Flank instability and sector collapses, which pose major threats, are common on volcanic islands. On 22 Dec 2018, a sector collapse event occurred at Anak Krakatau volcano in the Sunda Strait, triggering a deadly tsunami. Here we use multiparametric ground-based and space-borne data to show that prior to its collapse, the volcano exhibited an elevated state of activity, including precursory thermal anomalies, an increase in the island’s surface area, and a gradual seaward motion of its southwestern flank on a dipping décollement. Two minutes after a small earthquake, seismic signals characterize the collapse of the volcano’s flank at 13:55 UTC. This sector collapse decapitated the cone-shaped edifice and triggered a tsunami that caused 430 fatalities. We discuss the nature of the precursor processes underpinning the collapse that culminated in a complex hazard cascade with important implications for the early detection of potential flank instability at other volcanoes.
Volcanic islands are typically fast-growing edifices that rest on a complex morphology and weak substrata, and they are frequently made up of highly fragmented, mechanically unstable material. Therefore, many volcanic islands rise rapidly but also erode swiftly via volcano flank instability, leading to irregular shapes and embayments owing to sector collapses. Geomorphic amphitheaters are common subaerial remnants of fast lateral landslides; these events often recur at the same location. They may result in distal run-out submarine deposits, which demonstrate the intense dynamics of tsunami-genic mass movements in the oceans. In fact, data collected from around the world reveal that historical volcano-induced tsunamis have caused significant damage and loss; ~130 events have been recorded from 80 different source volcanoes since 1600 AD. These events have been caused by the entry of pyroclastic flows into the ocean and their submarine continuation, by caldera collapse, and by landslides entering the ocean or combinations thereof. Among the progenitors of these events, 17 historically identified source volcanoes are located in Southeast Asia. Volcano-induced tsunamis have probably led to the demise of ancient civilizations and are responsible (albeit uncommonly, i.e., 5% of all tsunami events) for approximately one-fourth of all fatalities attributed to volcanic activity.

It has been over 135 years since the infamous volcano-induced Krakatau tsunami occurred on 27 August 1883 (Fig. 1a). A common problem of such events is that they are rare, and thus, although volcanic islands introduce numerous recognizable threats such as instability, sector collapse and tsunamis, little is known about their precursor activity and possible strategies to mitigate the associated risks. Moreover, the preparation and initiation of sector collapses are complex, inasmuch that they could possibly be associated with faulting, slumping, and pyroclastic flows or combinations thereof. Consequently, at present, no consensus exists regarding what constitutes a reliable precursor signal for sector collapse on a volcanic island.

During the 1883 Krakatau eruption and tsunami, which is estimated to have killed over 36,000 people, 12 km³ of dense rock equivalent was erupted; a caldera collapse occurred as a result, leaving only small and steep subaerial remnants of the former volcano edifice along the rim of a 7-km-wide deep-water caldera basin. Volcanism continued after the 1883 events, eventually producing Anak Krakatau ("the son of Krakatau"), where several additional smaller tsunamis were triggered at this site by processes such as underwater explosions. It is possible that the island known as Anak Krakatau is preconditioned for landslide-triggered tsunamis, as it is situated on a steep morphological cliff. The edifice first breached the sea surface in 1928 and gradually formed a 150-m-high tuff ring by 1959. A gradual shift in activity then occurred toward the southwest, resulting in further growth of the edifice over the cliff and toward the deep submarine caldera basin. This was leading to recent concerns about a possible landslide from the southwestern island flank and the corresponding generation of a tsunami. These concerns and scientific assessments turned into reality following an intense (but...
theretofore unidentified) increase in precursor activity. Although flank motion was identified\(^{30,31}\), the hazard was not systematically monitored. On 22 December 2018, this volcanic center once again became the source of a tsunami that struck the highly vulnerable Sumatran and Java coasts. According to the Indonesian National Disaster Management Authority (BNPB), the 22 December 2018 tsunami caused over 430 fatalities, injured 14,000 people, and displaced 33,000 more along the Sunda Strait. The tsunami risk of this area is particularly high as the coast is very vulnerable Sumatran and Java coasts. According to the Indonesian National Disaster Management Authority (BNPB), the 22 December 2018 tsunami caused over 430 fatalities, injured 14,000 people, and displaced 33,000 more along the Sunda Strait. The tsunami risk of this area is particularly high as the coast is very

**Results**

**Preparation of the flank collapse event.** Satellite monitoring and ground observations reveal that Anak Krakatau showed clear signs of flank motion and elevated volcanic activity prior to sector collapse which triggered the destructive tsunami.

![Flank motion timeline](image)

**Fig. 2** Eruptions and island perimeter growth map. **a** Several selected Sentinel-2 images (band combination of 12, 11, 4) showing the emplacement of hot and new material (red-yellow) on the southern flank of Anak Krakatau during the increased eruptive activity in 2018 (see also Supplementary Figure 1). **b** Island perimeter maps derived from satellite radar amplitude images (Supplementary Figure 2) show little variation from January 2018 to June 2018, followed by southward growth from June 2018 to December 2018 prior to the sector collapse (light gray). The black lines indicate the new scarps formed by the sector collapse. The outer outline indicates the post-collapse island perimeter in January 2019 (dark gray). **c** Land area change based on monthly island perimeter analysis. The area changed gradually prior to the flank collapse, but more rapidly after the collapse event. Maps created using the GMT/MATLAB Toolbox\(^{49}\)

An estimate of the erupted volume derived from thermal data (see methods) indicates that the eruption phase produced 25.5 ± 8.4 Mm\(^3\) of deposits, implying a mean output rate of 1.7 ± 0.8 m\(^3\) s\(^{-1}\) from June 2018 to just prior to the collapse event. Thus, the load acting on the summit and especially the southern flanks of the island progressively increased over this time by ~54 million tons (assuming a mean density of 2110 kg m\(^{-3}\))\(^{33}\). The 2018 eruptive period was punctuated by 11 pulses with time-averaged discharge rates (TADRs) higher than 3 m\(^3\) s\(^{-1}\). The occurrence of these effusive pulses peaked between September and October 2018, with the three highest TADRs of 10.5 (±3.5), 33.4 (±11.1), and 50.9 (±16.8) m\(^3\) s\(^{-1}\) on 9, 15, and 22 September 2018, respectively (Fig. 1c). Starting in October 2018, the rate of these pulses declined, both in intensity and in frequency, except for a period in mid-November with a peak TADR of 23.2 (±7.6) m\(^3\) s\(^{-1}\). The general decrease in activity after mid-October is also suggested by the trend in the development of the cumulative volume of erupted materials (red line in Fig. 1c).

According to satellite images from the European Sentinel-2 mission (Fig. 2a), at least 0.85 km\(^2\) of the island (28% of the total area) was covered with abundant hot ejecta and new deposits (Supplementary Figure 2). Many of these entered the sea, adding 0.1 km\(^2\) of land surface to the southern shore of the island (the island area increased from 2.93 to 3.03 km\(^2\)) by early December 2018, as assessed by shoreline edge detection analysis (Fig. 2b,
Supplementary Table 2). A compositional analysis of ash sampled during the intense eruption phase on 22 July 2018 indicates a basaltic andesite composition (Supplementary Table 1), which overlaps with the typical compositional spectrum displayed by Anak Krakatau in recent decades (see Supplementary Figure 3).

Interferometric synthetic aperture radar (InSAR, Supplementary Figure 4) analysis and time-series analysis (Fig. 3a, Supplementary Figure 4) show that the southwestern and southern flanks of Krakatau were already slowly subsiding and moving westward at the beginning of our analysis window in January 2018 (Fig. 3b), despite the absence of significant thermal anomalies. The deformation that occurred in the subsequently collapsed sector was advancing at an approximately constant rate with a peak of almost 20 mm (or ~4 mm per month) in the satellites’ line-of-sight direction until the volcanic activity increased in late June 2018, at which point the deformation markedly accelerated (labeled “I” in Fig. 3c; ~10 mm per month). In addition, short-term eruptive pulses in Sep–Oct 2018 resulted in a minor step change (labeled “II” in Fig. 3c). Therefore, the data show that increased eruption rates coincide with increases in flank movement. An analysis of the deformation field pattern reveals that it affected over one-third of the island, exhibiting a moderate gradient on the west side and a well-identified gradient on the southeast side (Supplementary Figure 5). The cumulative deformation pattern indicates a progressively sliding flank that can be explained by a deep décollement plane, simulated as a rectangular dislocation34, with a dip of 35°, a strike of 163°, and a slip of 3.36 m (Supplementary Figures 6–7). Notably, deformation also affected the island summit, and therefore potentially shearing its main magmatic and hydrothermal-plumbing systems.

The dynamics of the moving flank were relatively slow; as a consequence, seismic stations installed on the mainland for tsunami early warning were hardly able to record this type of movement. Then, conditions started to change shortly before the sector collapse event. Satellite thermal data show a pulse (5.6 ± 1.9 m² s⁻¹) on 22 December 2018 at 06:50 UTC, just a few hours before the onset of the collapse (Fig. 1c). Compared with the thermal pulses recorded earlier in 2018, this eruption was relatively small. Infrasound records show the release of continuous high-frequency energy (0.5–5 Hz) from Krakatau, indicating high levels of volcanic activity in the hours prior to the collapse followed by a brief period of quiescence (Supplementary Figure 8). Both the intense activity earlier in the day and the quiet period were further confirmed by eyewitness accounts. Seismic stations (Fig. 4a) then suddenly recorded a high-frequency event (2–8 Hz, Fig. 4b), just ~115 s before the flank collapsed on 22 December 2018 (marked “1” in Fig. 4c), representing the last and most immediate precursor—or even trigger—of the main sector collapse (marked “2” in Fig. 4c). The seismic signal originated at Anak Krakatau and was associated with either an earthquake (local magnitude M_L = 2–3) or an explosion with seismic amplitudes that exceeded even those of the sector collapse in the 4–8 Hz frequency band (Fig. 4c) and was even recorded by
infrasound stations at large distances (Fig. 4d). The coda (1–8 Hz) of this event is unusually long compared with those of tectonic earthquakes of comparable magnitude; in fact, the coda is still discernible when the onset signal of the catastrophic sector collapse becomes identifiable (Supplementary Figure 9).

**The catastrophic event.** Local, regional, and even some teleseismic seismic stations (Fig. 4a) show clear signatures of the tsunami-trigging event. The abrupt onset of a short-period seismic signal is followed by ~5 mins of strong emissions at 0.1–4 Hz, approximately coinciding with a long-period signal (0.01–0.03 Hz) occurring over a shorter duration (~90 s) that we interpret as the seismic signature of the main mass movement of the landslide (Fig. 4c). The onset times of the short-period signals at stations in Sumatra and Java are consistent with the location of the volcano and an origin time of 13:55:49 UTC (Fig. 4d). The inversion of low-pass filtered (0.01–0.03 Hz) surface waves reveals an event with a moment magnitude of 5.3 (Supplementary Figure 10). A significant non-double-couple component is retrieved from the inversion of low-pass filtered seismograms, indicating a linear vector dipole oriented to the SW at 22° and a dip angle of 12° (or alternatively representing tensile opening mixed with a shear rupture dipping ~61° to the SW) (Supplementary Figure 11). As these parameters are close to those of the pre-eruptive décollement plane derived from InSAR data (NW–SE strike and SW dip), we conjecture that it was this plane that constituted the failure plane during the sector collapse. The effects of this event were recorded extensively. The Australian infrasound array (IO6AU) located over 1150 km to the SW of Anak Krakatau recorded a high-energy impulse at 15:01:09 UTC on 22 Dec 2018, which translates to a modeled origin time of 13:55:49 (±4 s) UTC at the Krakatau site (Fig. 4d, Supplementary Figure 12). This timing is consistent with the origin time of the short-period
seismic signal at Anak Krakatau (identified as the landslide signal). The duration of the impulse is broadly comparable to the long-period seismic signal and indicates that subaerial sliding lasted for ~1 min only (Fig. 4d). Both the seismic records at local stations and the infrasound records from the I06AU array (Supplementary Figure 12) continued to be dominated by coherent emissions from Anak Krakatau (presumably related to strong volcanic eruptive activity there) for at least several hours. The dominant frequency of the eruption signature in the infrasound signal shifted by nearly an order of magnitude (from ~0.8–4 Hz prior to the landslide to 0.1–0.7 Hz afterward). Even the closest local stations did not pick up a clear signature of any prelandslide eruption, but postlandslide eruptions dominated the seismograms of stations even a few hundred kilometers away. Together, these observations suggest a profound change in eruptive style following the landslide. Furthermore, on 23 December 2018 at 06:31 UTC, a large SO₂ cloud was detected (Supplementary Figure 13), likely resulting from the decapitated and degassing hydrothermal system. In contrast, no similarly strong degassing was detected in the weeks prior to the flank collapse event.

Tsunami arrivals were recorded by four tide gauge stations on the Sumatra and Java coasts (Supplementary Figure 14). Backtracing from these four stations, using the classic tsunami travel time approach (see methods), suggests that the source location corresponds to the southwestern part of Anak Krakatau and that the source origin time corresponds to that revealed by the broadband seismic analysis. Therefore, the backtracing simulation shows that the tsunami was triggered by the long-period landslide during the first minutes of the event and not by the following volcanic eruptions.

The full extent of the sector collapse event initially remained hidden owing to intense postcollapse eruptive activity but became visible when the eruption intensity decreased again by 27 December 2018. As a result, a new and steep amphitheater enclosing a deep valley became distinguishable on the southwestern sector of the island. The deposition of new material shifted the coastlines. The collapsed area is readily identified in satellite radar imagery (Fig. 5a) and is located in the area that was subsiding and moving laterally outward prior to the collapse event (Fig. 3). The area affected by landslides, however, is smaller than the area affected by precursory deformation; accordingly, we estimate that only 45–60% of the deforming subaerial flank actually failed. High-resolution camera drone records in January 2019 allow the partial derivation of a digital elevation model (Supplementary Figure 15). By comparing the digital elevation models from before and after the event, we ascertain that the sector collapse reduced the height of the island from 320 to 120 m (Fig. 5) and removed the former edifice peak, thereby decapitating the main eruption conduit (Fig. 6). Detailed volumetric estimates obtained upon differentiation the two digital elevation models suggest an estimated volume loss of 1.02 × 10⁸ m³, which is a minimum estimate, as it does not consider the volume gained by new eruptive deposits (which may exceed another 1 × 10⁸ m³, Supplementary Figure 16); furthermore, the submarine collapse volume is not included and necessitates forthcoming bathymetric surveys. Tephra deposition occurred immediately after the sector collapse (between 22 and 25 December 2018, as determined by satellite radar images), causing a shift in the perimeter of the island and overprinting the collapse scar geometry.

Profound changes continued to occur in the weeks following the catastrophic event. Numerous small slumps deposited material into the landslide amphitheater and an explosion tuff ring formed inside the decapitated volcano conduit area. The eruption site now appears slightly shifted to the SW, hosting a new 400 m-wide water-filled crater (Fig. 5c). Thermal activity was detected after the collapse, possibly linked to ongoing eruptions. Although the collapse of the southwestern sector into the ocean was associated with a considerable volume loss, area calculations of the island reveal rapid regrowth (over 10%) from December 2018 to January 2019 (Fig. 2b), which was mainly associated with the (re-)deposition of pyroclastic material.
Discussion

On the basis of the remotely sensed displacement data and thermal analysis, we conclude that the Krakatau volcano showed clear signs of flank motion and elevated volcanic activity prior to the 22 December 2018 sector collapse. The long-term hazard owing to Anak Krakatau’s steep volcanic edifice had already been described, and thus, the collapse event and subsequent tsunami were anticipated hazards\(^22\). The month-scale precursors included the strongest thermal activity recorded at Anak Krakatau in ~20 years and an accelerated flank motion; these characteristics made Anak Krakatau one of the most rapidly deforming volcanic flanks known on Earth prior to its collapse (Fig. 3). In fact, deformation was already identified along the southwestern flank of Anak Krakatau in InSAR time series over 10 years before December 2018\(^{30,31}\), but this deformation was not interpreted to be a potential precursor of a larger sector collapse. Compared with other volcanoes that exhibited flank deformation prior to sector collapse, the movement at Anak Krakatau also corresponded with eruption pulses, possibly associated with pressure changes in the volcano interior, and therefore Anak Krakatau shares a similar behavior with volcanoes elsewhere\(^{35,36}\).

We investigated whether changes in composition could explain the increase in magma production at Anak Krakatau prior to its collapse, but our analysis of syn-deformation tephra samples suggest that the material was not significantly different from the material erupted in past decades, implying that deep magmatic changes were likely not directly responsible for the observed dynamic changes at the surface. The orientation of the main sliding plane of the collapse event could be identified from the seismic records of the collapse, suggesting a steeply southwesterly dipping failure nodal plane. The strike and dip of this plane are geometrically in agreement with the amphitheater morphology and also notably with the inferred dislocation plane of precursory creep motion. Therefore, we conclude that the landslide décollement had already developed before the collapse.

A remaining question is whether the landslide of Anak Krakatau was triggered by volcanic or seismic activity. Our observations indicate that the climax of the eruptive phase was recorded in late September 2018, ~3 months prior to the flank collapse. Indeed, from September to December 2018, the volume of newly deposits followed a generally decreasing trend (Fig. 1c). In addition, SO\(_2\) gas emissions were low in the weeks prior to the collapse (Supplementary Figure 13). Moreover, because the deformation rate remained almost constant throughout this period (Fig. 3c), we suggest that only minor change, if any, was attributable to the accumulation of magma into the shallow portions of the edifice. However, the intense activity witnessed throughout the year likely increased the overall instability of the edifice owing to the rapid accumulation of new material. In fact, studies elsewhere show that slope instability at volcanoes is not always associated with eruptive phases\(^6\). This relationship is observed because slope instability changes over time; in addition, fault planes and other zones of weakness are strongly affected by pore pressure changes, hydrothermal activity, and mechanical weakening by alteration, as well as by sea erosion and oversteepening\(^3,6,41\). A similar but much smaller sequence recently occurred also at Mount Etna, where a short-term increase in the magma supply and eruption rate was accompanied by magmatic intrusion, leading to the collapse of an unstable cone\(^42\). This example demonstrates that under such critical conditions, minor internal and external perturbations can potentially trigger a collapse and eruption, leading to a disaster. From this perspective, our hypothesis that the seismic event identified herein 2 mins before the Anak Krakatau landslide acted as an external trigger is plausible but remains to be tested further.

Volcano-induced tsunamis are thought to be rare and are therefore not commonly considered in tsunami early warning centers. Historic documents reveal, however, that Southeast Asia experiences volcano-induced tsunami hazards relatively frequently, with 17 events during the 20th century and at least 14 events during the 19th century\(^7\), defining a recurrence rate of one event every 5–8 years. A volcano-induced tsunami from Anak Krakatau was anticipated\(^22\), but accurate predictions were impossible owing to a lack of understanding of the processes involved. Hence, the study of the 22 December 2018 sector

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**Fig. 6** Cascade of precursors leading up to the 22 December 2018 sector collapse event. **a** Precursors include flank motion (white arrow), eruptions (represented as eruption cloud), and increasing eruptive deposits (red shaded areas) as assessed by satellite data (thermal, InSAR). A décollement (black line beneath the island) dips SW, but faulting had not yet breached the surface. Approximately 2 mins before the collapse, a seismic event was recorded (shown by seismic trace symbol). **b** The landslide collapse along a failure plane (black curved line beneath island) showed a 1–2-min-long low-frequency signal (seismic waveform). Infrasound instruments (speaker symbol) measured the collapse before the tsunami waves arrived. The collapse decapitated the island (gray shaded area). The tsunami (blue wave) caused damage and loss along the coast. **c** Postcollapse volcanic explosions occurred coincident with increased degassing (gray plume) caused by unloading (arrow symbol); the old topography is indicated (black dashed line). New eruptive deposits increased the island area (red shaded areas). Finally, rapid erosion deeply carved incisions into the fresh eruption deposits.
collapse at Anak Krakatau provides us now with important information about the precursors and processes that culminated in the disaster.

The tsunami reached the coastal towns of Jambu, Ciwandan, Agung, and Panjang within 31, 38, 39, and 57 mins, respectively. The tsunami waves were overtaken by the faster seismic waves and the infrasound signals of the strong explosive eruption (Fig. 6b), that were associated with the landslide and decapitation of the hot interior of the volcano followed by steam-driven phreatomagmatic explosions (Fig. 6c).

In fact, the seismic records following the sector collapse event indicate that tremor activity continued for hours, resembling the volcanic tremors associated with steam-driven explosions elsewhere, although the large distance between the volcano and the seismic network may have blurred this interpretation. The eruptive style of the postdecapitation eruptions was different from that of the predecapitation eruptions. This is indicated by the different frequency contents in the seismic and infrasound data and the onset of significant SO₂ emissions on 22–23 December 2018, in agreement with the period characterized by a reduction in radioactivity and the deposition of a large amount of erupted material in the coastline, as seen in the ground-range detected (GRD) images on 22–25 December 2018. The productivity of the eruptions also appeared to increase, as evidenced by the marked growth of the island area after the collapse. This suggests a major effect of unloading on the magmatic and hydrothermal interior of the volcano.

It appears that a perfect storm of magma-tectonic processes at Anak Krakatau culminated in the 22 December 2018 tsunami disaster. Leading up to the event, different sensors, and methods measured distinct anomalous behaviors, which in hindsight can be deemed precursory. However, at the time and when considered individually, none of the parameters, including the thermal anomalies, flank motion, anomalous degassing, seismicity, and infrasound data, were sufficiently conclusive to shed light on the events that were about to unfold.

This study demonstrates that volcano sector collapses and the resulting tsunamis might be effectively anticipated by continuously monitoring the various preparation stages. Long-term flank motion, changes in thermal emission, and short-term seismic events precede the collapse, which itself was well monitored by low-frequency seismic waveforms and infrasound stations. Assessments of these parameters could be implemented in available early warning systems. Therefore, the next-generation tsunami early warning system must consider multiparametric observations, since our study reveals that a multitude of changes resulted in the unprecedented level of activity at Anak Krakatau prior to 22 December 2018. We hence recommend a dedicated search for island volcanoes that are susceptible to flank collapses and those with a history of tsunamis, and we advise the development of appropriate monitoring programs to identify critical systems at these sites.

Because the Anak Krakatau sector collapse and tsunami are rare events, insights such as those reported herein yield vital information on precursor processes and aid in refining existing monitoring and early warning technologies.

**Methods**

**Satellite thermal data.** Satellite thermal time series were generated using Middle Infrared Observations of Volcanic Activity (MIROVA), a volcanic hotspot detection system based on the analysis of MODIS data. Two MODIS sensors carried on board two NASA satellites, Terra and Aqua (in orbit since March 2000 and May 2002, respectively), provide approximately four images per day (two daytime and two nighttime) of the entire Earth surface with a nominal spatial resolution of 1 km² per pixel in the infrared band. Through a series of spectral and spatial processing steps, the MIROVA algorithm detects, locates, and quantifies any hotspots within an area of 2500 km² (50 x 50 km) surrounding the target volcano and provides near-real-time estimates of the VRP, which represents the radiative heat flux (in Watts) emitted by the detected volcanic activity (www.mirovaweb.it).

We excluded those with a poor under cloudy conditions, those with $\frac{\text{VRP}}{\text{c}_{\text{rad}}}$, where the radiant density $\text{c}_{\text{rad}}$ (W m⁻²) is an empirical parameter that embeds the rheological, topographic, and insulating conditions characterizing the observed lava flow. For the Anak Krakatau eruptive deposits we used $\text{c}_{\text{rad}}$ = 0.5–1.0 m⁻², a range of values consistent with lavas having a basaltic to andesitic composition. The integration of TADR values over time provides an estimate of the erupted lava volume with an uncertainty of ± 33% (based on the range of plausible $\text{c}_{\text{rad}}$ values).

**InSAR displacement analysis.** We measured surface displacements prior to the 2018 sector collapse through the InSAR time-series analysis generated from Sentinel-1 (S1) radar images in one ascending and two descending orbits (see Supplementary Table 3) using the StaMPS-MTI method, which is a freely available and widely used multimaster time-series analysis method (Supplementary Figure 5). The S1 Line-of-Sight (LOS) ground motion maps for the period between 1 January 2018 and 22 December 2018 were combined to calculate the vertical and horizontal motions before the eruption. To describe the overall flank motion time series, we estimated the average displacement values for all pixels located in the region identified as showing significant flank motion, and the possible contributions of the loading and compaction of new eruptive deposits, which overprint the landslide signal, are eliminated. The exact locations are identified in coherence maps and Sentinel-2 images (Supplementary Figure 4a, b). The time-series displacement data and the time-series coherence data were used to verify the coastline information obtained from the GRD scenes.
moment magnitude of Mw 5.3 was inferred from the full moment tensor inversion. The large difference between the Mw and Mw reflects the relative deficiency in high frequency components compared with the seismic earthquake. The data set obtained in the moment tensor optimization is lower than that obtained for a tectonic earthquake of similar size with the same setup. This finding suggests that a more complex source model may be needed to explain the observations, even for frequencies below 0.03 Hz.

**Drone photogrammetry.** Close-range drone photogrammetry data were acquired on 10 January 2019 by a GPS-controlled quadcopter drone (DJI Mavic Pro) equipped with a camera acquiring 1740 4 K images per flight minute and stabilized by a two-axis gimbal. In addition, we measured 14 reference points using a GPS-controlled quadcopter drone (DJI Mavic Pro) with a 10 s window length with 5% overlap with a spectrogram from the best beam is shown in Supplementary Figure 8. The beam, which is consisted of high-frequency dilatation operators) was applied with a structuring element of 5 × 5 pixels. This allowed us to remove noisy pixels and keep only large pixel clusters, which were assumed to be of volcanic origin when these were located in the proximity of Krakatau. The SO2 maps and time series provided here (Supplementary Figure 13) represent only the PBL.

**Data availability**

The seismic data are available through EIDR and IRIS data centers (AU: www.iris.edu, GE: http://www.ofrfe-usa.org/data/ida), or are available on request, to be directed at BMKG (IA: https://www.bmkg.go.id). MODIs data are available from the USGS hub at https://modis.gsfc.nasa.gov/data/ and Sentinel-2 satellite data available on the Copernicus Open Access Hub at https://www.sentinelservices.eu, and Sentinel-5P data on the Copernicus Sentinel-5P Pre-Operations Data Hub. Any requests should be made to the first author. Infrasound data from the International Monitoring System (IMS) can be made available on request at the CTBTO (https://www.ctbto.org/specials/vdec/).

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**SO2 emission monitoring from Sentinel-5P data.** SO2 emissions from Krakatau were recovered from the imaging spectrometer known as the Tropospheric Monitoring Instrument on board the Sentinel-5P satellite. Although the satellite was launched in 2017, the data have become progressively available only since late 2018. In this study, we analyze Level 2 (L2) offline (OFFL) data products down-loaded from the Copernicus Sentinel-5P Pre-Operations Data Hub, where all products recorded after 5 December 2018 are available (https://scihub.copernicus. eu/dhus?verb=GET&identifier=MSDI000400, SO2, gas–particulates (2022)). These products provide three different alti-tude ranges (as vertical column densities, VCDs): 0–1 km (the planetary boundary layer, PBL), 6.5–7.5 km (mid-troposphere), and 14.5–15.5 km (upper troposphere). SO2 VCDs were first converted from mol m−2 to Dobson units (DU) by a multiplication factor of 2241.5 (provided in the product metadata). The mass of SO2 was then calculated as follows:

\[ M_{SO2} = 0.0285 \times \sum_{i} A_{SO2} \]

where \( M_{SO2} \) is the mass of SO2 (in tons) and \( A_{SO2} \) are the area (7 × 3.5 km²) and VCD (in DU) of each pixel, respectively. Pixels contaminated with SO2 were isolated by creating a mask of DU > 1, to which a morphological filter (i.e., erosion + dilation operators) was applied with a structuring element of 5 × 5 pixels. This allowed us to remove noisy pixels and keep only large pixel clusters, which were assumed to be of volcanic origin when these were located in the proximity of Krakatau. The SO2 maps and time series provided here (Supplementary Figure 13) represent only the PBL.

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Author contributions

T.R.W. conducted the drone, Sentinel-1/2, and morphometry analysis, M.H.H. and M.M. conducted the radar interferometry and deformation analysis. J.S., F.T. and F.M.S. analyzed the seismic data; T.D. and S.H. performed the moment tensor analysis; F.M.S. and P.G. realized the infrasound data analysis and modeling, A.B. performed the tsunami modeling; D.C., M.L. and F.M. investigated the satellite thermal data; S.V. processed and analyzed the Sentinel-5 data; R.T. contributed to tsunami and impact assessment; R.K. contributed to remote-sensing assessment, V.R.T. and N.K. contributed to the computation of the lava and ash samples. T.R.W. prepared the manuscript draft. All authors provided information and/or critical comments during manuscript preparation.

Additional information

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