguy et al. 2011, Roperch et al. 2015). However, this method requires independently dated lavas in order to trace the path of the directional secular variation for the study periods and may not be suitable in densely vegetated areas where root development may disturb the initial orientation of lava blocks. Third, cosmogenic nuclides such as $^{36}Cl$, $^{3}He$, $^{10}Be$ or $^{26}Al$ have been used to date Late Holocene surfaces like lava flows (Staudacher and Allègre 1993, Dunbar 1999, Alcalá-Reygosa et al. 2018) or moraines (Shakesby et al. 2008). However, dating accurately surfaces younger than 1000 yrs is challenging and requires good estimates of the cosmogenic isotope production rate, time-invariant scaling methods and to be able to evaluate possible erosion of the initial surface (Young et al. 2015, Jomelli et al. 2016). It has therefore, to our knowledge never been applied to date lava flow eruptions younger than 1000 yrs.

Finally, vegetation characteristics can be considered as alternative to date lava flow eruptions. Surface dating methods such as lichenometry or dendrochronology may be used in primary succession context, with the idea that the development stage of the vegetation growing on lava flows mostly depends on the age of the substrate (Atkinson 1970), that is on the date of the eruption that produces the lava. Lichenometry is a method based on the known growth rate of lichen thalli, but it allows potentially to date eruptions on a short time range only in lowland tropical regions where lichens are totally replaced by vascular plants in less than 150 years after eruption (Kurina and Vitousek 1999). Dendrochronology has been carried out on volcanofluvial terraces (Pierson 2007), tephra deposits (Druce 1966, Yamaguchi 1983), post-eruptive ravines (Franco-Ramos et al. 2017) and exceptionally applied to lava flow (Yamaguchi et al. 1990, Alcalá-Reygosa et al. 2018). However, most plant species do not form distinct annual growth rings in tropical regions (Jacoby 1989, Stahle 1999) and dendrochronology has never been used to date lava flows in these areas, despite unsuccessful attempts on Réunion (Catry and Daux, unpublished data) and the recent development of new methods coupled with classical dendrochronology (Poussart et al. 2004, Jacquin et al. 2017, van der Sleen et al. 2017). Moreover, destructive methods may affect population survival of the model species and not be adapted to the legal framework regarding sampling in protected natural areas. Other vegetation features, such as biomass for instance, can also serve as an indirect proxy for the age of lava flow. Li et al. (2018) recently used the Normalized Difference Vegetation Index (NDVI) derived from satellite images as a proxy for vegetation development and biomass on lava flows produced by three volcanoes located in a tropical setting (Nyamuragira, Democratic Republic of Congo; Mt Cameroon, Cameroon; Karthala, Comoros Archipelago). They could determine a relationship between NDVI values and lava flow ages, which however becomes invalid for ages older than 388, 333 or 93 years depending on the volcano.

Considering chronosequences of lava flows traditionally used in ecological studies (Walker and Moral 2003), we propose here an original method that relates the age of lava flows to size of pioneer trees. The calibrated relationship is then used to estimate unknown ages based on the size distribution of pioneer trees. This approach focuses on pioneer tree species because these plants (i) can be easily reached and sampled in a simple manner, (ii) are able to establish on recent lava flows within less than five years after eruption (Cadet 1977, Strasberg 1994) and (iii) grow in diameter all along their life due to cambium functioning. Because in general, the bigger the trees within a population, the older they are (Worbes et al. 2003), one may expect maximum size observed on lava flows to be strongly related to flow age. One important condition is nevertheless to be able to sample trees that benefited from the most favourable conditions on each flow, *e.g.* where the growth of vegetation may be facilitated by external soil sources (Deligne et al. 2013) or smaller distance to seed source (Li et al. 2018). Moreover, if we want to use the model to date lava flows on a large time range, trees must not only belong to pioneer species, but they also need to be long-lived. Long-lived pioneer trees can reach 700 years old (Lusk 1999), they notably play an important ecological role on (sub) tropical islands across all the world's oceans (Atkinson 1970, Cadet 1977, Tagawa et al. 1985, Clarkson 1990, Kamijo et al. 2002, Elias et al. 2004). Hence, this method might be a relevant alternative to date lava flow eruptions in several (sub)tropical volcanic areas.

Réunion is an oceanic island that hosts the Piton de la Fournaise volcano (PdF) (Fig.1), one of the most active in the world (Roult et al. 2012, Morandi et al. 2016), and a common long-lived pioneer tree, *Agarista salicifolia* (Ericaceae), which plays a crucial role in early ecological succession (Fig.2) (Cadet 1977, Strasberg 1994, Meunier et al. 2014). Due to the late settlement of the island (1646 CE; Common Era), historical observations of eruptions do not exist before that (see Lénat, 2016; Michon et al., 2013; Stieltjes, 1986). Only six radiocarbon dated eruptions affected the lower flanks of PdF in the last thousand year (Tab.1), but field observations suggest that more recent eruptions may have occurred on lower flanks which are now inhabited (see Cadet, 1977; Strasberg, 1994). Thus, there is a crucial need to improve our knowledge on the temporal distribution of this volcanic activity to better assess the volcanic hazards in this inhabited area. In this respect, we first use the size distribution of *Agarista salicifolia* on dated lava flows of PdF to calibrate a statistical model relating flow age to tree size. Second, the size distribution of *Agarista salicifolia* on undated lava flows is used as a proxy to estimate the age of these flows based on the previously calibrated model. Finally, we integrate these new dates in a larger analysis of eruption events to describe and better understand the eruption recurrence pattern and evolution of the PdF dynamics that is likely understated.

## 2 Material and methods

### 2.1 Study site

Réunion island is a 5 Ma old basaltic volcanic edifice that is composed of two main shield volcanoes: Piton des Neiges (inactive) and PdF (PdF) that expands across the south-eastern third of the island (Fig.1). PdF is a highly active volcano with more than 238 eruptions that have been recorded since human settlement in the second half of the 17$^{th}$ century (Roult et al. 2012, Morandi et al. 2016). The historical activity of PdF is mostly restricted to the uninhabited Enclos Fouqué caldera and its downslope continuity named Grand Brûlé (97% of the post 1708 CE eruptions), and rarely propagated along the NE and SE inhabited volcano flanks (Fig.1) (Villeneuve and Bachèlery 2006, Michon et al. 2013). Only seven eruptions have been observed on these flanks since the settlement of this part of the island during the 18$^{th}$ century. They occurred during two eruptive clusters: four and three eruptions during the 18$^{th}$ and 20$^{th}$ centuries, respectively, with a pause of 177 years between 1800 and 1977 (Fig.1) (Michon et al. 2013). Beside this observed “historical” activity, the activity of the last thousand years was constrained by 16 radiocarbon ages spanning between 868 ± 30 BP and 130 ± 30 BP (Tab.1)

(Morandi et al. 2016). Only six of these dated eruptions affected the lower flanks, despite numerous observations reporting potential recent eruptions (Cadet 1977, Strasberg 1994).

PdF area experiences a humid tropical climate throughout the year below 800 m asl, i.e. annual mean temperature ranges from 18 to 25°C and precipitation of driest month ranges from 75 to 400 mm, with large inter- and intra- annual variations (Jumeaux et al. 2011). Where the lower flanks of PdF have not been cleared for croplands or urbanisation, they harbour tropical rainforest of which *Agarista salicifolia* is an important pioneer tree species (Cadet 1977, Strasberg 1994).

### 2.2 Radiocarbon ages of eruptions

Radiocarbon method has long been used to date the lava flows and tephra layers related to past eruptions of PdF volcano that occurred during the last thousands of years (see the synthesis in Morandi et al., 2016). To ensure their intercomparison, each radiocarbon age has been recently calibrated by Morandi et al. (2016) using the online Calib program (Stuiver et al. 2019) and the IntCal13 calibration curve (Reimer et al. 2013). However, radiocarbon ages obtained on tree rings that grew at the same time in opposite hemispheres present a shift, with samples of the southern hemisphere being older than in the northern one (McCormac et al. 1998). We therefore calibrated for this work the radiocarbon ages with Calib (Stuiver et al. 2019) and the SHCal13 calibration curve determined for the southern hemisphere (Hogg et al. 2013), and obtained an average interhemispheric difference for median probabilities of 41 yrs between both calibration procedure (Tab.1).

### 2.3 Focal species

*Agarista salicifolia* (Ericaceae), hereafter referred to as *Agarista*, is a long-lived tree that is native on Réunion island but occurs also in Mauritius, Madagascar and East Africa. It is well known as a pioneer species and is usually the first native woody species to establish on newly formed lava flows on Réunion island (Fig.2) (Cadet 1977, Strasberg 1994). *Agarista* produces numerous tiny seeds that are dispersed by wind away from mature mother trees and a recent study shows that this species does not suffer any dispersal limitation in the whole study area (Albert et al. 2020). Seedlings of the species are commonly observed on recent lava flows as soon as a few years after the eruption (Cadet 1977). Once settled, *Agarista* trees are able to survive during the complete course of ecological succession to mature forests in which it occurs as large trees up to 15-20 m high settled in the canopy. Importantly, the species does not regenerate under vegetation cover: individual settlement stops as the vegetation cover develops and becomes continuous. As a consequence, on a given lava flow on which primary ecological succession happens without further disturbance events, its populations consist in cohorts made of individuals of the same age rather homogeneous in size. The species occurs from sea level up to ca. 1200 m asl, but we sampled below 800 m asl in the tropical rainforest biome where climatic conditions for *Agarista* growth are assumed to be comparable. *Agarista* identification on the field is easy, notably because of the longitudinally cracked reddish bark.

**2.4 Sampling**

To calibrate a statistical model of flow age vs tree size, we selected 20 lava flows with *Agarista* populations on them. Most of these flows, 17, occurred after 1708 and were historically recorded (see a recent review in Michon et al. (2013)) (Fig.1). To extend temporal sampling, we considered two additional lava flows emplaced before human colonization (575 ± 75 BP and 364 ± 25 BP; Morandi et al., 2016) and dated a third one with radiocarbon method 385 ± 25 BP (Tab.1). We included the median probability of these dates in the *Agarista* calibration procedure.

We then selected 11 lava flows for which no date was known, but which were described as “young lava flows” by Cadet (1977). Six lava flows were located in the Grand Brûlé, downslope in the PdF caldera (Cald1 to Cald6) and five along south volcano flanks, four in Saint Philippe municipality (S-Ph1 to S-Ph4) and one in the inhabited valley of Langevin (S-Jo1; Fig.1).

On each studied lava flow, we characterized the size distribution of *Agarista* in order to estimate the maximum size reached by the species. In this prospect, the first crucial step was to identify the spatial limits of each lava flow. Lava flows can be of very variable width, occur at different elevations and sometimes reach the sea. Their lateral margins are generally perpendicular to elevation contours.  Recent lava flows (< 1000 years old) show a very thin topsoil (in the order of mm)  on continuous rock (Meunier et al. 2010), with tree roots running on the lava. One can easily distinguish a single lava flow outside the Grand Brûlé when looking along elevation contours for a deep soil that materialise the flow limits. At elevations <500 m asl, these deep soils are usually cultivated. Thus, some lava flows are easily distinguishable, especially outside the Grand Brûlé where recent lava flows rarely overlap. In areas where lava flows overlap, features as changes in the type of lava flow or in the size of the largest *Agarista* trees were carefully identified to prevent any sampling issue. In any event, *Agarista* trees in doubtful areas were not sampled.

Once the flow boundary is clearly delineated, at least 30 *Agarista* trees should ideally be sampled per flow and special attention must be paid to large trees so that they are not forgotten. The sampling area can be highly variable and depends on the density of the trees and the difficulty in accessing some locations because of remoteness, plant invasion or relief complexity. This may limit the possibility of reasonably extending the sampling.

In order to take into account all *Agarista* cohorts including seedlings and saplings of small height, we measured diameter at base (at ground level) and height using a caliper, a tape measure and a telescopic rule depending on the size of the plants. *Agarista* does not display buttresses, but older individuals often show a very irregular base that was sometimes difficult to measure. Diameter at base was consequently defined as the cross-sectional wood area expressed as a circle. Heights above 8 m were eye-estimated and total length was estimated instead of height for large trees whose trunks could have a section growing sub-horizontally.

### 2.5 Statistical analysis of size-age relationship

Our analysis is based on the simple observation that tree size increases with time (Worbes et al. 2003). After visual inspection of the observed relationship between the two study variables (age flow and maximal tree size), we first consider a simple power-law model as it is simple and allows for non-linearity. Considering that the largest trees on a lava flow are the oldest and have settled shortly after the flow, we therefore assume: $Age = a * D_m^b$, where

where $D_m$ is an estimator of the maximal size reached by the trees on the flow and *Age* the age of the flow. After log-transformation, we obtain model $log(Age) = a' + b * log(D_m)$. In order to account for potential non-linearity on the log-log scale, we finally consider a quadratic model: $log(Age) = a' + b * log(D_m) + c * log(D_m)^2$ as full model and test its components.

For maximal tree size, we consider three different estimators of $D_m$ on each lava flow. $D_m$ is successively estimated by the absolute maximum of the diameter distribution of censused trees ($D_{max}$), the 95$^{th}$ percentile of the diameter distribution ($D_{95}$), and eventually the mean of the five larger diameters observed ($D_5$). We obtain the best model for each estimator of $D_m$ using analyses of variance. We finally retain the estimator of $D_m$ of which the best linear model displays the highest adjusted R-squared. All models were fitted using ordinary least squares regression using R ver. 3.4.4 (R Core Team).

## 3 Results

The mean number of measured plants across all lava flows is 30.1 and varies from a minimum of five individuals to 46 on the 2007 and 1559 lava flows, respectively (Fig.3). For the former, the limited sample size relates to *Agarista* seedlings established in 2012 being very rare on the 2007 flow. These seedlings however demonstrate that *Agarista* is able to settle on a lava flow under the age of five years old. The 95$^{th}$ percentile of the diameter distribution ranges from 0.19 cm on the 2007 lava flow to 177.47 cm on the 1401 lava flow. 711 and 255 *Agarista* trees were respectively sampled for the calibration model (elevation mean: 198 m asl, precipitation of driest month mean: 226 mm) and dating purpose (elevation mean: 354 m asl, precipitation of driest month mean: 210 mm).

Among the three linear models that estimate the maximal size reached by *Agarista* ($D_m$), the 95$^{th}$ percentile of the diameter distribution ($D_{95}$) displays the highest adjusted R-squared, with small differences however compared to the other estimators: ($R^2_{D95} = 0.988 > R^2_{D5} = 0.986 > R^2_{Dmax} = 0.983$). The best model using a logarithmic linear regression with a quadratic form (Appendix Tab.1) is as follows:

$log\ (age) = 0.969 + 0.530 * log\ (D_{95}) + 0.126 * (log\ (D_{95}))^2$ (n = 20, $R^2 = 0.988$, $p < 2.2e\text{-}16$),

where $D_{95}$ is the 95$^{th}$ percentile of the diameter distribution in cm and *age* the age of lava flows on which *Agarista* trees were measured (Fig.3 and Appendix Tab.2). The explicative power of the quadratic term remains weak compared to the linear trend (Appendix Tab.1). The study of model residuals shows no significant relationship between residuals and elevation or precipitation of driest month (Appendix Fig.1). Hence, climatic heterogeneity has no particular effect on the discovered relationships.

Using the calibrated model, 11 lava flows are dated between 1447 (CI: 1349-1531) at S-Ph1 and 1823 (CI: 1806-1839) at S-Ph4 (Tab.2). These new dates show that (i) at least one eruption occurred around 500 years ago in a currently urbanised valley (S-Jo1: 1598 CE), (ii) several eruptions occurred along the South flanks at historical times (S-Ph2, S-Ph3, S-Ph4: 1726, 1765 and 1823 CE, respectively) and (iii) the caldera still hosts old-growth native forests settled at low elevations on lava flows that occurred before permanent human settlement (Cald-5: 1581 CE) (Tab.2).

Field work revealed a strong observer bias to estimate the height of trees > 8 m by eye. Consequently, we did not retain this method for lava flow dating. We note nevertheless that the 95$^{th}$ percentile of the height distribution allows a good prediction of lava flow age despite sample bias, which offers promising perspectives for future work (Appendix Fig.2).

## 4 Discussion

### 4.1 A relevant alternative method to date past volcanic activity

We show evidence of a very strong relationship between the maximum diameter at base of *Agarista* trees and the age of lava flows. Hence, we demonstrate for the first time that dating volcanic activity from size distribution of pioneer trees is a relevant method, especially when no $^{14}C$, paleomagnetic secular variations assessments nor historical records are available. Classical dendrochronology has recently developed in the humid tropics (Giraldo et al. 2020), but could not be successfully tested on *Agarista* because of indistinct ringing in wood (Catry and Daux, unpublished data). Coupling dendrochronology to X-ray densitometry or to the analysis of stable isotopes offers promising prospects to obtain independent dating of *Agarista* trees (Poussart et al. 2004, Jacquin et al. 2017). However, the former is cumbersome to implement, while the latter can cause substantial uncertainties in the interpretation because of major methodological issues, e.g. model parameterization used to calculate carbon and oxygen isotope fractionation or potential confounding effects of ontogenetic changes on isotope ratios (van der Sleen et al. 2017). Li et al. (2018) have also recently proposed dating volcanic activity from remote sensing techniques. However, this technic was limited to the last few centuries (between 93 and 388 years depending on the volcano) and does not allow to have access to longer time spans. On the contrary, the longevity of *Agarista* enables to date lava flows as old as 1447 CE. This method is also interesting because it implements undestructive, simple and cheap methods, i.e. diameter measurement using tape measure. By contrast with remote sensing methods, good knowledge of the field and good physical condition are required to access remote locations and to measure numerous trees, which may be time consuming and demanding. Dating volcanic activity from size distribution may be tested in areas where long-lived trees also play a major role as an early shade-intolerant pioneer species on volcano slopes: *Metrosideros* spp in Hawaii (Atkinson 1970, Drake and Mueller-Dombois 1993) and New Zealand (Clarkson 1990); *Weinmannia* spp in Chile (Lusk 1999), New Zealand (Clarkson 1990) and in Comoros (Charahabil et al. 2013); *Casuarina* spp in Indonesia (Tagawa et al. 1985).

Dating volcanic activity from size distribution relies on (i) undisturbed pioneer cohorts of *Agarista* since their initial establishment on a newly-formed lava flow, (ii) accurate measurement of the maximum diameter at base among well-identified cohorts and (iii) use of the model in an area where climatic conditions for *Agarista* growth are relatively homogeneous. One would otherwise undoubtedly underestimate the age of this lava flow.

Alcalá-Reygosa et al. (2018) emphasize that dating a lava flow using pioneer tree may provide minimum ages and that the discrepancy between pioneer tree age and lava flow age may be substantial. They state that “this may be due to the impact of fires, the volcanic activity or the natural mortality in a pioneering community”. In our study, the calibration model based on 20 lava flows shows a strong correlation that makes very unlikely a strong disturbance of pioneer cohorts since their establishment. The question arises above all with regard to lava flows that were dated with *Agarista* model and that do not have other independent dating. Natural mortality within *Agarista* population on lava flows does not lead to new recruitment of younger cohorts. On older lava flows, senescent *Agarista* individuals are replaced by late successional canopy tree species (Cadet 1977, Strasberg 1994, Albert et al. 2020) and isolated individuals can occasionally survive because of favourable light conditions, such as forest gaps. Before the beginning of forest clearings for agriculture in this wet area in the late 18$^{th}$ century, fires were probably related to volcanic activity. Two situations must be distinguished: the lower flanks of PdF outside the caldera and the Grand Brûlé. On the former, the low occurence of eruptions makes unlikely the destruction of previous *Agarista* populations. In the caldera where lava flows frequently occur, it cannot be ruled out that the growth of *Agarista* population in the kipukas was not disturbed by adjacent lava flows (fire, gas) and thus might lead to an underestimation of the flow age. Hence, future work aimed at obtaining independent dating could first focus on the caldera where disturbances have been numerous.

One other limitation is the difficulty to identify the boundaries of each single lava flow to precisely sample tree cohorts and their whole size distribution. A great attention should especially be given to lateral margins of lava flows. Indeed, field observations show that *Agarista* trees can be bigger and higher at the edge of lava flows than in the middle part. This pattern suggests a front of plant colonisation from the nearest source of seeds (Li et al. 2018), not only from *Agarista*, but also from numerous species. This might strongly facilitate the growth of *Agarista* that might benefit from a higher nutrient availability and from buffering environmental stress (Walker and Moral 2003). In addition, the type of basaltic lava might have a significant influence on the growth of *Agarista*, Cadet (1977) reported for instance that vegetation growth was faster on Pāhoehoe lava than on ‘A‘ā lava and field observations show that tree roots are able to penetrate through Pāhoehoe lava probably to access nutrients below (Fig.2b). Because several eruptions produced mixt Pāhoehoe-ʻAʻā lava (e.g. 1401, 1559, 1977, 2004), future work at finer scale to include these factors in a multiple linear regression may substantially improve our capacity to date volcanic activity from size distribution of pioneer tree.

Finally, *Agarista* model was calibrated in an area where climatic heterogeneity probably has a minor influence on the estimation of the age of lava flows (Appendix Fig.1). We used *Agarista* model to date lava flows up to 800 m asl, which characterizes the upper limit of the tropical rainforest biome on Réunion (Cadet 1977, Strasberg 1994, Albert et al. 2020). At higher elevations where *Agarista* is at edge-range or absent, one could attempt to use other ecological “analog” species that could help in dating some lava flows and associated eruptions.

### 4.2 An underestimated lava flow recurrence along the volcano flanks of PdF

The analysis of the historical reports of PdF recently revealed that the volcanic activity in the Enclos Fouqué caldera evolved from an intense, continuous lava lake dynamics at the top of the Central Cone between at least the first summit observations (1751 CE) to 1860 CE, to the current dynamics made of short, frequent eruptions on the flanks of the Central Cone and on the floor of the Enclos Fouqué caldera (Michon et al. 2013). This study also proposed that the edification of the Central Cone was almost complete before 1750 and ended in 1860 with a main phreatomagmatic eruption following the emptying of the last lava lake (Maillard 1862, Michon et al. 2013). The cone growth resulted from a twofold evolution characterized by a lava fountain dynamics building a first cone until the collapse of a large pit crater that was subsequently filled by a lava lake activity centred on the Bory crater, which led to the formation of the Bory shield until around 1750 (Peltier et al. 2012, Michon et al. 2013). Despite a lack of any direct dating of the beginning of the Central Cone activity nor observations before 1751, Michon et al. (2013) interpreted the absence of unconformity between the lava sheets forming both the basal cone and the Bory shield as indicative of a long-lasting continuous activity. This interpretation is supported by radiocarbon ages between 340 and 130 BP (median ages of 1560 and 1856 CE) of eruption fall deposits preserved on the northern rim of the Enclos Fouqué caldera (Tab.1; Fig.1; Morandi et al. 2016). However, despite an increasing amount of evidence for an intense volcanic activity affecting the summit area before the 19$^{th}$ century, our knowledge of its impact on the volcano flanks was based on only 4 radiocarbon ages of lava flows and a few historical reports after 1708 CE.

Our alternative method of dating lava flows with *Agarista* allows to track the volcanic activity on the flanks of PdF (11 newly dated lava flows). Figure 1 indicates that at the exception of the Grand Brûlé where sampling is relatively dense, our dating sites are homogeneously distributed in the volcano lower flanks (i.e. about <400 above sea level). Furthermore, as mentioned above, lava flows emplaced since the 15$^{th}$ century, on which *Agarista* trees are still present, are not covered by any deep soils. By contrast, the spatial distribution of the agricultural activity gives insight in the location of lava flows on which deep soils had time to develop. Thus, Figure 1 reveals that our analysis of the lower flanks takes most of the areas not covered by crops into account and therefore correctly integrates the areas affected by recent lava flows. The main sampling bias in the lower slopes of PdF would therefore result from the 0.8 km wide area located between the lava flow of Piton Nelson dated at 260 BP and the northern limit of the Grand Brûlé, where no soil developed.

Altogether the eruptions observed outside the Enclos Fouqué and Grand Brûlé structures since 1708 and those dated either from radiocarbon or *Agarista*-calibrated methods form a comprehensive database of 34 ages that allows to determine the temporal evolution of the volcanic activity during the last millennium (Fig.4). We split the database considering the location of the eruption sites, i.e. inside or outside the Enclos Fouqué and Grand Brûlé structures, in order to evaluate potential differences in the central versus flank dynamics.

Outside the Enclos Fouqué caldera, the evolution is characterized by 24 ages. The relative probability distribution of these ages shows three main peaks, the last one been defined by the three eruptions that recently occurred between 1977 and 1998 (Fig.4b). Interestingly, the temporal distribution of the 10 ages related to eruptions located in the Enclos Fouqué caldera reveals an overall evolution similar to the one deduced outside the caldera. Lava flows emitted from the Central Cone or adjacent eruptive fissures have partly resurfaced the Grand Brûlé area since the 19th century. However, the occurrence of a few small scattered kīpuka allowed to date older lava flows between 1558 and 1812 CE (Tab.2 & Fig.4). Moreover, the probability distribution of the observed lava flows entering the ocean in Grand Brûlé since 1753 confirms an intense activity of PdF until around 1820 that progressively declined until a renewal since around 2000 (Fig.4b). Thus, these data suggest (1) a similar dynamics outside and inside the Enclos Fouqué caldera and (2) the existence of three successive periods of intense activity drawn by three clusters of eruption and lava flow ages (1460-1630, 1690-1840, 1970-present).

We show above that the Central Cone of PdF results from a long-lasting period of intense lava fountaining and lava lake activity between at least the 16th and 19th centuries (Peltier et al. 2012, Michon et al. 2013). The present work reveals that the volcano flanks and the summit area experienced two successive periods of intense activity before the 19th century (clusters 1 and 2 in Fig.4b). Considering these results, we tentatively propose that both the building of the Central Cone and the eruption occurrence outside the Enclos Fouqué caldera, in the summit zone and the volcano flanks, result from large magma supply. Moreover, the distribution in clusters could indicate a pulsating rather continuous magma supply. Such pulses could yield large overpressures in the magmatic system promoting lateral migrations and eruptions and lava flows outside the Enclos Fouqué caldera (Fig.5). Such magmatic pulses would be comparable to those experienced by the Hawaiian volcanoes during the last centuries

(Klein 1982). Thus, our data give potential insights to refine the periods of edification of the Central Cone ($15^{th}$-$19^{th}$ centuries) for which chronological constraints were lacking. Indirectly, they raise the question of the volcanic structures existing in the Enclos Fouqué caldera between this period of intense activity and the large explosive eruptions dated at around 2140 BP possibly related to the last Enclos Fouqué caldera collapse events (Morandi et al. 2016). Only the remnant relief of Puy Mi-Côte at the northwestern base of the Central Cone (Michon et al. 2013) could attest of a volcanic activity within the Enclos Fouqué caldera during this time span. Finally, if the two first magmatic pulses led to the building of the Central Cone with a long-lasting lava lake activity, the eruptive dynamics of the third, current cluster clearly differs and is characterized by frequent, few hours-to-few months long eruptions located of the floor of the Enclos Fouqué (Roult et al. 2012).

In terms of hazard assessment, our work also shows that dating lava flow with *Agarista* calibration represents an accurate alternative method to refine the hazard map of lava flow inundation. At least 24 lava flows covered the volcano slopes since 1401 CE (Fig.4). It appears that 18 out of 24 lava flows were located on the south and north flanks nowadays inhabited. Most of them affected the southern and southeastern slopes (13 out of 18) where they were either channelized in the deeply incised valleys (Rivière Langevin and Basse Vallée, Fig.5) or resurfaced the volcano flanks. The spatial distribution of the lava flows could indicate a higher lava flow hazard in Saint-Joseph, Saint-Philippe and Le Tremblet areas, than in Sainte-Rose despite the recent 1977 lava flows (Fig.1). This is supported by the almost continuous footprint of the agricultural surface in the lower part of the northern flank compared to the south flank (Fig.1 & Fig.5) It is also important to note that the valley incised in the southern flank can efficiently channelize the lava flows related to eruptions located in the summit zone. Such an effect is supported by the Plaine des Sables eruption that occurred between 1424-1628 cal CE (median probability at 1558 CE), which fed a lava flow that flew down in the upper part of the Rivière Langevin valley (Principe et al. 2016). This lava flow whose downstream continuity is not established could correspond to the remnant of the lava flow that we dated dated with *Agarista* at 1598 CE (CI between 1540-1649) at 285 m above sea level in the now inhabited Rivière Langevin canyon (Fig.5.a). However, if the lava flows of the Plaine des Sables and in the lower part of the valley are not related, it suggests a lava flow inundation hazard even higher in the now inhabited Rivière Langevin canyon (Fig.5.a). The Basse Valley canyon would have played a similar role with lava flows emitted from the Puys Ramond area (Fig.5.b). To this respect, the recent lava flow dated at 1823 CE (CI between 1806-1839) with *Agarista* could correspond to the mysterious eruptions of 1820 described by Hoarau and Vinet (1820) but never identified in the field so far. Finally, the higher volcanic hazard of the southern flank of PdF must be confirmed by future sampling north of the Grand Brûlé (*e.g.* Bois Blanc; Fig.5) where several eruptions have already been reported in Morandi et al. (2016) and where several undated eruptions might have occurred before 1700 CE.

## 5 Conclusion

The main conclusions of our work can be summarized as follows:

- We built from a statistical approach a robust relationship between the age of secular lava flows of Piton de la Fournaise and the size of the long lived pioneer tree *Agarista salicifolia*.
- This relationship allows to date 11 lava flows that covered the volcano lower southern and eastern slopes between the 15$^{th}$ and 19$^{th}$ centuries. Combining ages obtained with $^{14}C$ and *Agarista* calibration methods, and observed historical lava flows between 1700 and 1800, the timing of the eruptions of PdF is now constrained by 31 ages between 1000 and 1900 CE (Fig.4).

- The temporal distribution of these dates is organised in three clusters (1460-1630, 1690-1840, 1970-present) interpreted as the result of pulses of high magma supply. This intense dynamics during the two first identified pulses may have led to the building of the Central Cone with a lava lake activity in the Enclos Fouqué caldera and the occurrence of eruptions outside the caldera and on the volcano flanks which are now inhabited. The third pulse may explain the activity renewal outside the Enclos Fouqué caldera and a higher rate of lava flow entrance in the ocean.
- Finally, our original approach of dating lava flows from size distribution of pioneer trees might be tested in numerous areas where long-lived trees also play a major role as an early pioneer on volcano slopes: *Metrosideros* spp in Hawaii and New Zealand; *Weinmannia* spp in Chile, New Zealand and in Comoros archipelago; *Casuarina* spp in Indonesia.

**Sample CRediT author statement**

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**Data availability**

Dataset related to this article can be found at https://data.mendeley.com/datasets/j77dpvj5mc/draft?a=fc4f3bced5a3-4dca-93af-721c89030159 an open-source online data repository hosted at Mendeley Data.

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## Appendix

***Tab.1.*** *Comparison of calibrated models: Model 1 with intercept only, Model 2 with maximal distribution of Agarista ($D_{95}$, see main text for definition), Model 3 with an additional quadratic term ($I(D_{95}^2)$). Adding a quadratic term has a weak effect (increase of R-squared = 1.75%), but the difference is nevertheless highly significant. Rse.Df: Residual Degrees of Freedom; RSS: Residual sum of squares; Df: degrees of freedom; Pr(>F): P-value.*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| *Model 1: age ~ 1* | | | | | | | |
| *Model 2: age ~ $D_{95}$* | | | | | | | |
| *Model 3: age ~ $D_{95}$ + $I(D_{95}$^2)* | | | | | | | |
| | *Res.Df* | *RSS* | *Df* | *Sum of Squares* | *F value* | *Pr(>F)* | *R²* |
| *1* | 19 | 7.8681 | | | | | |
| *2* | 18 | 0.2242 | 1 | 7.6439 | 1499.746 | < 2.2 E-16 | 0.971 |
| *3* | 17 | 0.0866 | 1 | 0.1376 | 26.997 | 7.289E-05 | 0.988 |

***Tab.2.*** *Calibrated model of the functional relationship between the 95$^{th}$ percentile of the diameter distribution of* Agarista (D95) *and the age of lava flows. The best model includes a hump-shaped transformation. Residual standard error: 0.07509 on 17 degrees of freedom. Multiple R-squared:  0.9881, Adjusted R-squared:  0.9867. F-statistic: 708.5 on 2 and 17 DF, p-value: < 2.2e-16.*

| | *Estimate* | *Std. Error* | *t value* | *Pr(>\|t\|)* |
|---|---|---|---|---|
| *(Intercept)* | 0.9686 | 0.0284 | 34.0886 | 4.31E-17 |
| *Log(D95)^2* | 0.1260 | 0.0243 | 5.1958 | 7.29E-05 |
| *Log(D95)* | 0.5301 | 0.0461 | 11.4892 | 1.95E-09 |

***Fig.1.*** *Study of calibrated model residuals depending on fitted values, elevation and precipitation of driest month (dm precipitation) of sampled plot. The test of Spearman's rank correlation coefficients shows there is no significant relationship between model residuals and elevation/precipitation. The variable precipitation of driest month was log-transformed prior to analyses.*

***Fig.2. a-*** *Relationship between 95$^{th}$ percentile of height distribution and age of lava flows.* ***b-*** *Relationship between 95$^{th}$ percentile of diameter distribution and 95$^{th}$ percentile of height distribution. Note the log-log scale for both relationships and that height measurements are not available for four lava flows that have been used in the model calibration based on the 95$^{th}$ percentile of diameter distribution (1986, 1961, 1889, 1830).*

**Sample CRediT author statement**

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**+++ Saint-Pierre, 6 March 2020**

**Dear Editor,**

**On behalf of my co-authors, I hereby declare that we have no conflict of interest to declare.**

**Best regards,**

**Sébastien Albert**

# Figures

***Fig. 1****. Historical and recent (<1000 yr) volcanic activity of Piton de la Fournaise volcano, Réunion Island. Pre-historical or unreported eruptions have been dated with radiocarbon method (Morandi et al. 2016). Radiocarbon ages of the summit eruptions have been obtained from charcoal sampled below tephra deposits. Here, we further constrain the recent volcanic activity from a size/age relationship based on* Agarista *tree development to date the recent lava flows of Piton de la Fournaise. Agricultural and urban footprints from www.peigeo.re. Contour lines every 200 m.*

***Fig. 2****.* Agarista salicifolia *at different stages of growth (white arrows).* ***a-*** Agarista *sapling settled on the 1986 lava flow at Saint-Philippe.* Agarista *is usually the first native woody plant to settle rapidly after the initial lava cooling at low elevations, as reflected on this recent lava flow. Agarista further provides shade to newly settled plants and produces litter locally, thus bringing organic matter to the system.* ***b-*** Agarista *tree settled on the 1708 lava flow at Sainte-Rose. Note the Pāhoehoe lava that overhangs the ravine due to the higher weathering of underlying soil and the big root of* Agarista *that prospects this soil.*

***Fig. 3****. Calibration of volcanic activity dating based on the relationship between age of lava flows and maximum diameter at base of* Agarista*. Dots and triangles respectively display* Agarista *measurements and the $95^{th}$ percentile of the diameter distribution of* Agarista *populations; solid and longdash lines respectively display mean and upper/lower bounds of confidence interval predicted by the best linear model (Tab. 2). The date of the lava flows on which* Agarista *trees were measured is given. The year of eruption is based on $^{14}C$ dating for the three oldest lava flows (errors bars are consequently shown) and is exactly known for the 17 historical lava flows.*

***Fig. 4****. a- Temporal distribution of the dated and observed eruptions of Piton de la Fournaise since the $12^{th}$ century. b- Relative probability plot determined for eruptions or lava flow that occurred outside the Enclos Fouqué and Grand Brûlé structure (thick line), inside the Enclos Fouqué caldera and in Grand Brûlé (thick dashed line), and observed lava flows reaching the sea in Grand Brûlé. It is worth noting that the observation in Grand Brûlé are totally lacking before 1759 and sparse until 1774. Two clusters (1460-1630; 1690-1850) of eruption and lava flow occurrence are defined by calibrated radiocarbon, Agarista-calibrated ages and observations both inside and outside the Enclos Fouqué caldera. Interestingly, the probability low highlighted by dates (1) outside and inside the Enclos Fouqué and Grand Brûlé structures between around 1850 and 1977 (thick lines) also corresponds to a lower rate of observed lava flow entering the ocean within Grand Brûlé (thin line).*

***Fig. 5.*** *Spatial distribution of the dated sites ($^{14}C$ and Agarista calibration) that give insights into the eruption occurrence related to the two first clusters of volcanic ages determined from Fig. 4b between 1460-1630 and 1690-1840.*

*Tab. 1. Available radiocarbon ages of the recent (<1000 yrs) eruptions of Piton de la Fournaise. Calibrated ages have been computed with Calib 7.1 online version (Stuiver et al., 2019). For the current work, we determined the calibrated radiocarbon ages with SHCal13 (Hogg et al., 2013), calibration specifically determined for the southern hemisphere, instead of the IntCal13 (Reimer et al., 2013) calibration curve. Eruptions highlighted in grey are used for calibrating the Agarista model. EF cald: Enclos Fouqué caldera.*

| Eruption | Location | 14C age (BP) | ± | SHCal13 calibration | | | IntCal13 calibration | | | X (UTM, WGS 84 40S) | Y (UTM, WGS 84 40S) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Median probability (CE) | Calibrated min (CE) 2σ | Calibrated max (CE) 2σ | Median probability (CE) | Calibrated max (CE) 2σ | Calibrated min (CE) 2σ | | |
| Langevin plateau 1 fall | W of EF cald | 868 | 30 | 1218 | 1162 | 1271 | 1177 | 1046 | 1251 | 360177 | 7650158 |
| Langevin plateau 2 fall | W of EF cald | 620 | 30 | 1354 | 1312 | 1422 | 1349 | 1292 | 1399 | 360177 | 7650158 |
| Le Baril 1 lava flow | S flank | 575 | 75 | 1401 | 1287 | 1491 | 1358 | 1281 | 1444 | 365841 | 7638410 |
| Petit Cratère cone | NW of EF cald | 420 | 25 | 1488 | 1448 | 1622 | 1455 | 1431 | 1615 | 361290 | 7655172 |
| Ravine Ango lava flow | SE flank | 455 | 70 | 1493 | 1408 | 1632 | 1457 | 1318 | 1635 | 374810 | 7638926 |
| Piton Indivis cone | NE flank | 420 | 80 | 1532 | 1410 | 1655 | 1500 | 1327 | 1649 | 376296 | 7655301 |
| Ravine Citrons Galets lava flow | SE flank | 385 | 25 | 1556 | 1462 | 1627 | 1486 | 1443 | 1626 | 374463 | 7644286 |
| Plaine des Sables fall | W of EF cald | 380 | 25 | 1558 | 1464 | 1628 | 1493 | 1446 | 1630 | 361199 | 7651747 |
| Mare Longue lava flow | South flank | 364 | 25 | 1559 | 1484 | 1636 | 1517 | 1451 | 1632 | 369289 | 7637962 |
| Partage cliff 1 fall | N of EF cald | 340 | 30 | 1560 | 1497 | 1649 | 1559 | 1470 | 1639 | 366110 | 7653616 |
| Piton Taipoul cone | S of EF cald | 355 | 75 | 1567 | 1443 | 1798 | 1549 | 1427 | 1794 | 366431 | 7645459 |

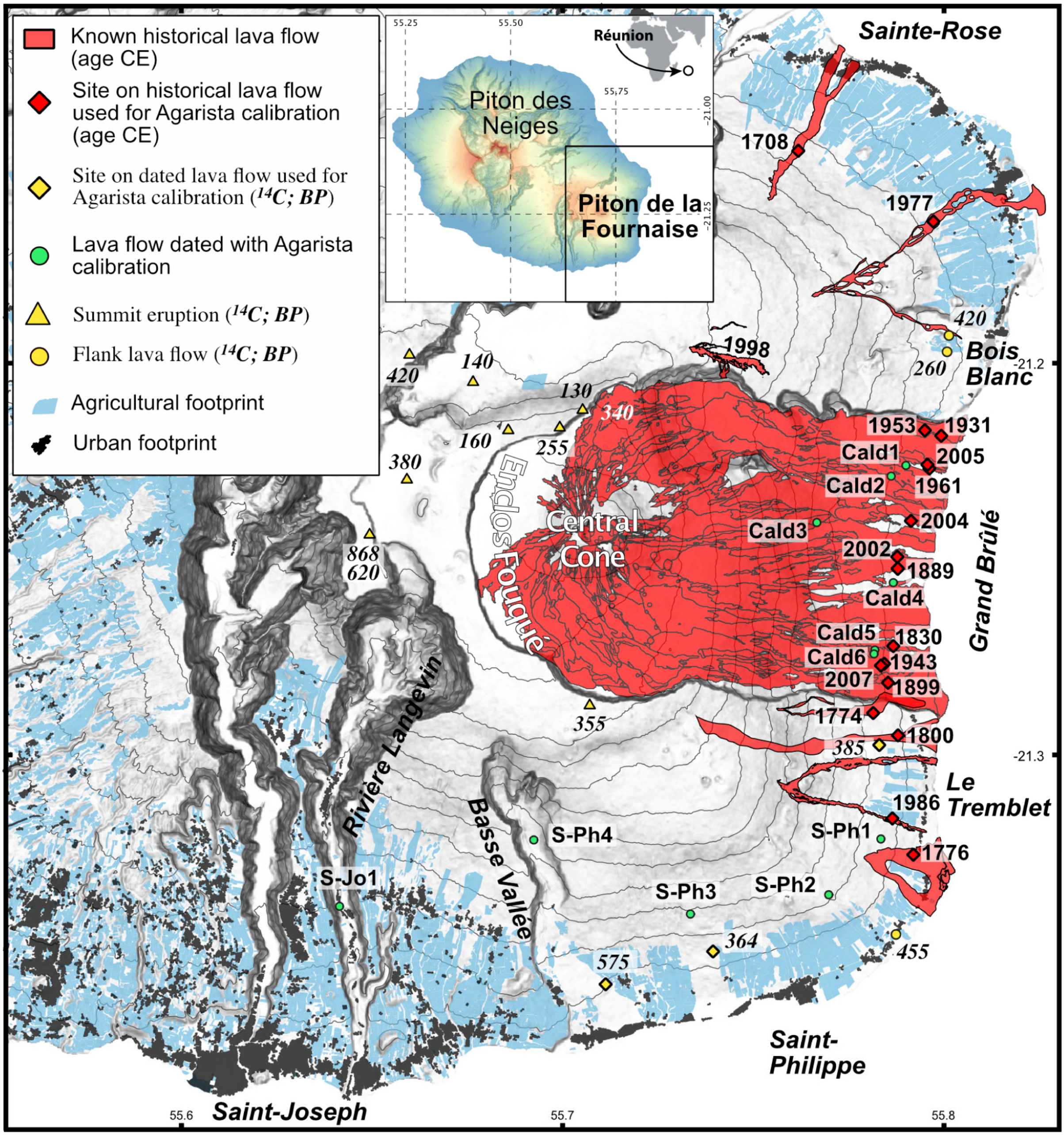
| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Piton Nelson cone | NE flank | 260 | 80 | 1707 | 1497 | 1950 | 1643 | 1450 | 1950 | 376296 | 7655597 |
| Partage cliff 2 fall | N of EF cald | 255 | 30 | 1743 | 1633 | 1802 | 1650 | 1521 | 1950 | 365582 | 7653225 |
| Piton Rampe 14 lava flow | NW of EF cald | 140 | 90 | 1812 | 1655 | 1950 | 1791 | 1528 | 1950 | 363034 | 7654507 |
| Partage cliff 3 fall | N of EF cald | 160 | 30 | 1838 | 1673 | 1950 | 1773 | 1664 | 1950 | 364087 | 7653099 |
| Partage cliff 4 fall | N of EF cald | 130 | 30 | 1856 | 1690 | 1950 | 1821 | 1675 | 1941 | 365582 | 7653225 |

***Tab.2***. *Dating of lava flows based on calibrated* Agarista *model. Id: Lava flow with* Agarista *population; D95: 95th percentile of the diameter distribution of* Agarista*; n: number of* Agarista *measurements; Age: age predicted by the calibrated mode; Date: 2012 – Age; CI min: minimum confidence interval value; CI max: maximum confidence interval value.*

| *Id* | *D95* | *n* | *Age* | *Age CI max* | *Age CI min* | *Date* | *Date CI min* | *Date CI max* |
|---|---|---|---|---|---|---|---|---|
| *Cald1* | 82.97 | 24 | 281,65 | 312,03 | 254,23 | 1730 | 1700 | 1758 |
| *Cald2* | 76.42 | 25 | 259,24 | 285,93 | 235,03 | 1753 | 1726 | 1777 |
| *Cald3* | 73.62 | 20 | 249,70 | 274,92 | 226,79 | 1762 | 1737 | 1785 |
| *Cald4* | 79.14 | 28 | 268,52 | 296,71 | 243,02 | 1743 | 1715 | 1769 |
| *Cald5* | 125.10 | 20 | 431,04 | 492,79 | 377,02 | 1581 | 1519 | 1635 |
| *Cald6* | 57.17 | 20 | 194,57 | 212,45 | 178,19 | 1817 | 1800 | 1834 |
| *S-Jo1* | 120.43 | 16 | 414,04 | 471,69 | 363,43 | 1598 | 1540 | 1649 |
| *S-Ph1* | 160.93 | 26 | 564,67 | 662,55 | 481,25 | 1447 | 1349 | 1531 |
| *S-Ph2* | 84.24 | 25 | 286,04 | 317,18 | 257,96 | 1726 | 1695 | 1754 |
| *S-Ph3* | 72.78 | 26 | 246,85 | 271,64 | 224,32 | 1765 | 1740 | 1788 |
| *S-Ph4* | 55.54 | 25 | 189,18 | 206,45 | 173,35 | 1823 | 1806 | 1839 |

**Highlights**

- We develop an original method to date young lava flows (<1000 yrs) in the Tropics
- Pioneer tree diameters are used to date lava flows of PdF over the last 700 years
- PdF experienced two volcanic pulses shortly before human settlement on Réunion



Known historical lava flow (age CE)
Site on historical lava flow used for Agarista calibration (age CE)
Site on dated lava flow used for Agarista calibration (14C; BP)
Lava flow dated with Agarista calibration
Summit eruption (14C; BP)
Flank lava flow (14C; BP)
Agricultural footprint
Urban footprint
Réunion
Piton des Neiges
Piton de la Fournaise
Sainte-Rose
Bois Blanc
Grand Brûlé
Le Tremblet
Saint-Philippe
Saint-Joseph
Rivière Langevin
Basse Vallée
Enclos Fouqué
Central Cone
1708
1977
1998
1953
1931
2005
1961
2004
2002
1889
1830
1943
2007
1899
1774
1800
1986
1776
Cald1
Cald2
Cald3
Cald4
Cald5
Cald6
S-Ph1
S-Ph2
S-Ph3
S-Ph4
S-Jo1
420
260
140
130
340
160
255
380
868
620
355
385
364
575
455
55.6
55.7
55.8
-21.2
-21.3


Figure 1

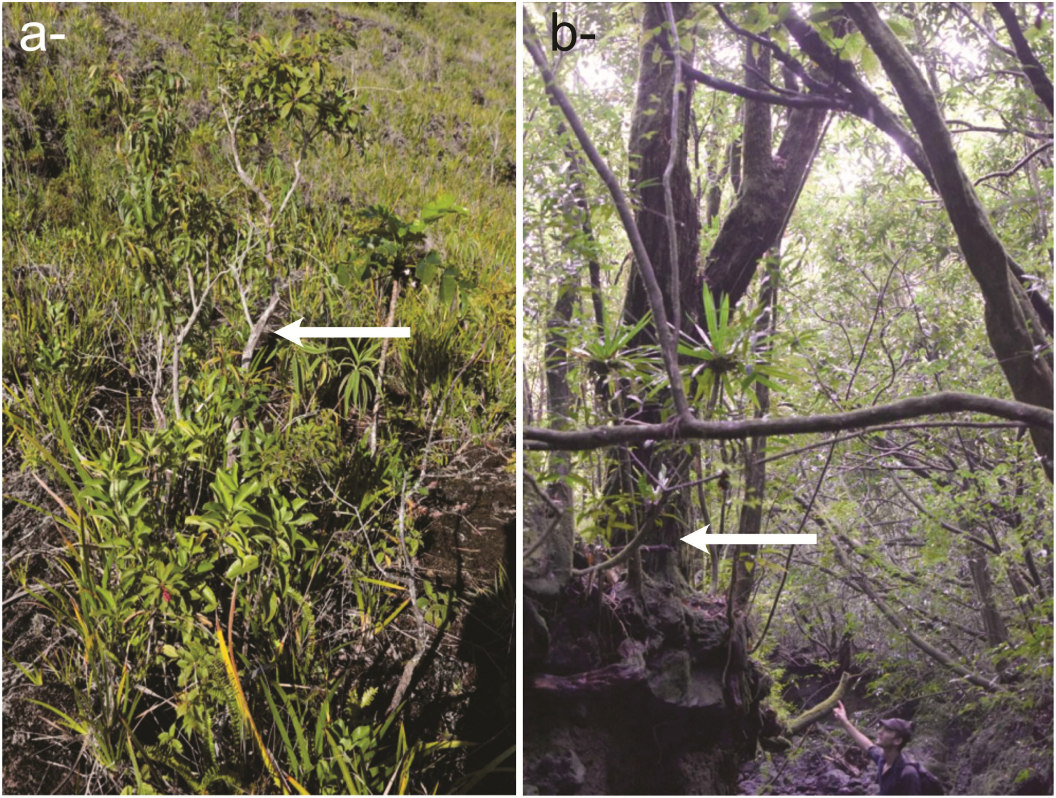
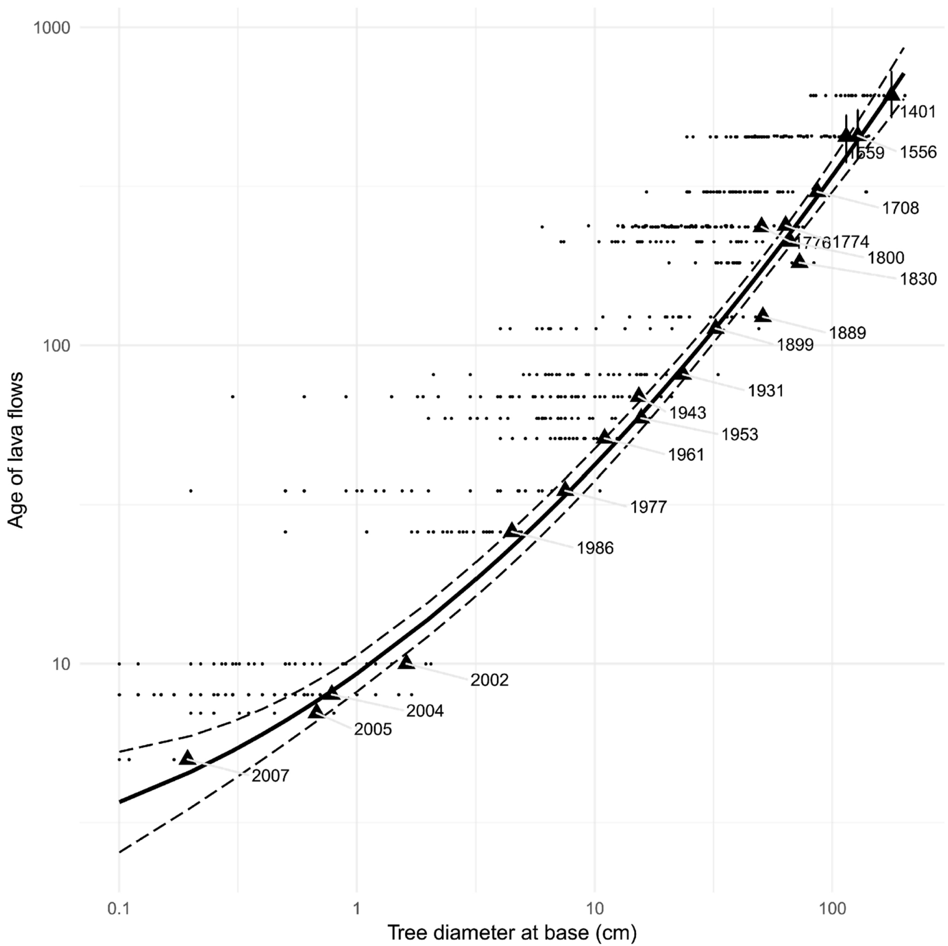



Figure 2



1000
100
10
Age of lava flows
0.1
1
10
100
Tree diameter at base (cm)
1401
1556
1559
1708
1776
1774
1800
1830
1889
1899
1931
1943
1953
1961
1977
1986
2002
2004
2005
2007


Figure 3

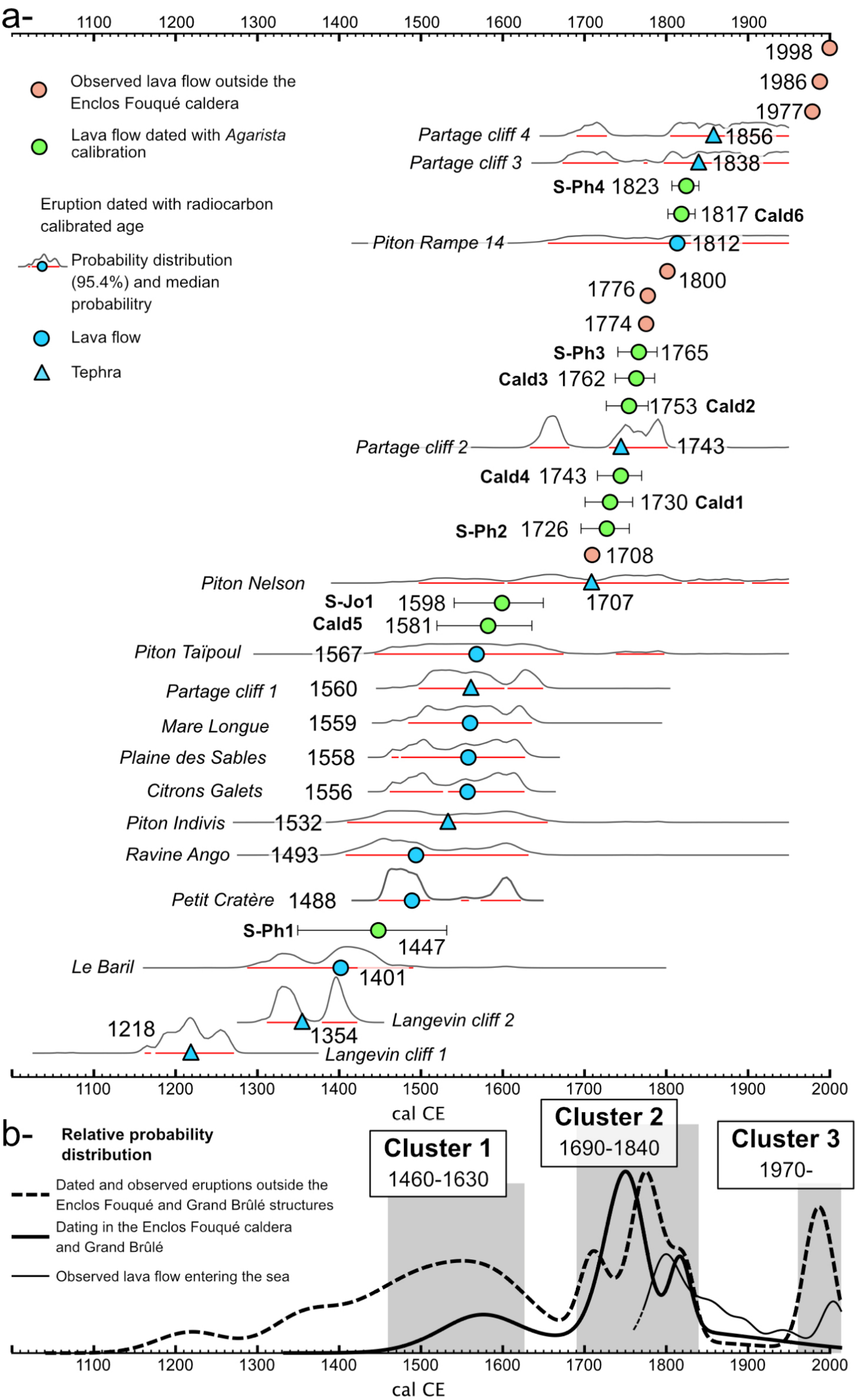
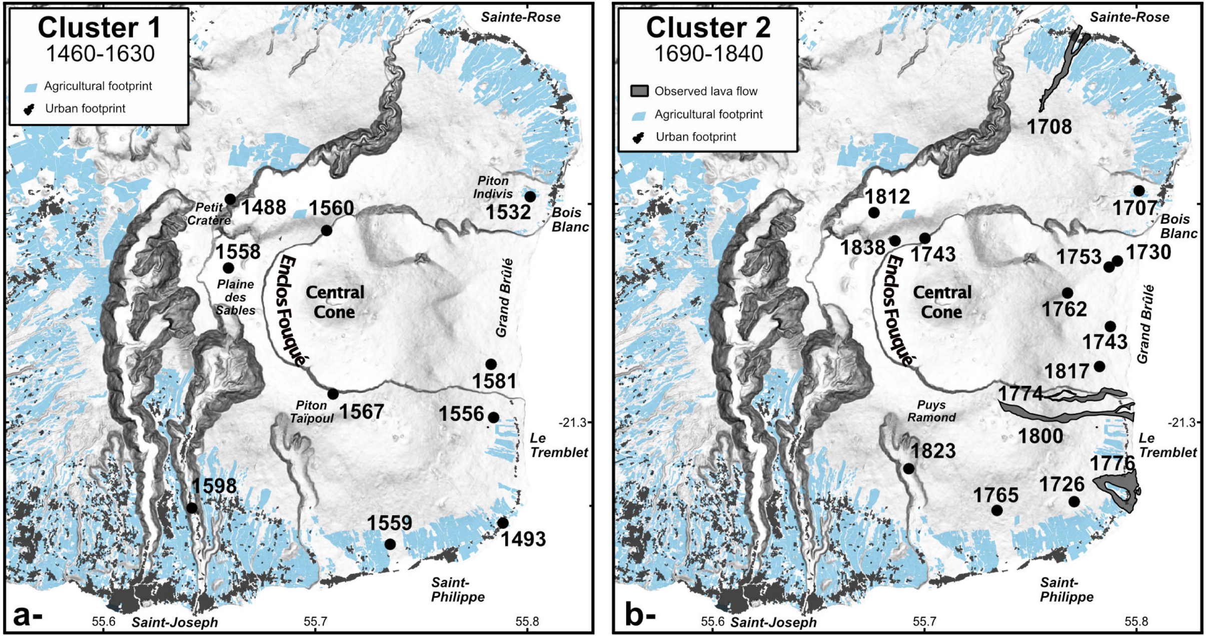

a-
Observed lava flow outside the Enclos Fouqué caldera
Lava flow dated with Agarista calibration
Eruption dated with radiocarbon calibrated age
Probability distribution (95.4%) and median probability
Lava flow
Tephra
1998
1986
1977
Partage cliff 4 1856
Partage cliff 3 1838
S-Ph4 1823
1817 Cald6
Piton Rampe 14 1812
1800
1776
1774
S-Ph3 1765
Cald3 1762
1753 Cald2
Partage cliff 2 1743
Cald4 1743
1730 Cald1
S-Ph2 1726
1708
Piton Nelson 1707
S-Jo1 1598
Cald5 1581
Piton Taïpoul 1567
Partage cliff 1 1560
Mare Longue 1559
Plaine des Sables 1558
Citrons Galets 1556
Piton Indivis 1532
Ravine Ango 1493
Petit Cratère 1488
S-Ph1 1447
Le Baril 1401
Langevin cliff 2 1354
1218 Langevin cliff 1
cal CE
b-
Relative probability distribution
Dated and observed eruptions outside the Enclos Fouqué and Grand Brûlé structures
Dating in the Enclos Fouqué caldera and Grand Brûlé
Observed lava flow entering the sea
Cluster 1 1460-1630
Cluster 2 1690-1840
Cluster 3 1970-
cal CE

Figure 4



Cluster 1
1460-1630
Agricultural footprint
Urban footprint
Sainte-Rose
Petit Cratère
1488
1560
Piton Indivis
1532
Bois Blanc
1558
Plaine des Sables
Enclos Fouqué
Central Cone
Grand Brûlé
1581
Piton Taïpoul
1567
1556
-21.3
Le Tremblet
1598
1559
1493
Saint-Philippe
a-
55.6
Saint-Joseph
55.7
55.8
Cluster 2
1690-1840
Observed lava flow
Agricultural footprint
Urban footprint
Sainte-Rose
1708
1812
1707
Bois Blanc
1838
1743
1753
1730
Enclos Fouqué
Central Cone
1762
1743
Grand Brûlé
1817
1774
Puys Ramond
1800
-21.3
Le Tremblet
1823
1776
1726
1765
Saint-Philippe
b-
55.6
Saint-Joseph
55.7
55.8


Figure 5