GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G50693.1

Manuscript received 23 August 2022
Revised manuscript received 20 November 2022
Manuscript accepted 23 November 2022

Published online 10 February 2023

Interactions of magmatic intrusions with the multiyear flank instability at Anak Krakatau volcano, Indonesia: Insights from InSAR and analogue modeling

Edgar U. Zorn[1]*, Magdalena Vassileva[1], Thomas R. Walter[1], Herlan Darmawan[2], Leonie Röhler[1] and Falk Amelung[3]
[1]German Research Centre for Geosciences (GFZ), Telegrafenberg, 14473 Potsdam, Germany
[2]Geophysics Study Program, Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada, 55281, Yogyakarta, Indonesia
[3]Department of Marine Geosciences, Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, 4600 Rickenbacker Causeway, Miami, Florida 33149, USA

ABSTRACT

Volcano flank collapses have been documented at ocean islands worldwide and are capable of triggering devastating tsunamis, but little is known about the precursory processes and deformation changes prior to flank failure. This makes the 22 December 2018 flank collapse at Anak Krakatau in Indonesia a key event in geosciences. Here, we provide direct insight into the precursory processes of the final collapse. We analyzed interferometric synthetic aperture radar (InSAR) data from 2014 to 2018 and studied the link between the deformation trend and intrusion occurrence through analogue modeling. We found that the flank was already moving at least 4 yr prior to collapse, consistent with slow décollement slip. Movement rates averaged ~27 cm/yr, but they underwent two accelerations coinciding with distinct intrusion events in January/February 2017 and in June 2018. Analogue models suggest that these accelerations occurred by (re)activation of a décollement fault linked to a short episode of magma intrusion. During intrusion, we observed a change in the internal faults, where the outward-directed décollement accelerated while inward faults became partially blocked. These observations suggest that unstable oceanic flanks do not disintegrate abruptly, but their collapse is preceded by observable deformations that can be accelerated by new intrusions.

INTRODUCTION

Tall volcanoes tend to become structurally unstable and experience catastrophic flank collapses, capable of producing major tsunamis if they enter the sea (Siebert, 1984; van Wyk De Vries and Francis, 1997). Persistent flank motion may precede complete failure, sometimes forming characteristic deformations, morphology, and faults at the surface (Poland et al., 2017), which may be followed by changing magma pathways (Maccaferri et al., 2017). Here, we investigated the preparation phase of a flank collapse at Anak Krakatau, Indonesia, which has a history of instability and produced at least eight tsunamis in the past (Paris et al., 2014; Hidayat et al., 2020). The most significant tsunami occurred in 1883 with the collapse of the Krakatau edifice, killing over 34,000 people on the shorelines of Southeast Asia. Renewed volcanic activity rapidly rebuilt the island afterward, resurfacing as Anak Krakatau in 1927, which had reached a height of 320 m by 2018 (Ismail et al., 2020). Its southwest flank then collapsed on 22 December 2018 (Walter et al. 2019), producing another tsunami and killing 437 people around nearby shores (Syamsidik et al., 2020). A tsunami early warning system was installed and active in the area during the collapse (Lauterjung et al., 2010; Annunziato et al., 2019), but it was designed for earthquake-generated tsunamis and thus could not produce a warning. This highlights the need for alternative means to monitor flank instability prior to the occurrence of catastrophic failure.

Volcanic flank instability is often associated with gradual movement along a deep-seated basal décollement (van Wyk De Vries and Borgia, 1996; Byrne et al., 2013). Flank instability, intrusions, and volcanism may be closely related and even cause complex structural interactions (Delaney et al., 1998; Schaefer et al., 2019). Volcanoes with higher rates of magmatism generally show increased rates of flank motion (Poland et al., 2017), and earthquakes or magmatic intrusions may intermittently accelerate flank slip (Famin and Michon, 2010; Chaput et al., 2014; Schaefer et al., 2015), although this strongly depends on the depth of the intrusion (Cayol et al., 2000). On the other hand, ongoing décollement slip is also known to favor further magmatic intrusions, which follow topographic stress (Varugu and Amelung, 2021). Understanding such short-term accelerations is vital, as they may culminate in catastrophic flank failure with potentially devastating consequences (Ward and Day, 2001; Abadie et al., 2012). Here, we compared new interferometric synthetic aperture radar (InSAR) data and experimental modeling on Anak Krakatau's destabilizing southwest flank preceding the December 2018 collapse. The results show how magmatic intrusions interact with a destabilizing flank, accelerating deformations that lead to catastrophic failure.

DEFORMATIONS ON THE SOUTHWEST FLANK OF ANAK KRAKATAU

We measured the evolution of flank instability using multitemporal InSAR data with the small baseline (SB) method applied to *Sentinel-1* data in both ascending (orbit 171) and descending (orbit 47) acquisition orbits over an ∼4 yr period prior to the sector collapse (detailed processing methods are provided

*Current address: Department of Earth and Environmental Sciences, Ludwig-Maximilians-Universität München, 80539 Munich, Germany; E-mail: e.zorn@lmu.de

CITATION: Zorn, E.U., et al., 2023, Interactions of magmatic intrusions with the multiyear flank instability at Anak Krakatau volcano, Indonesia: Insights from InSAR and analogue modeling: Geology, v. XX, p. , https://doi.org/10.1130/G50693.1

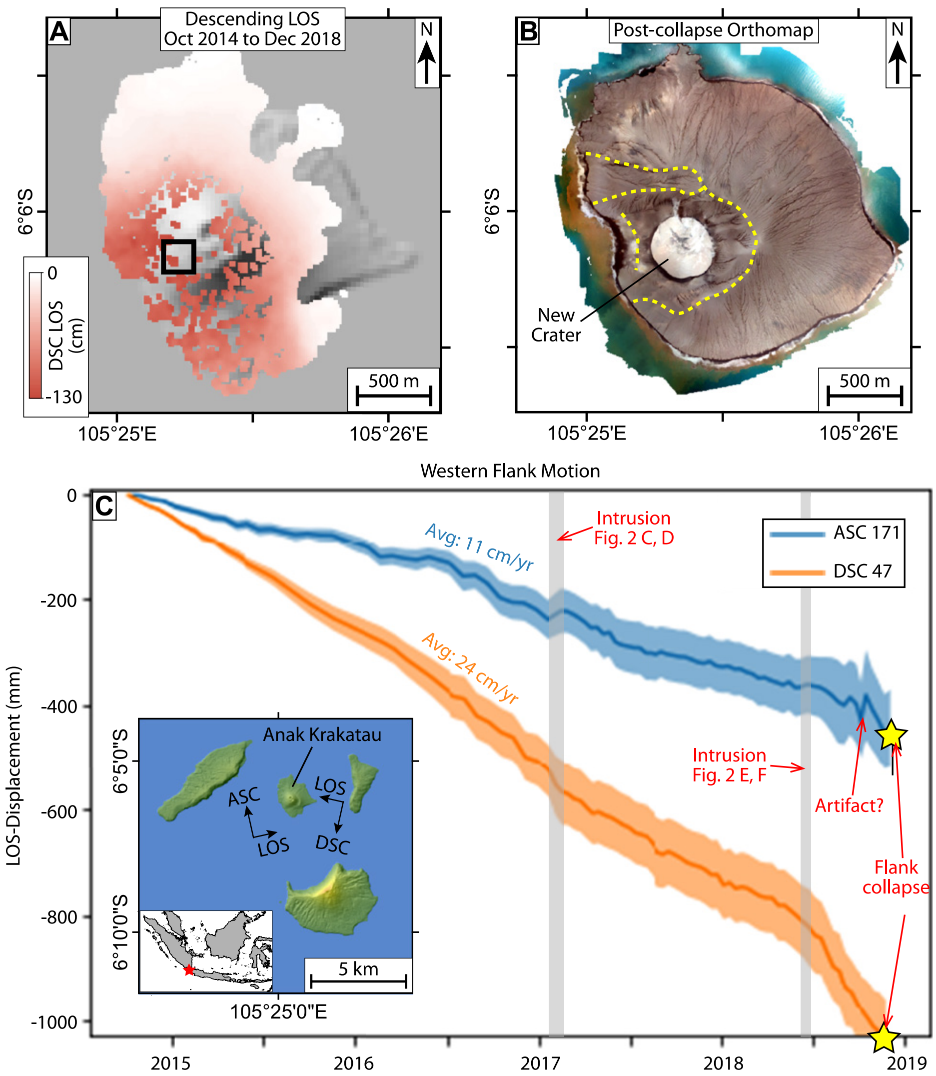

Figure 1. (A) 2014–2018 ground displacement of Anak Krakatau from the descending orbit in line-of-sight (LOS). (B) Orthomap of Anak Krakatau after its collapse, modified after Darmawan et al. (2020). Remnant structures are highlighted with yellow lines. (C) Displacement time series for the southwest flank from both ascending and descending orbits over a 4 yr observation period. Solid lines represent average values, while colored regions show standard deviation measured inside the black box marked in A. Gray-shaded areas mark magmatic intrusion events. Ascending (ASC) and descending (DSC) acquisition geometries are shown in the regional map inset.

in Supplement A of the Supplemental Material[1]). The data acquired between 8 October 2014 and 19 December 2018 showed that the southwest flank of Anak Krakatau had been gradually sliding seaward with an average line-of-sight (LOS) velocity of ~11 cm/yr (ascending) and ~24 cm/yr (descending), respectively (Fig. 1). Flank sliding accelerated between late January and February 2017 and again in June 2018. After both events, a lasting increase in flank instability was observed for ~2 mo in 2017 and ~6 mo in 2018 until the catastrophic flank collapse (Fig. 1C). The data from June 2018 were previously characterized by Walter et al. (2019), and our measured rates agree well.

Vertical and horizontal displacement maps from decomposed LOS deformations show that the flank was moving downward at a rate of ~25 cm/yr and westward at ~11 cm/yr (Figs. 2A and 2B), which are consistent with a total seaward displacement occurring at ~27 cm/yr with an ~65° downward angle at the upper cone (inferred from the ratio of vertical and horizontal motions). In total, the flank moved a cumulative ~1.1 m over the entire 4 yr observation period. A sliding direction steeper than the slope in the upper region suggests a rotational landslide mechanism, which agrees with postcollapse assessments (Walter et al., 2019; Williams et al., 2019). The consistent long-term motion suggests gravitational flank failure, which is considered to be the most likely explanation (Hunt et al., 2021; Cutler et al., 2022). Over a 24 d period between 22 January and 18 February 2017, the velocities on the southwest flank reached values equivalent to ~92 cm/yr downward and ~118 cm/yr westward (or a total of ~150 cm/yr; Figs. 2C and 2D). During this same period, the eastern flank showed an additional eastward velocity of ~76 cm/yr, indicating a spreading pattern around the central cone (Fig. 2D). This coincided with increased thermal emission (Supplement C) and a short eruptive episode producing Strombolian explosions and a lava flow. This evidence points to a short-lived magmatic intrusion. In June 2018, the velocities increased again, likely caused by another intrusion. At this time, the flank slip rates in the 12 d between 10 June and 25 June 2018 were equivalent to ~26 cm/yr downward and ~70 cm/yr westward (equivalent to ~75 cm/yr total displacement; Figs. 2E and 2F). As with the previous intrusion, the eastern flank also moved eastward at ~89 cm/yr, spreading the central cone (Fig. 2F). However, due to lower coherence, the pattern was not as clear compared to that observed for January/February 2017. This time, the velocities stayed elevated until the flank catastrophically failed on 22 December 2018 (Fig. 1C).

INTERACTION OF FLANK MOTIONS AND MAGMA INTRUSIONS SIMULATED IN ANALOGUE EXPERIMENTS

We studied the interaction of décollement flank failure and magmatic intrusions by conducting analogue sandbox experiments (details on the experimental setup, scaling, recording, processing, and limitations are provided in Supplement B). We reconstructed Anak Krakatau with sand by building a simplified circular cone on a flat surface. We then tested two types of deformation mechanisms consecutively: (1) gradual sliding of the flank through a basal décollement, and (2) magma ascent through a circular conduit. As a result of the artificial décollement in the first stage, the flank started to slide in two blocks separated by a set of steep antithetic faults (Figs. 3B and 3D). This is consistent with similar experiments incorporating décollement slip in cones (Acocella, 2005; Le Corvec and Walter, 2009). While the outer block moved laterally, we found that the inner block moved both down and outward. This included the cone summit, reducing the overall height of the sand-volcano. The inner block motion was also remarkably consistent with the type of motion observed by InSAR at the southwest flank of Anak Krakatau (cf. Figs. 2A, 2B, 2G, and 2H), including the angle of the forming fault, which dipped ~62° downward (Fig. 3E), similar to the inferred ~65° dip from InSAR. The outer block produced positive vertical change; however, this was not due to upward

[1]Supplemental Material. Method details and supplementary figures. Please visit https://doi.org/10.1130/GEOL.S.21919386 to access the supplemental material and contact editing@geosociety.org with any questions. We further provide access to our processed InSAR data via the GFZ Data Repository: please visit https://doi.org/10.5880/GFZ.2.1.2022.003 to access the data files.

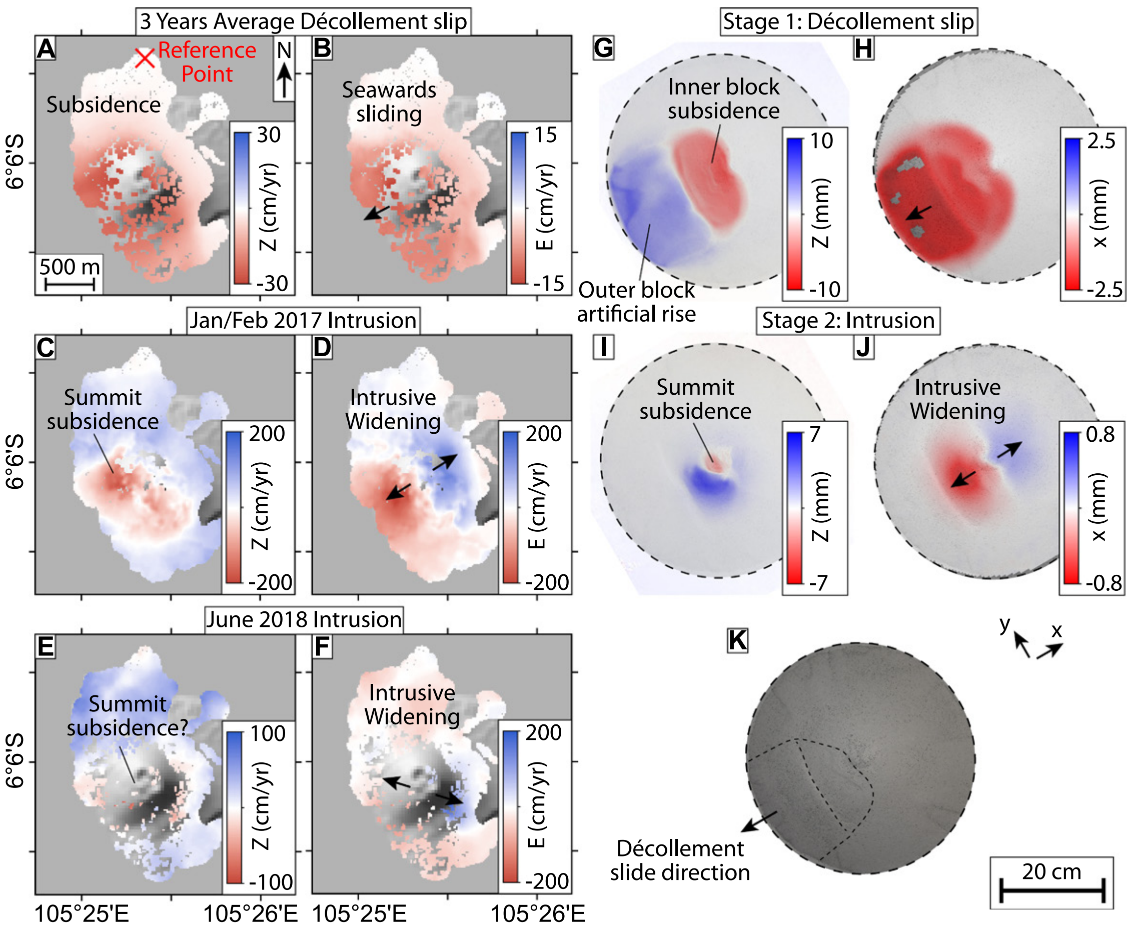

Figure 2. (A–F) Decomposed interferometric synthetic aperture radar (InSAR) maps and (G–K) analogue modeling data showing ground deformation in vertical (z) and horizontal eastward (E or x) components. (A,B) 3 yr average flank motion due to décollement slip, which is compared against artificial décollement deformation (stage 1) in G and H. Both show a matching pattern of subsidence on the upper cone and lateral movement toward the west. Height increase of the lower flank in G is due to the purely horizontal décollement plane, which moves the lower block outward and thus causes an artificial height increase. (C,D) January-February 2017 intrusion. (E,F) June 2018 intrusion. (G,H) Analogue décollement deformation (stage 1). (I,J) Analogue intrusion (stage 2). These changes caused summit subsidence and lateral spreading of the cone. (K) Photo of experiment cone for reference.

movement, but rather the horizontal outward-directed slide next to the inclined slope (Fig. 2G).

During the second stage, we intruded a circular column of sand into the center of the sand cone (with the preexisting décollement). This simulated an intrusion through an assumed circular conduit, similar to lava dome growth (Zorn et al., 2020), which was observed at Anak Krakatau in October 2018 (Hochfeld et al., 2022). During the initial intrusion, we observed a reactivation of the décollement fault, meaning the intrusion caused further slip, despite the décollement being stopped before (Figs. 3F and 3G). With continued intrusion, the magma then was deflected toward the unstable flank; however, in repeated experiments, we saw that it could also be deflected toward the opposite side. Evidently, the intrusion did not result in uplift of the summit cone, but rather its subsidence (Fig. 2I). We found this to be caused by a set of inward-dipping faults originating at the conduit, which are similar to the spine-bounding faults seen in Zorn et al. (2020). These laterally pushed the outer flanks, in turn causing subsidence at the summit. As a result, the vertical change showed a height reduction in the cone center and height gain (or bulging) in the outer flanks (Figs. 2I and 2J). This deformation pattern also agrees well with modeled cryptodome intrusions (e.g., Donnadieu et al., 2003).

CONJOINT FLANK SLIP ACCELERATION AND VOLCANIC ACTIVITY INCREASE

Based on geomorphologic studies, a possible flank collapse and tsunami were already anticipated at Anak Krakatau prior to 2018 (Giachetti et al., 2012). Our InSAR observations demonstrate that the southwest flank of Anak Krakatau had gradually been sliding seaward for at least 4 yr prior to the catastrophic collapse in December 2018 (Fig. 1C). It is likely that the instability persisted for longer, as earlier studies had already noted subsidence, but they interpreted it to be magma chamber deflation and not flank instability (Chaussard and Amelung, 2012). Thus, we speculate that the flank instability may have been ongoing for over a decade before the collapse. This sheds light on the potential precursors of sector collapses, as the instability can be clearly identified years in advance, which may become highly relevant for mitigating potential future disasters at volcanoes elsewhere. Our data also provide insights into the geologic processes occurring during the developing instability and the interaction of the unstable flank with magmatic intrusions. The flank accelerations of Anak Krakatau coincided with significant rises in the volcanic radiative power seen in Moderate Resolution Imaging Spectroradiometer (MODIS) data, indicating an increase in eruptive activity (Supplement C). This occurred in January-February 2017 and again, more intensely and prolonged, in June 2018 onward. Additionally, there were significant peaks in the thermal activity of Anak Krakatau between 2008 and 2012 (Supplement C), and it is likely that these changes also caused décollement slip accelerations similar to those we identified here (Fig. 1C). While no other tangible data linking flank accelerations as a precursor to catastrophic collapse exist for volcanoes so far, there is abundant evidence for this from nonvolcanic giant landslides (e.g., Kilburn and Petley, 2003; Kang et al., 2019; Chen et al., 2021). A key difference is the gradual deformation increase interpreted to occur as a result of slow cracking (Kilburn and Petley, 2003), as opposed to episodic accelerations corresponding to discrete intrusion events (Fig. 1C), highlighting the increased role of magmatism in the collapse of volcanic flanks.

Our findings are consistent with the suggestion that the flank of Anak Krakatau moved and failed via a décollement (Walter et al., 2019; Borrero et al., 2020). Despite the simplification to a conduit-like intrusion and a horizontal sliding plane in our analogue experiments, both the resulting deformation patterns and the geometry of the developing main fault matched the InSAR displacement observations well. The

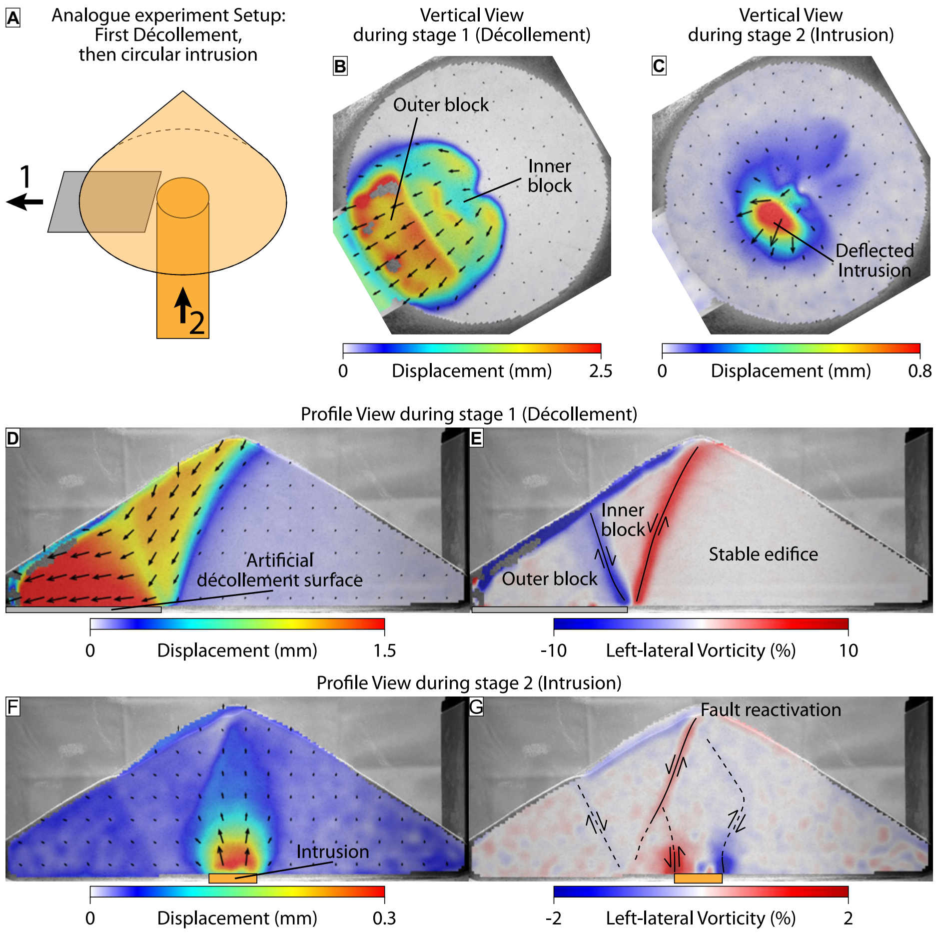

Figure 3. Particle displacement tracking from (A) two-stage analogue sandbox models, with (B,C) vertical views, and (D–G) profile views for both décollement slip (stage 1) and intrusion (stage 2). Décollement slip produced faults that are consistent with proposed long-term motion of Anak Krakatau. Subsequent intrusion reactivated these faults, potentially explaining increased flank slip during intrusion events.

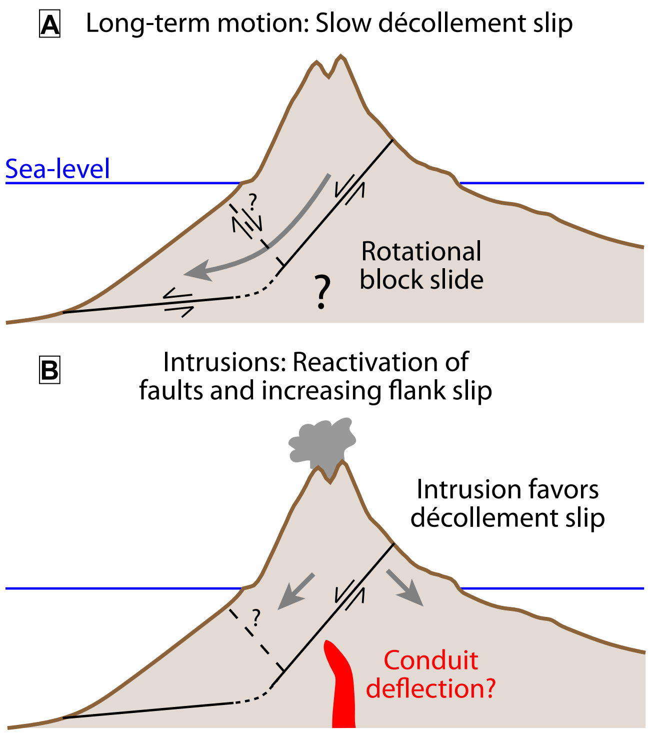

Figure 4. Schematic illustration of deformations associated with (A) décollement and (B) intrusions at Anak Krakatau increasing décollement slip.

experiments predicted subsidence of the summit both during décollement slip and during magmatic intrusions, which can be seen in the upper portion of the cone at Anak Krakatau (Figs. 2A, 2C, and 2E) and in the analogue experiments (Figs. 2G and 2I). Similarly, the horizontal spreading associated with the intrusions can be seen in both the volcano and the model (Figs. 2D, 2F, and 2J). Our analogue experiments also produced a set of horseshoe-shaped detachment faults. While we could not observe any such discrete surface faults at Anak Krakatau via InSAR, similar faults did appear in the final *Sentinel-1* image on the day of the collapse, separating the flank into distinct blocks with two failure planes from a rotational slide (cf. Williams et al., 2019, their figure 2). The postcollapse orthomap also shows a north-south–striking structure that could be indicative of the antithetic fault in our models (Fig. 1B).

Finally, we observed a direct impact of the sand-intrusion on the preexisting fault structures that formed through the décollement slip. Despite no active slip being induced, the faults were reactivated during the start of the intrusion, causing further décollement slip (Figs. 3F and 3G). This appears to have been induced by the added stress field from the conduit intrusion, as it had a similar shear direction as the décollement fault and resulted in a favored fault activation. In turn, the developing shear faults along the conduit margins were redirected toward the unstable side (Fig. 3G), which may explain the shift of the vent toward the unstable southwest flank at Anak Krakatau in July 2018 (Hunt et al., 2021), and which may indicate a stress reorientation resulting from the onset of edifice collapse (Maccaferri et al., 2017). We observed the interaction of intrusion and increased décollement slip twice during our observation period as the accelerations matched well with the January-February 2017 and June 2018 intrusions (Figs. 1C and 2C–2F). While the January-February 2017 intrusion was short-lived, it did cause a brief increase in the décollement slip rates to more than 5 times the normal rate. The June 2018 intrusion caused an increase of ~3 times the normal rate, but, this time, the slip rates stayed elevated until the collapse 6 mo later.

Our results highlight the conclusion that intrusions may act as destabilizing forces on the flank, making their detection vital for hazard and risk assessments. The deformation patterns and structural insights provided here may further aid in identifying key areas for monitoring instruments to characterize flank instability. At Anak Krakatau, our findings point to distinct magmatic intrusions playing a major role in the instability progression because they can significantly accelerate ongoing destabilization by activating existing faults (Fig. 4). Previous studies found no evidence for a direct magmatic trigger for the 22 December 2018 collapse (Cutler et al., 2022), but it is clear that magmatic intrusions at least significantly affected the long-term movement and stability of the flank.

ACKNOWLEDGMENTS

We acknowledge financial support by the Federal Ministry of Education and Research of Germany in the framework of TSUNAMI_RISK (project number 03G0906A), a part of the funding initiative CLIENT-II. We further acknowledge the past contributions made by the German-Indonesian Tsunami Early Warning System for the Indian Ocean (GITEWS), upon which this project builds.

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Printed in USA