Deconstructing the role of hydrothermal alteration in 3D volcanic dome collapse in La Soufrière de Guadeloupe

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1. Motivation

Here, we investigate the effect of **hydrothermal alteration** on volcanic dome stability, where alteration typically results in mechanical weakening of volcanic rock. This makes the dome unstable and can lead to geohazards such as landslides (Figure 1).

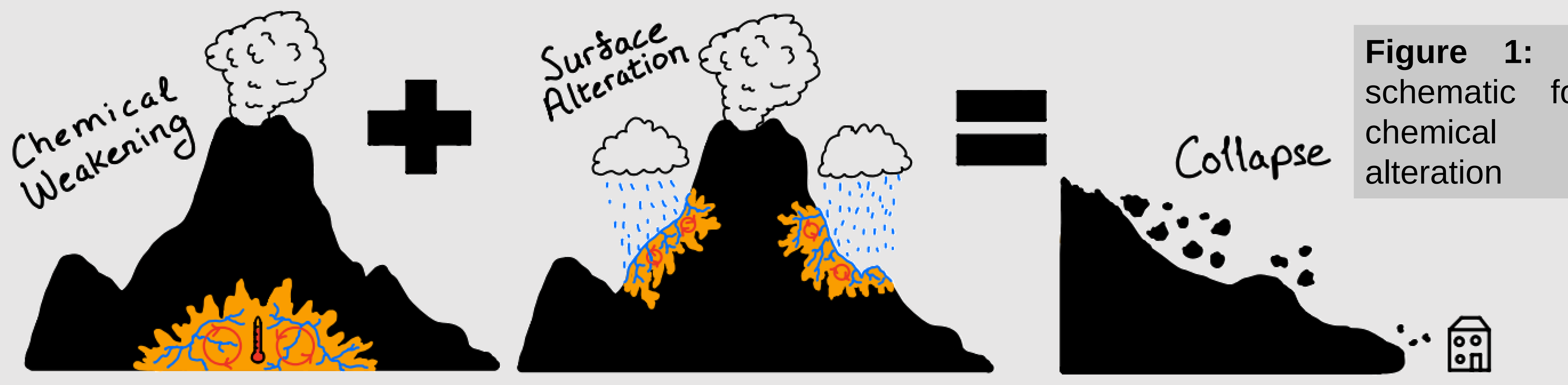


Figure 1: A schematic for chemical alteration

We aim to create **3D numerical models** of volcanic lava domes, while considering how varying the degree of **alteration-induced weakening, spatial extent, and size of alteration zones** affect their **post emplacement 3D stability**. Our models will feed into assessments of alteration-induced volcanic hazards.

3. Results: Displacement

We show here results of alteration scenario testing. Firstly, we look at varying the degree of alteration-induced weakening in an alteration zone, in this case, "The Bulge". This consists of a **resistive, dense rock** lying above a zone of pervasive hydrothermal alteration that surfaces on the south of the dome. This represents a potential **detachment plane** and is thus a focus for our **collapse models.** We test collapse scenarios for a bulk rock strength of 10% and 50% of the original strength. This is achieved by reducing the **tensile strength, cohesion** and **Young's modulus** between particle contacts in PFC.

Alteration: Induced Weakening

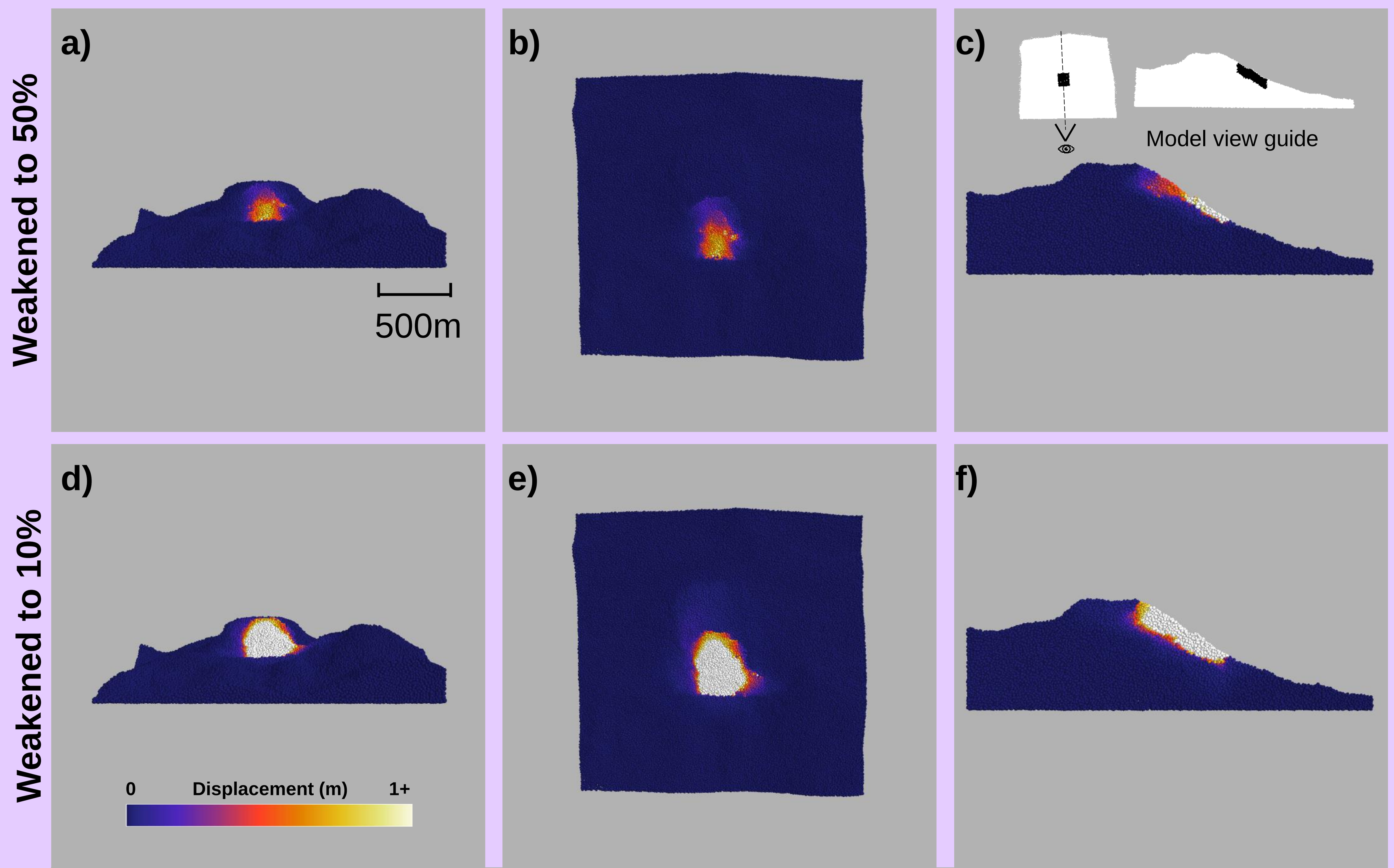


Figure 4: Displacement from 0 m to 1+ m in PFC models, visualised with the Mayavi Python package, with an induced weakened zone located in the top 100 m; (a)-(c) Front view, aerial view and cross section (across the x-axis) for weakening to 50% strength, respectively, and (d)-(f) Front view, aerial view and cross section (across the x-axis) for weakening to 10% strength, respectively.

There are **greater displacement magnitudes** in the model that has been reduced to 10% of its original strength, than the one that has been reduced to 50%, as is expected. The displacement is also affected by local topographic variation.

Alteration: Spatial Extent

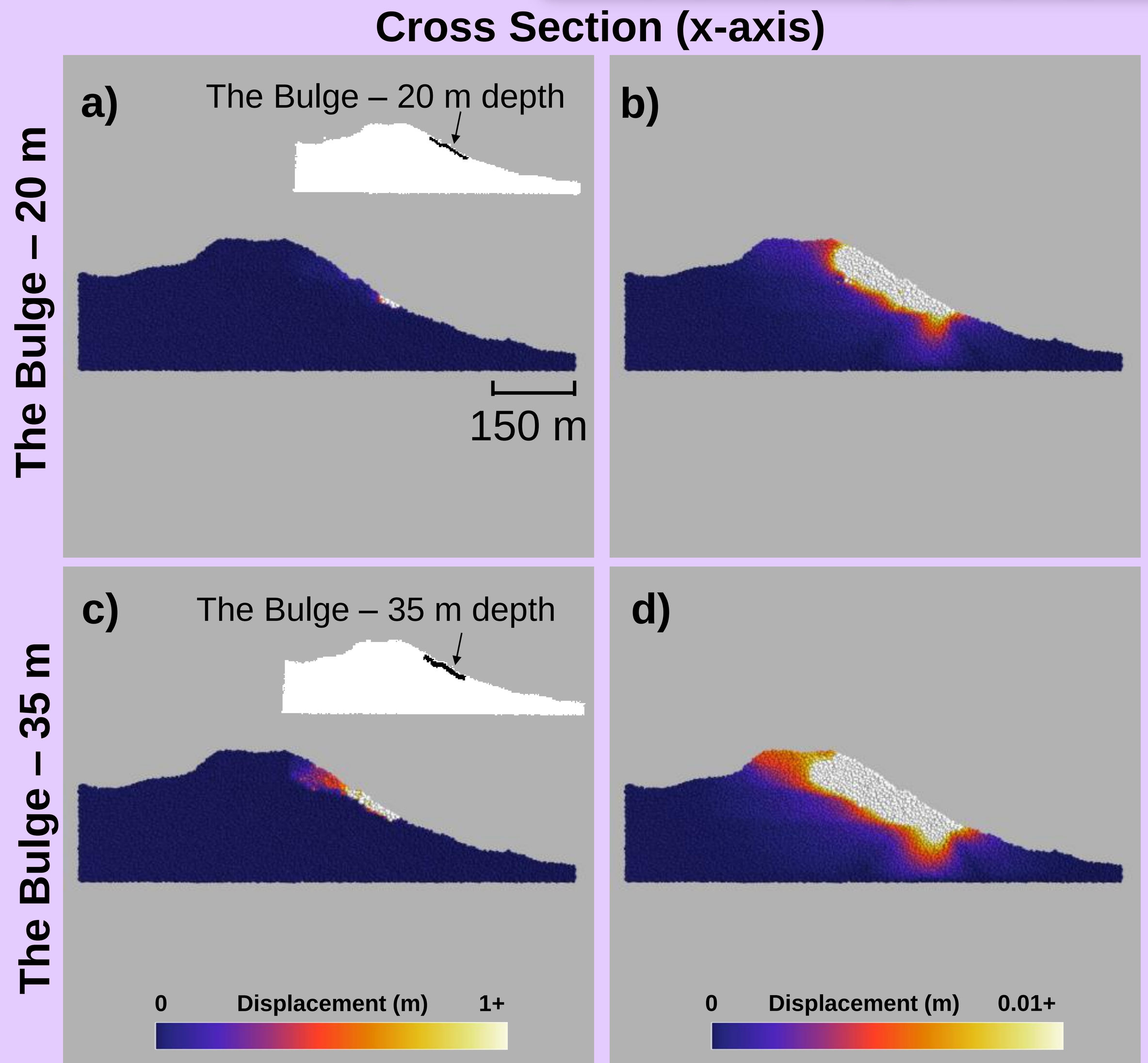


Figure 5: Models demonstrating the effect of near-surface alteration, all weakened to 10% of their original strength. We show aerial view and cross section (across the x-axis), respectively, for "The Bulge"; at (a)-(b) 20 m depth, and (c)-(d) 35 m depth. We show displacements on a metre scale or larger in (a) and (c) and a millimetre scale or larger in (b) and (d).

In Figure 5, all collapse models are tested for a bulk rock strength of 10% of its original strength. This is again achieved by reducing the **cohesion, tensile strength** and **Young's modulus** between the particle contacts. However, this time we vary the spatial extent of the alteration zone. We simulate an alteration zone:

(a-b) at a 20 m thickness surface layer

(c-d) at a 35 m thickness surface layer

We show:

(a&c) on a metre scale

(b&d) on a millimetre scale.

Even when weakening only the top 20-35 m of the dome, we can see displacement to depths of up to 300 m.

This indicates that surface level alteration can have **deep-seated effects**. We also see that more pervasive near-surface alteration results in increased displacement.

2. Methodologies

- Used **Particle Flow Code 3D** (Itasca Consulting Group Ltd.) to design new 3D models.
- Modelling uses the Discrete Element Method (DEM)
  - Simulates an assembly of particles that behave as rigid bodies and interact at interparticle contacts
  - Contact behaviour primarily governed by user-defined stiffness, strength (compressive and tensile), and Young's modulus

- Internal structure of the La Soufrière de Guadeloupe dome was mapped by Heap et al. (2021)
  - **Muon tomography** surveys carried out to obtain the density variation within the dome.
  - **Wet** density contrasts correlated with mechanical parameters (i.e., uniaxial compressive strength of volcanic rock) to obtain a **3-D internal strength map** of the dome (Figure 3).
  - Rare data as domes are too hazardous to enable the deployment of geophysical equipment.

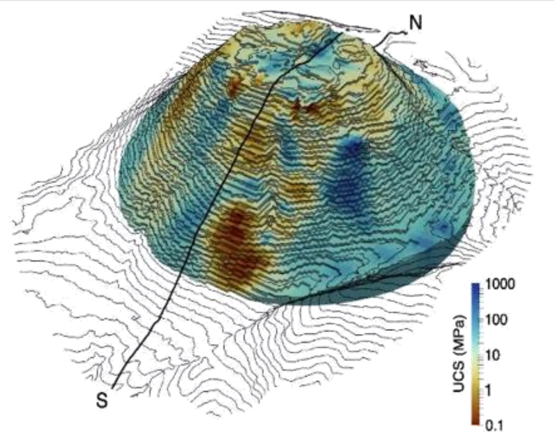
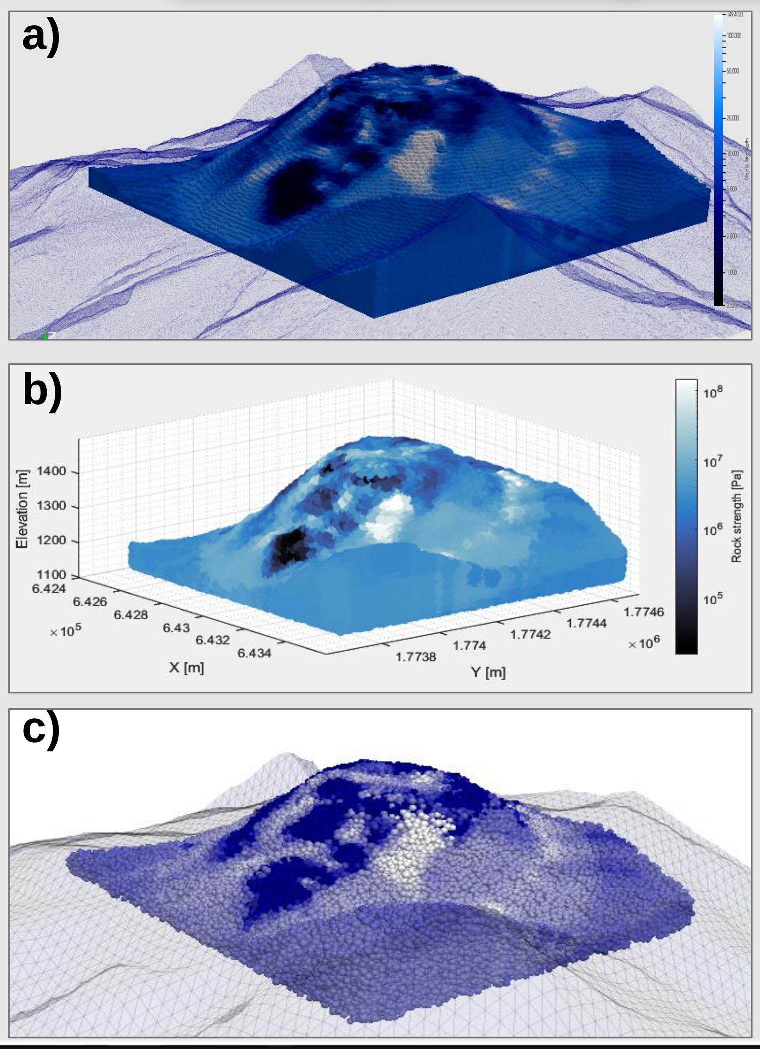


Figure 2: A 3-D internal strength map of La Soufrière de Guadeloupe by Heap et al. (2021). Rock strength is measured in Mega Pascals.

Reproducing an Internal Strength Map



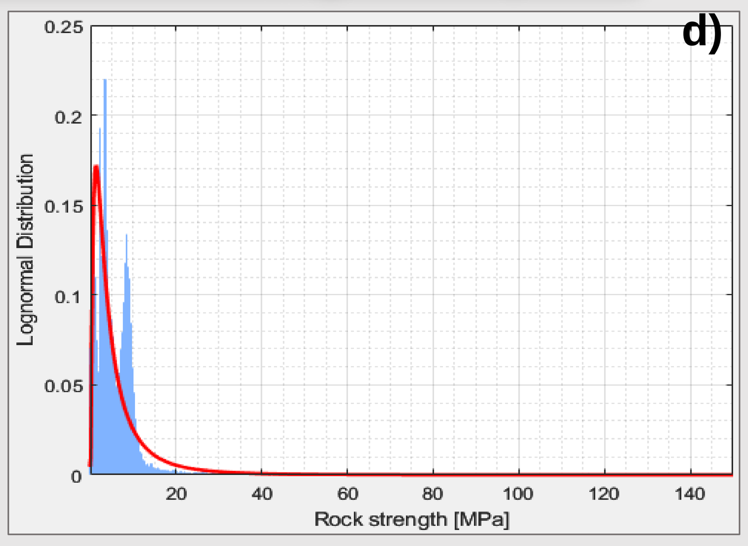
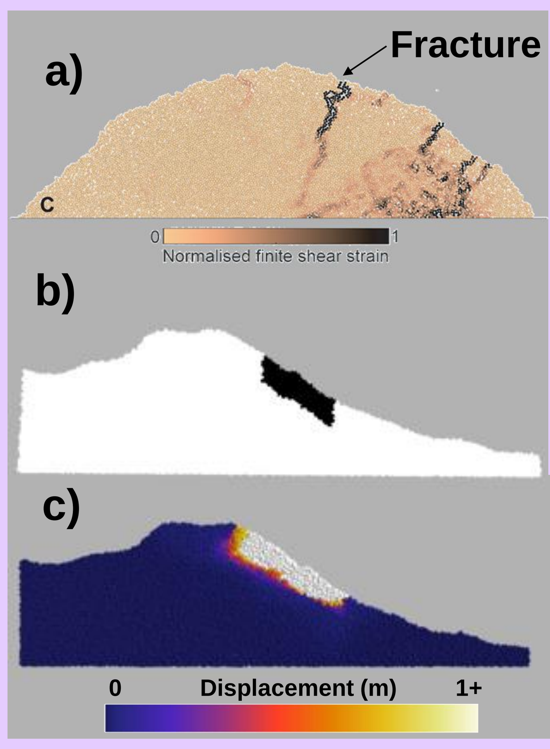


Figure 3: Model set-up incorporating the geophysical rock strength data where it's: (a) gridded in ParaView (b) interpolated between gridded points and ball positions with a nearest neighbourhood algorithm in MATLAB and (c) created in PFC where each ball is now associated with a rock strength. (d) Shows a lognormal distribution in Mega Pascals of the strength distribution in the model.

4. Results: Strain



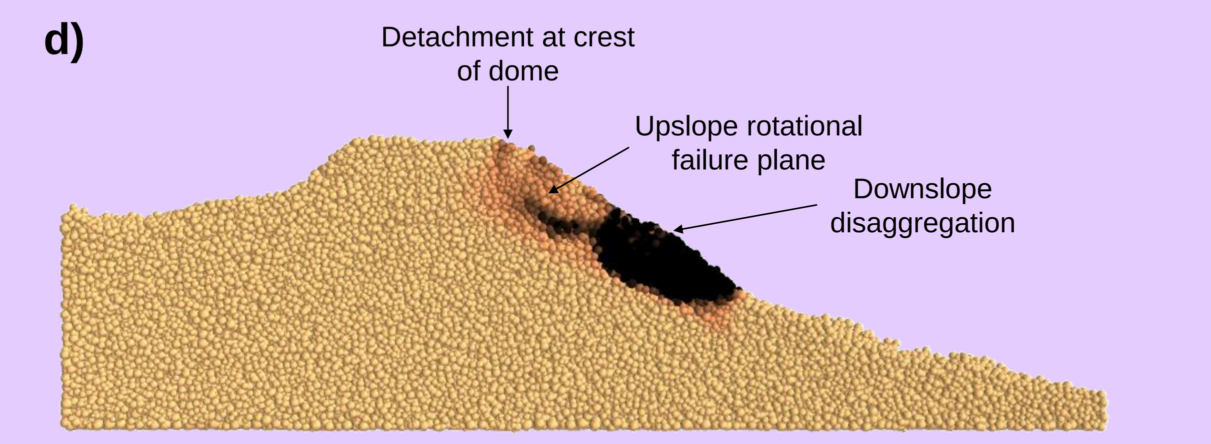


Figure 6: Image (a) shows 2D strain modelling by Harnett et al. (2022) in a lava dome. Then, we show results in cross section simulating an alteration zone at 100m depth at "The Bulge". The bulk strength is reduced to 10% of its original strength where (b) shows the alteration zone, (c) shows the displacements on a metre scale, and (d) shows normalised strain accumulation.

Visualising **strain** accumulation instead of displacement allows us to locate **faulting** and areas of relative motion. In Figure 6, we can see two potential upslope rotational failure planes. In the lower one, we observe downslope disaggregation where there is no localisation of strain. The upper one is forming due to the first rotational slope falling away. There is detachment at the crest of the dome, which indicates fracturing. Both displacement and strain spread further than the original altered zone.

Collapse Volumes

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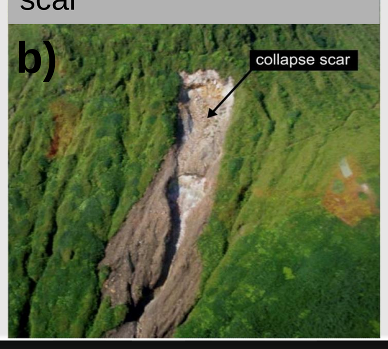
5. Conclusions

Figure 7: La Soufrière de Guadeloupe (a) dome, and (b) collapse scar



- Inducing **weakening** due to alteration increases dome **instability**
- **Surface** level alteration causes **deep-seated** displacements
- Thicker zones of near-surface alteration results in increased magnitude and extent of displacement
- Strain calculations newly possible in 3D
- Bigger collapse volumes due to increased alteration
- Future work
  - Comparing dry vs wet data
  - Comparing experimental vs upscaled models
  - Thermo-hydro-mechanical coupling

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