# Using apatite records of volatile budget and magma ascent rates to investigate eruption dynamics

Olivier Bernard[1,2,*], Weiran Li[1,3], Fidel Costa[1,2], Caroline Bouvet de Maisonneuve[1,2]
[1]Earth Observatory of Singapore, NTU, Singapore [2]Asian School of the Environment, NTU, Singapore [3]University of Cambridge, UK
*bern0027@e.ntu.edu.sg

NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

EARTH OBSERVATORY OF SINGAPORE

NATIONAL RESEARCH FOUNDATION
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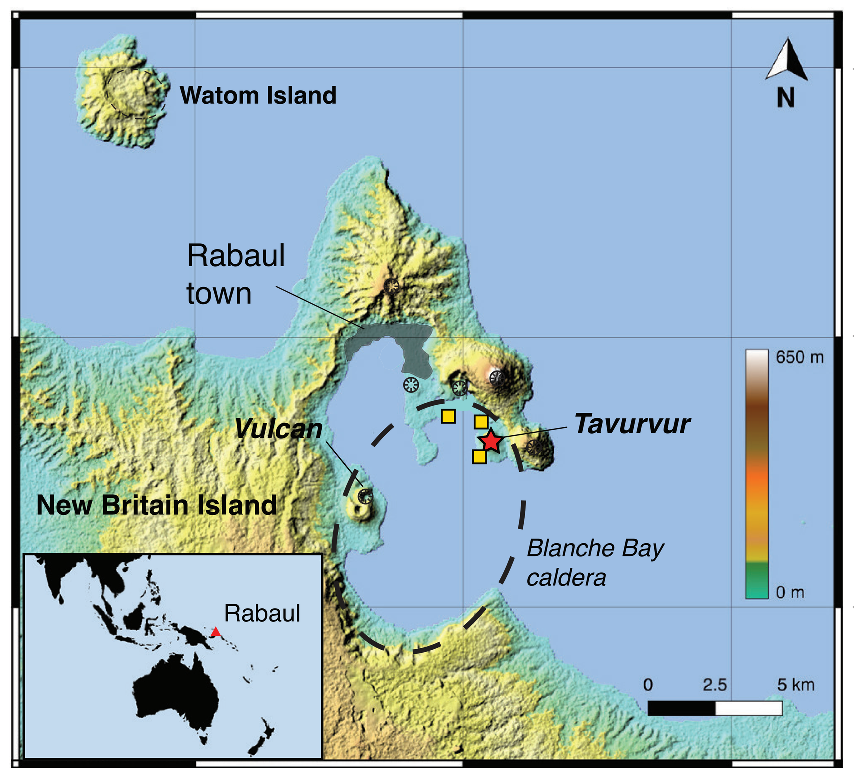
## 1. Study aim

Quantifying both pre-eruptive volatile budgets and timescales of magma ascent is challenging and crucial to understand controls on eruption dynamics. One solution would be to use the abundance and zoning pattern of F, Cl and OH in apatite to determine these two parameters, that can, under some conditions be related to magma ascent rates (**1**; **2**).

Here we apply the two methods to apatite in the Rabaul 2006 deposits (Papua-New-Guinea). This was a VEI-4 eruption with a sub-plinian, a mixed strombolian/effusive and a vulcanian phase (see below). This is the perfect system to apply our methods on as the petrology of these deposits have already been characterized in previous studies (**3**; **4**).

**Our aim is to:**

- Charcterize apatite composition in each unit of the eruption;
- Use (1) model to calculate pre-eruptive water content from apatite in inclusion in pyroxene;
- Use (2) F-Cl-OH diffusion model on matrix apatite to estimate magma ascent rate for each eruption phase
- And, combine these results to understand the controls on the 2006 eruption.

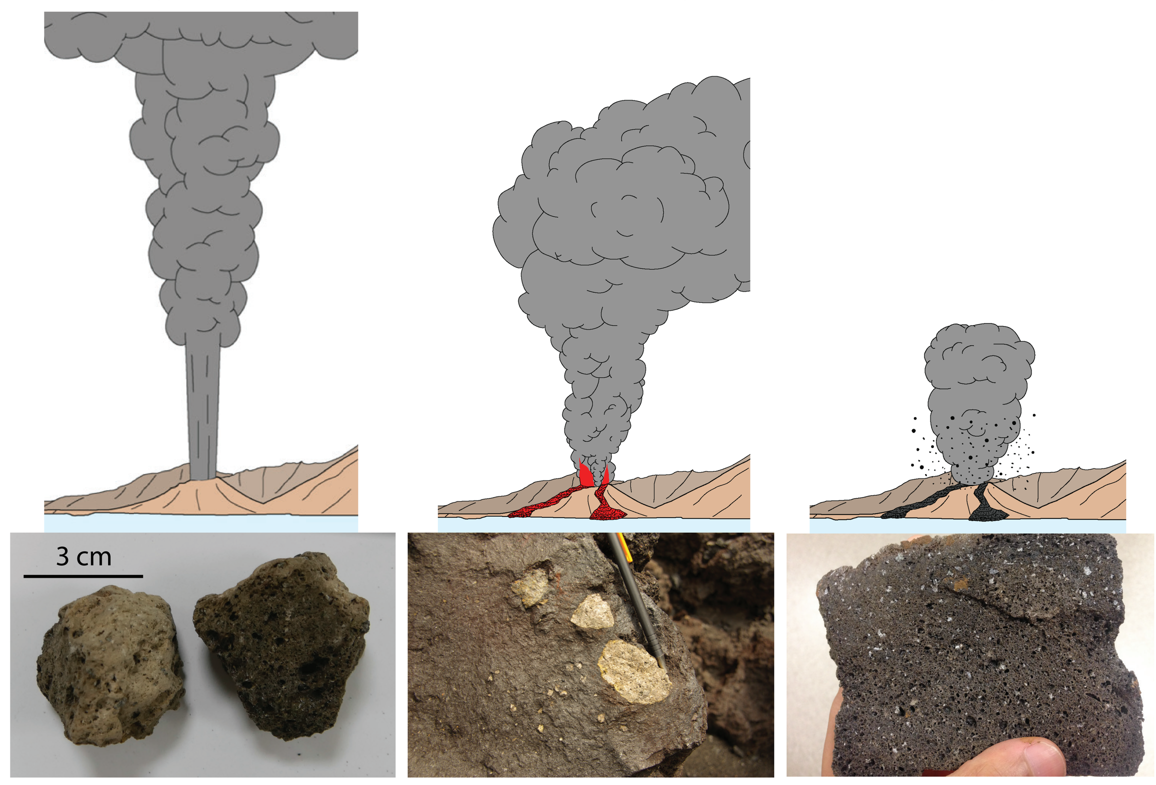



*Topographic (SRTM) map of the Rabaul volcanic complex (modified from **4**). The red star is the eruption vent, yellow squares are the sample locations.*

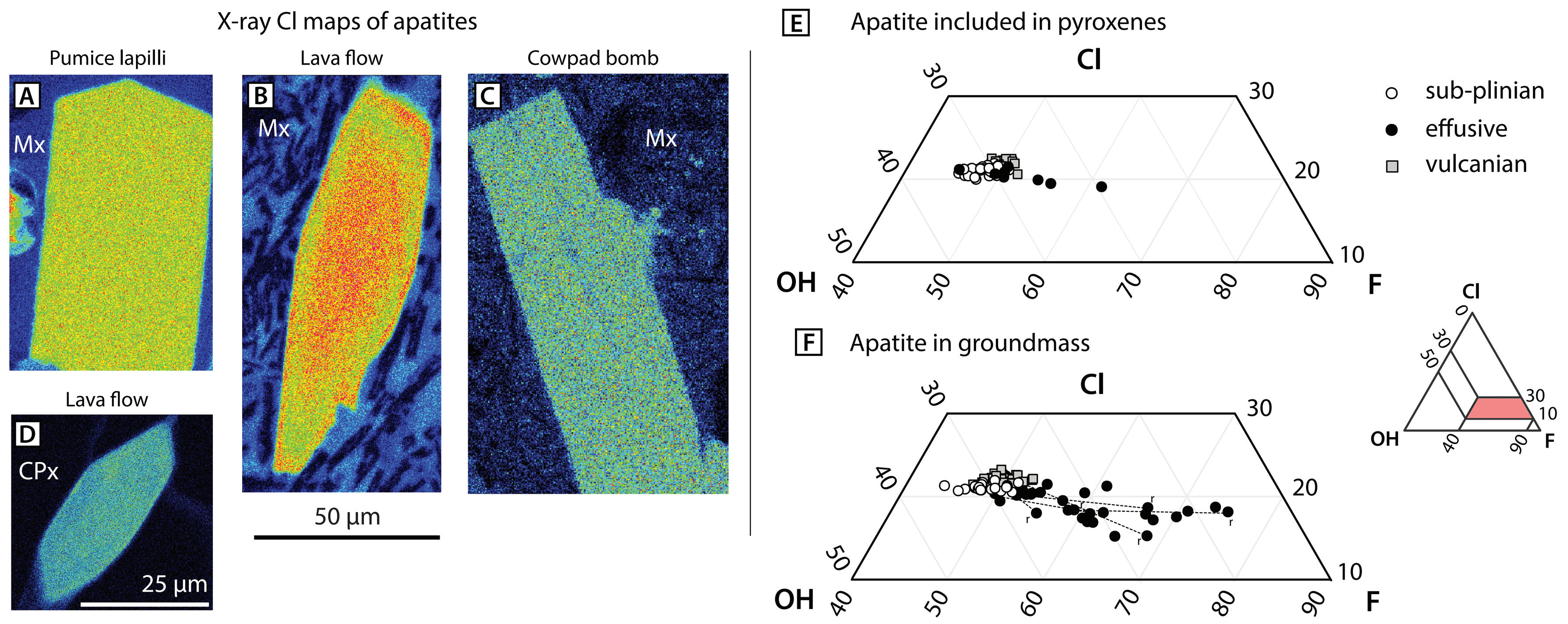
2006 eruption timeline

- **Pre-paroxysm (1994 – Oct 2006)**
  Semi-continuous activity at Tavurvur with breaks of 2 years at most
- **Sub-plinian opening phase (Oct 7th 2006)**
  Starts at 8.45am and transition to Strombolian at 2.15pm
- **Strombolian/effusive phase (Oct 7th - 8th 2006)**
  Emplacement of two lava flows overnight
- **Vulcanian phase (Oct 8th – 28th 2006)**
  Vulcanian explosions with decreasing rate
- **Post-paroxysm Nov 2006 - 2010**
  Discrete small vulcanian or ash venting events with some small peaks in activity

Main Phase




## 2. Apatite volatile composition



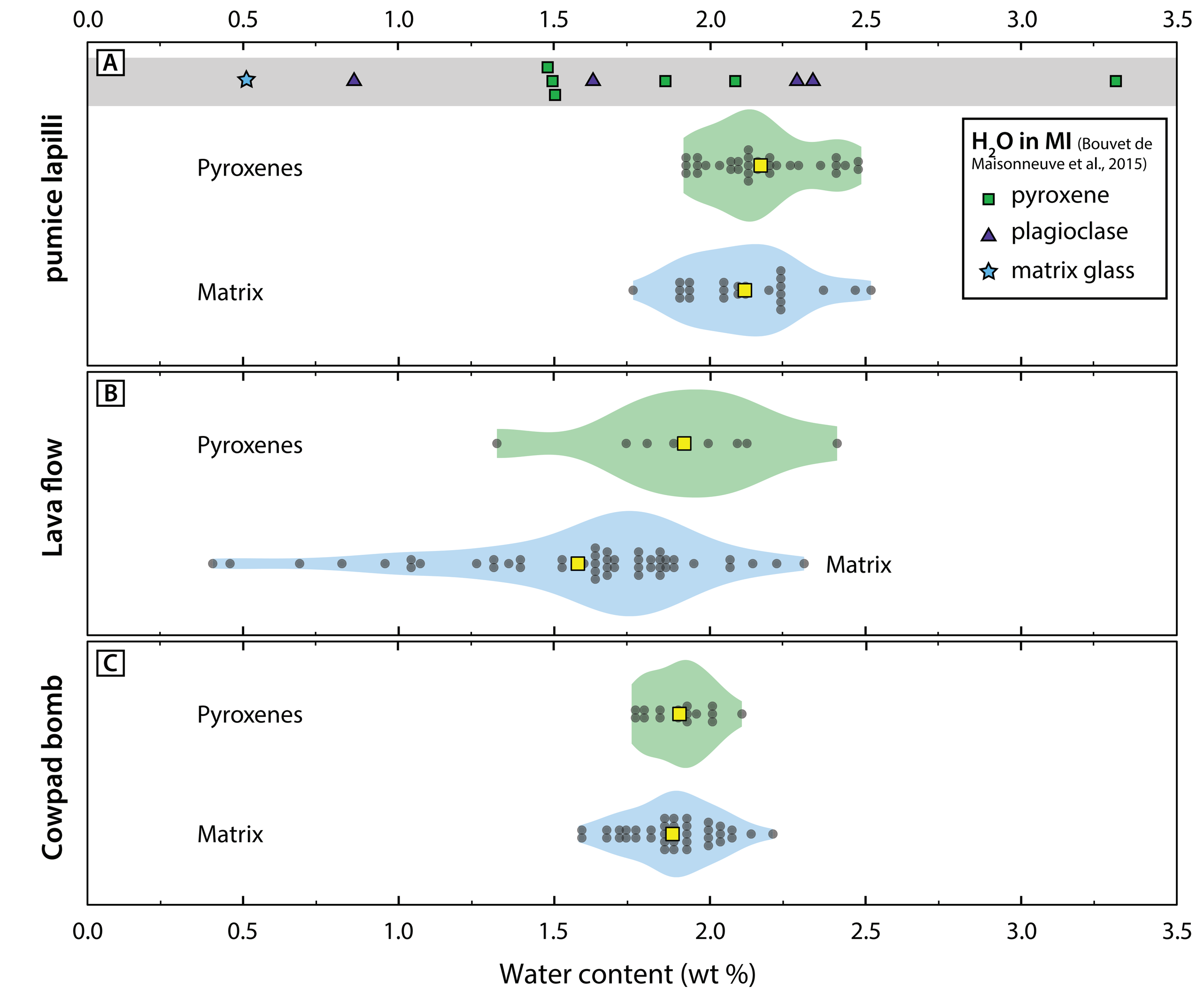

*Apatite composition of Rabaul 2006 eruption. A–D) X-ray maps of Cl in apatite (color bars are different for different maps). A–C) present matrix apatite from each phase of the eruption (the 50 µm scale is the same for the 3 crystals). Cl zoning is visible in the matrix apatite erupted during the effusive phase (B), but not in the apatite erupted during sub-plinian (A) and vulcanian (C) phases, nor in the apatite in inclusion in pyroxene of the lava flow (D). E–F) Zoomed (see diagram in the middle) ternary plots showing apatite Cl-F-OH composition acquired from single point analysis using EPMA. E) presents apatite inclusions in pyroxenes, F) shows apatite in the groundmass. Apatite in the lava flow, especially those in the matrix, show F enrichment and OH depletion towards the crystal rim due to partial reequilibration with the degassed matrix. Dotted lines link the core and the rim (annoted with a little r) point analyses made in the same apatite for the lava flow.*

## 3. Water content

We calculated water content from apatite using the exchange coefficient ($K_D$) of OH-Cl between apatite and melt formulated by (**1**):

$$\ln\left(K_{D^{Ap-melt}_{OH-Cl}}\right) = -\frac{1}{RT} \times \left(\begin{matrix} 72900(\pm 2900) - 34 \pm (0.3) \times T \\ -1000 \times [5(\pm 2) \times (X^{Ap}_{Cl} - X^{Ap}_{OH}) - 10(\pm 8) \times X^{Ap}_{F}] \end{matrix}\right)$$

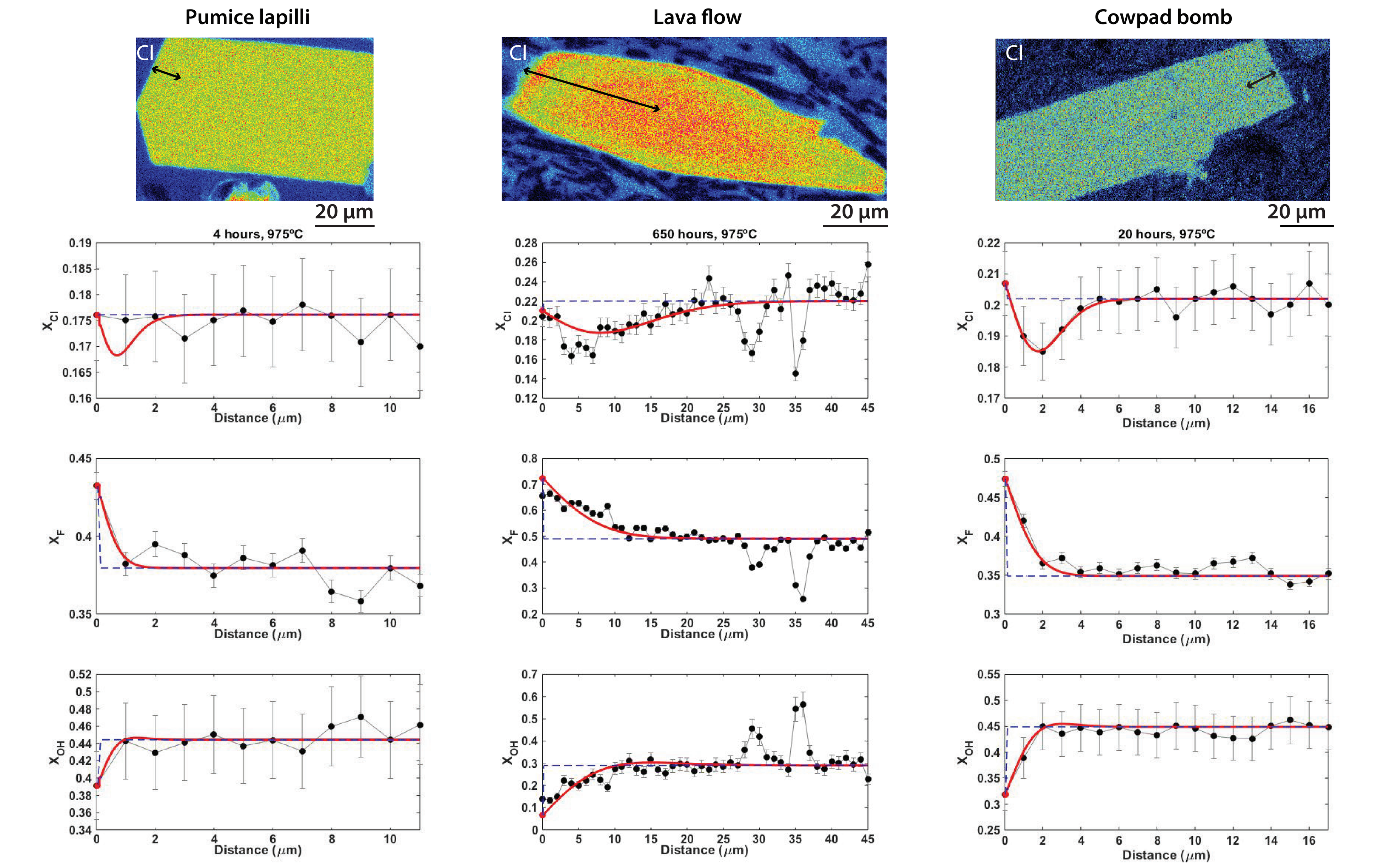
With this formulation, we can calculate water content if we know the apatite F-Cl-OH and the melt Cl concentrations, as well as the temperature. F, Cl in apatite and Cl in melt can be easily measured at the electron microprobe, and OH in apatite is determine by stoichiometry.




*Melt water contents calculated using the exchange coefficient for Cl-OH between apatite and melt from the model of (**1**). Data in the grey band on panel A) are direct measurements of water in melt inclusions (MIs) using SIMS reported by (**3**). Uncertainties in these data are smaller than the symbol size. The yellow squares represent the mean of each sub dataset. The circular grey points each represent one apatite crystal, binned every 0.025 wt% H2O.*

## 4. Multi-component F-Cl-OH diffusion modelling along apatite c-axis to determine magma ascent rates

We performed multi-component (F, Cl, OH) diffusion modelling of apatite in the matrix of each phase of the deposit. Apatite crystals in lava flow appeared Cl-zoned in X-ray mapping. Crystals in the cowpad bomb were very slightly zoned at the rim, while crystals in the pumice did not show any evident zoning:




Apatite in the sub-plinian deposit showed flat profile which are evidence of no diffusion of F, Cl and OH. Here we put 4h diffusion time which corresponds to a distance of 2 µm of Cl diffusion and the minimum distance on which we can accurately measure a compositionnal change at the EPMA. As we cannot fit this profile (no Cl-zoning), this shows that there was less than 4h diffusion in the pumice crystals.

Apatite in the lava flow are zoned in F, Cl and OH. Diffusion time at 975°C obtained on these apatite are between 650–2200 h (1-3 months).

Apatite in the vulcanian deposit show a slight zoning at the rim that translates into a 10–20h of diffusion time at 975°C.

## 5. Volatile and magma storage Pressure

Water content obtained from apatite that grew at equilibrium that were then encapsulated by pyroxenes can inform us of the pre-eruptive melt water content:

We obtained a range of 1.5–2.5 wt% $H_2O$ from these crystals with pumice apatite having an average at 2.1 wt% $H_2O$, 0.3 wt% higher than for the lava flow and the vulcanian crystals (1.8 wt% $H_2O$) - see part 3.

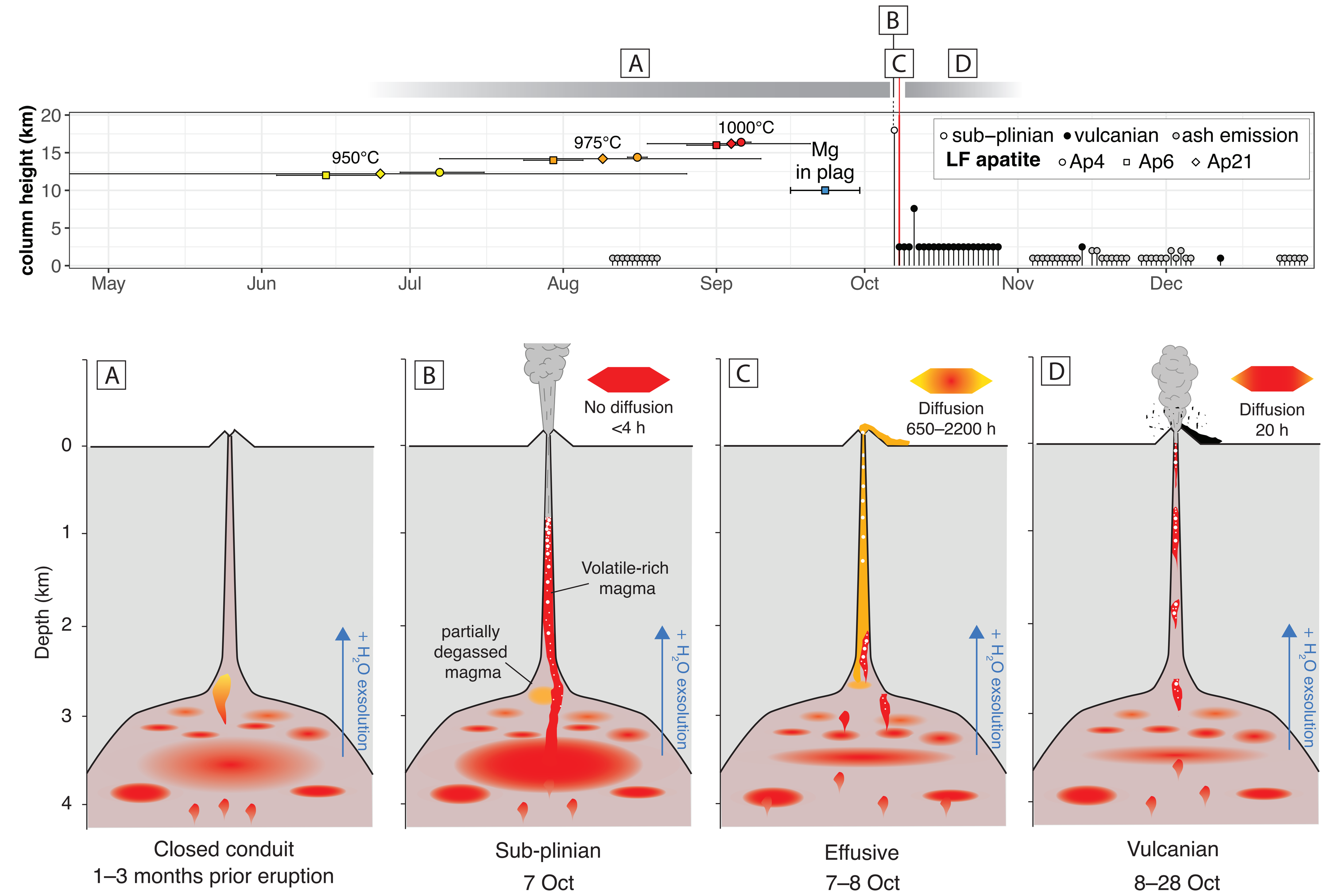
We estimate storage pressure difference between the deposits using the model of (**5**) in two conditions: no $CO_2$ added and 150 ppm of $CO_2$ added for all deposits (value based on Melt inclusion analysis at the SIMS in the pumice - **3**):

In the first case (no $CO_2$), the **pressure difference is 80 bars** (approx. 300 m) between deposits from the sub-plinian and the deposits of the other phases.

In the second case (150 ppm $CO_2$), we obtain **160 bars of pressure difference** which translates into approx. 600 m difference in depth between sub-plinian and the remaining deposits.

So overall, the difference in water content from apatite can be translated into an approx. **0.5km difference in storage pressure**. Based on literature (**6**), Rabaul's reservoir is located between 3 and 6km depth, with dacitic products sitting on top. We can then propose that **the sub-plinian magma batch rose from approx. 3.5 km depth while the lava flow and vulcanian batches were initially stored at approx. 3km.**

## 6. Timing and reservoir processes during the 2006 Rabaul eruption




Based on the results from apatite we propose a model for the timeline of the 2006 eruption:

**A: 1–3 months** before the onset of the eruption, magma started rising in a shallower part of the plumbing system, and started degassing. This is evidenced by F-Cl-OH zoning in matrix apatite crystals in the lava flow.

**B:** Apatite crystals in the pumice present no zoning. This implies, fewer than **4h** of degassing (see part 4.). As a result, we estimate the **average ascent rate** for this phase to be at least **0.25 m/s** using a source depth at 3.5 km (see part 5.).

**C:** Following the sub-plinian phase, **a lava flow is emplaced in a few hours**. This is the result of the first batch of magma (A), that was degassing for 1-3 months before the eruption being **remobilized by the sub-plinian magma batch**. The diffusion is unlikely to have occured at the surface while the flow was cooling as diffusion time of F-Cl-OH in apatite increases by 3 orders of magnitude at 700°C (which is the temperature the surface of the flow would have reached almost upon emplacement).

**D:** After the effusive phase, vulcanian eruptions with decreasing frequencies over the span of two weeks were observed. The water content calculated from apatite included in pyroxene in the ballistic bomb indicate a similar depth of storage and equilibration as the one in the lava flow (see part 5.). However, the zoned crystals indicate only **10–20 hours of degassing prior to eruption**, thus spending <20 h at a depth where melt-water loss was significant enough to be recorded by apatite rims. This can be translated into **0.04–0.08 m/s** of ascent from 3km depth.

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