1. STATE-OF-THE-ART AND CURRENT CHALLENGES

Motivation: Why study volcanic flank collapses?

Volcanoes are among the most rapidly growing geological structures on Earth. Consequently, volcanoes commonly suffer structural instability (Fig. 1a) that may result in lateral flank collapses, such as the 1980 Mt St Helens collapse. Collapses of ocean island volcanoes or those along shorelines can trigger ocean-wide tsunamis with extreme effects. The world just witnessed a small example of such an event: the 22 December 2018 collapse of Anak-Krakatau in Indonesia (Fig. 1b) that caused a tsunami with 430 fatalities at the surrounding coasts. The collapse involved only ~0.12 km³ of subaerial material[1]. For comparison, collapse of the Mount St Helens volcano in 1980 involved ~3 km³(2). The Nuuanu volcanic landslide off Oahu, Hawaii, moved ~5,000 km³ of rocks over a distance of more than 200 km about 2 Ma ago[3] and must have caused a Pacific-wide tsunami with up to 70 m high waves in North America and Japan[4]. Around Hawaii, more than 68 major landslide deposits document a geologic history of repeated volcano collapses[5]. Collapses of large basaltic volcanoes (Fig. 1a), such as the Canaries or Hawaii, are much less frequent than those of smaller island arc volcanoes (global recurrence intervals of ~100 years[6]), such as Anak-Krakatau. However, geological evidence is abundant that they occur and that they are devastating.

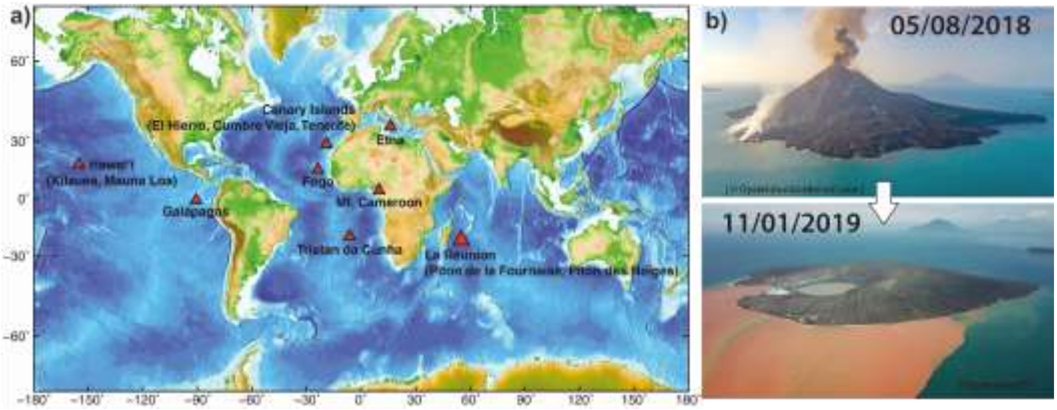

Figure 1: *a) Large basaltic volcanoes with known flank instability[8]. The map excludes numerous unstable subduction arc volcanoes, such as Anak-Krakatau (b) that collapsed catastrophically on 22 December 2018.*

Flank collapses of coastal or ocean island volcanoes are at the high risk-low frequency extreme of risk matrices. Yet, society's tendency to settle in coastal areas and its increasing reliance on global maritime traffic and associated coastal infrastructure to maintain international commerce and commodity supply means that they pose an ever-increasing threat to our civilisation. As historical records of large collapses are rare, their hazard potential is not as obvious as highly frequent events, such as volcanic eruptions or earthquakes. However, catastrophic collapses have occurred in the geological past and will occur again. Given the extreme direct and indirect hazards of flank collapses there is an urgency for both the assessment of their hazards and the development of early warning strategies. While most volcanoes in densely populated areas are intensively monitored with the aim of forecasting eruptions, flank collapses are not routinely considered in monitoring schemes or hazard assessments. This is mainly due to a lack of understanding of the causes of collapse and, consequently, our inability to identify and interpret potential precursory signals.

Possible causes for volcanic flank collapse

Numerous hypotheses have been put forward to explain structural failure of a volcanic edifice, including explosive eruptions, earthquakes, basement uplift or subsidence, climatic effects, water infiltration, and changes in sea level. Satellite geodetic measurements available since the 1980s clearly document slow movement of numerous volcanic flanks worldwide (Fig. 1a). For example, the southeastern flank of Mt Etna in Italy continuously slides seawards at about 2-3 cm/yr[7]. In Hawaii, Kilauea's south flank moves into the Pacific Ocean at ~10 cm/yr[8]. The edifices of both Etna and Kilauea have partly failed in the geological past; forming the Valle del Bove depression at Etna about 8000 years ago[9] and the proto-Hilina slump at Kilauea[10]. Other examples of large volcanoes with current flank sliding and evidence for past collapses are Piton de la Fournaise (La Reunion), Cumbre Vieja, El Hierro, Teide (all Canary Islands), or Fogo (Cape Verdes) (Fig. 1b). There is also compelling evidence that the flanks of Mombacho (Nicaragua)[11] and Ritter Island (Papua New Guinea)[12] had been sliding prior to their collapses in 1570 and 1888, respectively. Finally, Anak-Krakatau's western flank also gradually moved seawards at a rate of ~20 cm/yr prior to its collapse[1]. These observations suggest **that slow flank sliding precedes catastrophic collapse[11,13]. I propose that observation of this deformation can help identify flanks that are in transition to collapse**.

Problem statement

Slow volcanic flank movement is recognizable by ground deformation monitoring onshore and offshore[14] and could potentially permit prediction of volcano flank collapse. However, there is as yet no rigorous physical explanation for a potential transition from slow sliding into catastrophic collapse. Consequently, it is currently impossible to identify slow-sliding precursors, which might indicate imminent collapse (Fig. 2). It also remains enigmatic whether all volcanoes with currently slow sliding flanks will collapse catastrophically in the future. PRE-COLLAPSE aims to understand the physical explanation for and hence predictability of precursory slow flank movement. Once the effect of slow flank sliding on volcano stability is understood, it should be possible to use the characteristics of precursory sliding and its changes to constrain the probability of catastrophic collapse.

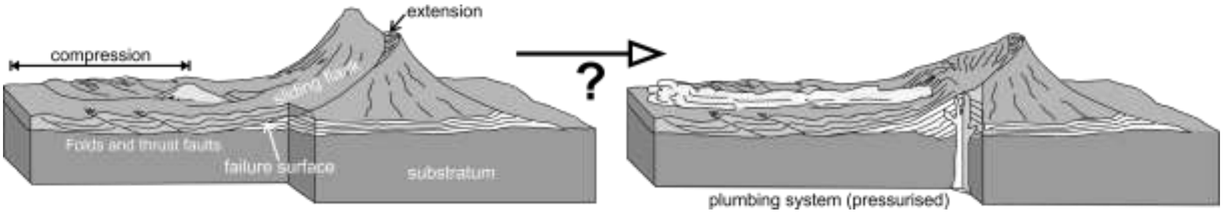

Figure 2: *How can slow flank movement (left panel) turn into runaway acceleration (right panel)?*

I propose two hypotheses for slow sliding to turn into collapse: (1) Reduction of edifice stability through strain-weakening material behaviour and/or formation of internal shear zones, and (2) interaction of increased magmatic activity and flank deformation leading to a run-away positive feedback loop.

Hypothesis (1): Flank sliding alters the stability of the volcanic edifice by changing the rocks' mechanical properties due to continuous shearing, inducing tensile and compressive stresses in the sliding mass, or modifying slope topography to an unfavourable setting. These processes may either cause direct flank collapse or weaken the flank to an extent that an external trigger, such as an earthquake, can cause collapse. This hypothesis also explains the transition of ultraslow landslides into catastrophic events[15,16]. Volcano stability analyses under consideration of a wide range of destabilising factors have so far provided valuable insights into static stability[17-20]. Yet, flank sliding has never been considered in these analyses. Whether transition into runaway acceleration is possible also strongly depends on the frictional properties of the prevailing rocks, which have a complex dependence on magnitude and velocity of shearing[21]. Shear tests are typically conducted at rates of millimetres per second. This is much faster than observed flank sliding rates (cm/yr). Thus, the potential of volcanic rocks to runaway acceleration in response to flank slip is unknown.

Hypothesis (2): Field observations and numerical studies show that flank collapse impacts on the magmatic plumbing system due to changes in pressure conditions[22,23]. Equally, flank sliding may also alter the pressure regime in the magmatic source with one effect being the rapid rise of large amounts of magma. This is a possible explanation of the exceptionally long eruption at Kilauea in summer 2018, following flank slip of up to 3.5 m during the Mw 6.9 earthquake on 4 May[24]. In turn, large and rapid dike intrusions could cause horizontal acceleration of already unstable flanks leading to their collapse. This is likely the cause for frequent collapses of Mount St Augustine volcano in Alaska[25]. The two-way interplay between a slow sliding flank and the volcano's plumbing system has not been systematically investigated yet.

If neither hypothesis 1 nor 2 can explain catastrophic flank collapse, then only a coincidental interplay of different triggers will hold. A catastrophic collapse then will be unpredictable with the current state of knowledge and hazard assessments will have to rely on statistical approaches.

Aims and objectives

PRE-COLLAPSE aims to provide the first means to physically assess the hazard potential from catastrophic collapse at volcanoes affected by slow flank sliding worldwide through three objectives:

1) Assessing how slow sliding can transition into catastrophic collapse under consideration of frictional properties of prevailing rocks at flank-sliding driving rates, true geologic and modern sliding rates, detailed volcanotectonic structures, and feedbacks between flank deformation and the magmatic system.
2) Identification of transients in physical parameters indicative of flank collapse (precursory signals), failure mechanisms (preferential monitoring locations), and temporal evolution (preparatory phase). PRE-COLLAPSE will assess how existing monitoring schemes would detect precursory signals, and how hazard monitoring can improve.
3) Disseminating results to the responsible volcano observatories and geological surveys through close networking with respective scientists. The numerical tools that will be developed in PRE-COLLAPSE can form the basis for predictive scenarios and will be made openly available.

2. IMPACT, RISK, AND INNOVATION

Numerous volcanoes worldwide are affected by slow flank sliding. If there is a causative link between slow sliding and collapse then all these volcanoes could potentially collapse in the future. By 2060 more than 1 billion people might be living in low-elevation coastal zones that would be impacted by tsunamis[26]. Worldwide, around 500 million people live near volcanoes including megacities, such as Tokyo (Mt Fuji), Manila (Taal), Mexico City (Popocateptl) that are expanding rapidly. Yet, slow flank sliding is measureable by ground deformation monitoring onshore and offshore[14] and could potentially permit forecasting flank collapses and disastrous tsunamis. The outcome of PRE-COLLAPSE will not only have an immense impact on the assessment of collapse hazards at these volcanoes, but also on hazard monitoring and mitigation.

There is an overall risk that gradual slip may not be able to yield signs or act as a predictor for eventual flank collapse. It is also possible that local effects, such as strain localisation, mask such phenomena. However, this risk is well balanced by the impact if a clear connection between slow flank sliding and runaway acceleration into catastrophic collapse can be established.

The approach of PRE-COLLAPSE is new and innovative because it incorporates state-of-the-art knowledge and methodologies from several disciplines beyond classical volcanology. These components have as yet not been combined with respect to volcano flank instability, and their individual results will already significantly advance our understanding of flank collapses:

<u>A coast-crossing "amphibious" approach linking onshore and offshore analyses:</u> The flank collapse hazard at ocean island and coastal volcanoes involves both the subaerial and submarine portions of the volcano. Most research and monitoring activities are biased towards the comparatively small part of the volcano above sealevel, however, the earliest and most important precursory signals may occur below sealevel. Acquiring data in the deep sea is technologically and logistically challenging but possible[27], and will significantly extend onshore data sets with the potential to revolutionise current views[14]. Therefore, PRE-COLLAPSE will merge sub-sea data sets with those collected on land to pave the way for monitoring of slow sliding precursory signals.

<u>Frictional behaviour of volcanic rocks at velocities representative of flank slip:</u> Some plate boundary faults show different slip styles within the same segments[28]. In the laboratory, this wealth of slip behaviour can only be reproduced when samples are sheared at plate-moving rates of centimetres per year[29]. I propose that this also holds for volcanoes: Friction experiments conducted at true flank slip rates can reveal the capability of these rocks to host both slow slip and runaway behaviours as well as the conditions under which a transition occurs. This relationship will allow inferring critical precursory slip patterns directly.

<u>Coupled edifice stability and magma numerical models:</u> It is numerically extremely challenging to describe the physics of magma and volcano deformation in one model, e.g. due to the large discrepancy in viscosities. However, it is exactly this two-way coupling between the magma source and the sliding flank that is possibly decisive for the transition from slow sliding to collapse. PRE-COLLAPSE will implement a new method, in which three numerical methods, each addressing one of the three components of 'magma', 'flank sliding', and 'collapse', will be directly coupled and which will find widespread application beyond this project.

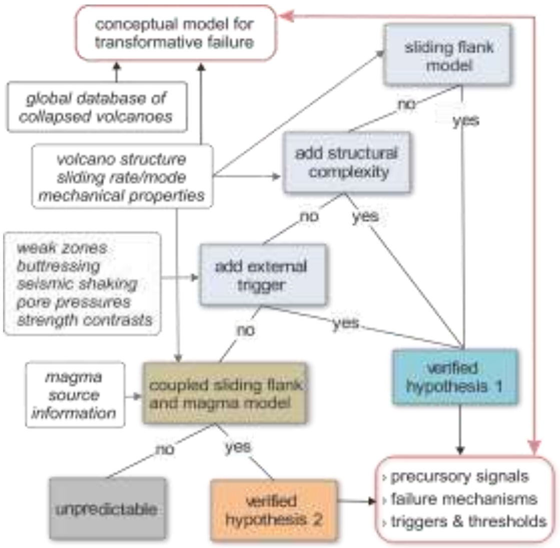

Figure 3: *Overall strategy in PRE-COLLAPSE. This scheme will be applied to each of the four case studies and one conceptual volcano.*

3. SCIENTIFIC APPROACH

Four work packages (WP) define the overall project structure (Fig. 3). Each WP will deliver its own unique and innovative results, providing essential steps towards improved understanding of volcanic flank collapses.

<u>WP1: Develop a conceptual model for failure mechanisms involved in transformative collapse</u>

We will create a global shoreline-crossing database of collapsed volcanoes that includes morphometric parameters of the collapse scars and environmental parameters. Statistical analyses of this database will reveal general patterns of collapsed volcanoes. In-depth analyses of the volcanotectonic structures, pre- and postcollapse morphologies, flank sliding rates and modes and potential link to the volcanic plumbing system, as well as frictional properties at appropriate flank slip rates at four selected case studies will constrain further common patterns. New and published bathymetric, geodetic, seismic, and seismological data will be explored. Cohesion and shear strength will be determined in the laboratory by shearing representative samples at their typical flank sliding rates (5-10 cm/yr) at different stresses. Finally, we will come up with a conceptual model of how volcanoes have collapsed that explain both the global and case study observations.

WP2: Stability loss due to strain weakening and internal shear zones (test hypothesis 1)
Finite Element models set up for one conceptual volcano as well as four case studies will incorporate the respective internal structures and mechanical behaviours analysed above. Displacement boundary conditions will impose a sliding flank at respective slip rates and modes. If the simulations develop failure naturally, hypothesis 1 will be approved and failure mechanisms will be compared to the conceptual model developed in WP1. If the simulations fail to collapse, their complexity will be increased stepwise until approval or disapproval of hypothesis 1.

WP3: Interaction between flank slip and the volcanic system (test hypothesis 2)
Because magmatic, tectonic and slope processes cannot be captured within one single type of model due to large viscosity contrasts, there is a need to couple different numerical approaches. PRE-COLLAPSE will consider the magma source as a system of initially predefined ‘veins’ that respond to pressure changes by changing volume and pathways. We will couple a continuum system-scale base model for calculating stress and strain fields due to combined gravitational stresses and magma pressure (Finite Element Method), a dike propagation model (Boundary Element Method), and a particle model for large flank collapse deformations (Discrete Element Method). The models will be calibrated to the four case studies. We will seek to simulate collapses of Anak-Krakatau and Ritter, where the failure mechanism is constrained by post-collapse morphologies. For Kilauea and Etna we will identify factors that could have led to flank collapses during recent slip events in May and December 2018, respectively (counterfactual approach[30]).

WP4: Implications for precursory signals and hazard monitoring
Through comparing simulation results for all case studies and the initial conceptual model we will be able to establish a connection between slow flank sliding and catastrophic collapse. This will allow deducing general behaviours regarding failure mechanisms and precursory signals, which can be used for identifying volcano flanks that are in transition to catastrophic collapse globally.

Study areas: I propose four volcanoes as case studies, which I selected because of their flank sliding and collapse histories, available data, and hazard potential: Anak-Krakatau (Indonesia), Ritter (Papua New-Guinea), Etna (Italy), and Kilauea (Hawaii, US). The collapse of Anak-Krakatau in December 2018 is the best-monitored flank collapse with many different types of remote sensing data that characterize gradual flank sliding, volcanic activity, temperature, and seismicity before, during, and after the collapse[1,31]. The submarine part was surveyed in August 2018 with multibeam bathymetry and sparker seismics. The 1888 collapse of Ritter is the largest historically recorded volcanic landslide (5 km^3) with strong evidence of persistent flank sliding prior to collapse from seismic data[12,32]. This data is well suited to constrain slip rates and modes using palinspastic restoration. Etna and Kilauea both have unstable flanks that are slowly moving into the ocean at rates of 3 and 10 cm/yr, respectively[8], and are among the best-studied volcanoes in the world. Their onshore portions are intensively monitored and, more recently, also their offshore parts[14,33,34] (though limited in time and space). Monitoring is motivated by the volcanoes' persistent activity and the risks they pose to communities and infrastructure. Scientists have emphasised a potential flank collapse hazard at both volcanoes[35,36]. If appropriate, other case studies will be added depending on current events.

Data: In order to reduce the number of assumptions in the models, PRE-COLLAPSE will rely on a large variety of data sets and methodologies. Marine data will include ship-based bathymetric and 2D seismic data from national databases (for volcanoes globally and Kilauea), data owned by the PI (Ritter[37], Etna[38,39]), and data for which access has been granted to PRE-COLLAPSE (Anak-Krakatau by D. Tapping and J. Hunt). PRE-COLLAPSE will use 3D and refraction seismic data from Ritter and Etna, microbathymetry and seafloor geodesy from Etna (data sets owned by PI or accessible through being project partner). Seafloor samples will be collected in upcoming granted and scheduled research cruises (RV Meteor M169 in 11/2020 at Etna, RV Falckor in 06/2020 at Ritter). Onshore samples from Kilauea and Etna will be collected in the project. A large body of literature constrains the onshore parts of Etna and Kilauea. Modern monitoring data is available through the Geohazard Supersites and Natural Laboratories initiative (geo-gsnl.org). For Anak-Krakatau InSAR data is available from the Copernicus hub (Sentinel-1) and the German Aerospace Centre (TerraSAR-X). Drone imaging will be provided by team member T. Walter.

Risks and mitigation: Risk related to the use of specialty machines needed for friction experiments could result from machine failure or unavailability. This could be circumnavigated by conducting experiments at other institutes, where shear devices are also available, but with less high ranges in shearing rates (e.g. Prof Stipp, University of Halle). In the case of failure of seafloor sampling we will revert to onshore samples, where there is little associated risk. If access to restricted data is denied, the duration of this project will allow waiting until embargo is lifted (typically 2 years after acquisition) or the data has been published. If coupling of numerical models proves challenging, it will be possible to switch to other software or codes. Manually transferring strains and stresses between the models at distinct calculation steps is an alternative[18].

Deliverables: (i) The first comprehensive shoreline-crossing database of volcano flank collapses, (ii) comprehensive shoreline-crossing structural interpretations of Anak-Krakatau, Etna, and Kilauea, (iii) flank deformation history of Ritter and Anak-Krakatau, (iv) magma sources and pathways at Ritter and Anak-Kraktau, (v) friction properties of volcanic rocks at flank-sliding driving rates, (vi) sensitivity of the stability of a volcano with downwards sliding flank to various strength-reducing factors, (vii) coupling scheme to simulate fully coupled kinematic and magmatic processes, (viii) triggers and failure mechanisms of the collapses of Ritter and Anak-Krakatau, (ix) hypothetical collapse scenarios at Etna and Kilauea, (x) recommendations for hazard monitoring globally, and at Etna and Kilauea specifically, (iii) numerical tools that can be used for predictive scenarios.

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