This version of this paper is non-peer-reviewed and under review in Nature Geoscience

This paper has been submitted for publication to Nature Geoscience on June 8 2020
A revised version of this paper has been submitted on December 15 2020 and is under review.

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Birth of a large volcanic edifice through lithosphere-scale dyking offshore Mayotte (Indian Ocean)

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Volcanic eruptions are foundational events that shape the Earth’s surface and provide a window into deep Earth processes. How the primary asthenospheric melts form, pond and ascend through the lithosphere is, however, still poorly understood. We document an on-going magmatic event offshore Mayotte Island (North Mozambique channel), associated with large surface displacements, very low frequency earthquakes and exceptionally deep (25-50 km) seismicity swarms. We present data from the May 2019 MAYOBS1 cruise, which reveal that this event gave birth to a 820m tall, ~5 km³ deep-sea volcanic edifice. This is the largest active submarine eruption ever documented. The data indicate that deep magma reservoirs were rapidly drained through dykes that intruded the entire lithosphere and that pre-existing subvertical faults in the mantle were reactivated beneath an ancient caldera structure.
The new volcanic edifice is located at the tip of a 50 km-long volcanic ridge on the eastern insular slopes of Mayotte. The ridge is composed of many other recent edifices and lava flows and is an extensional feature that opens inside a wide transtensional boundary to transfer the strain between the East-African and Madagascar rifts. A hot asthenosphere at the base of a thick damaged lithosphere could be at the origin of this massive eruption.

Since May 10 2018, Mayotte Island (Comoros archipelago, north Mozambique Channel between Africa and Madagascar, Figure 1a) has experienced a major magmatic event off its eastern coast. This event generated more than 11000 detectable earthquakes (up to Mw 5.9), surface deformation rates of up to 200 mm/year and unusual very low frequency (VLF) earthquakes. As of December 2020 (the time of writing), Mayotte is still deforming and both VLF events and earthquakes with Mw up to 5 are still being recorded. Prior to this event, no recent eruption or significant seismic activity was reported around Mayotte. Only two earthquakes were detected within 100 km of the island by the global network since 1972 and the most recent volcanic exposure is a 4-6 kyr-old pumice layer sampled in the lagoon surrounding the island.

Recent geodynamic reconstructions suggest that the archipelago was built on ~150 Ma old oceanic lithosphere accreted to accommodate the opening of the Western Somali Basin. This Comorian volcanism may result from partial melting of the base of this old oceanic lithosphere in interaction with plume material possibly super plumes originating from Africa. This volcanism may have been controlled by reactivation of the fractures zones or by diffuse zones of right-lateral shear deformation. Subaerial volcanic activity on Mayotte
island began 11 My ago\textsuperscript{13}. Well-preserved cones, tuff rings and maar craters in the northeastern part of the island (on Petite Terre and in and around Mamoudzou\textsuperscript{15,7} and further offshore\textsuperscript{16} (Figure 1b) testify to relatively recent (probably Holocene)\textsuperscript{3} subaerial explosive volcanic activity. Gas emissions on Petite-Terre with a high percentage of carbon dioxide and helium indicate magma degassing\textsuperscript{17}.

The discovery of the new volcanic edifice

The French national research program “SISMAYOTTE” was launched in February 2019 to determine the origin of the seismicity and deformation, to search for any seafloor volcanic activity and to understand the scale, chronology and implications of the crisis. As part of this program, we 1) set up seismic and Global Navigation Satellite System (GNSS) stations on Mayotte and Grande Glorieuses Islands, 2) deployed Ocean Bottom Seismometers (OBS) with attached Absolute Pressure Gauges (APG) around the seismic swarm area, and 3) acquired high-resolution marine data (bathymetry, seafloor and water column backscatter, sub-bottom, magnetic and gravity profiles), rock dredges and CTD (Conductivity-Temperature-Depth)- Rosette during the MAYOBS1 cruise aboard the R/V Marion Dufresne\textsuperscript{18}.

A systematic 12 kHz multibeam echosounder survey east of Mayotte revealed a 820 m tall new volcanic edifice (NVE) 50 km east of Mayotte (Figure 1). The NVE was detected by comparing our data to those acquired during a 2014 survey by the French Naval Hydrographic and Oceanographic Service (SHOM)\textsuperscript{19} (Figure 2a). The edifice sits on an area that, in the 2014 seafloor topography, was locally almost flat at around 3300 m below sea level (bsl).

The Mayotte volcanic ridge

The NVE has grown on the lower insular slope of Mayotte, near the end of a WNW-ESE trending volcanic ridge (Mayotte ridge) emplaced on the submarine flank of Mayotte (Figure 2).
The NVE and many other volcanic features along the ridge are highly reflective in seafloor imagery (Figure 1c and extended data Figures 1, 3) indicating recent volcanic activity all along the ridge. The ridge is 50 km long, extending from the most recent subaerial cones and maar craters on Grande-Terre and Petite-Terre islands (MPT Volcanic zone) to the NVE (Figure 1b). It is segmented into two main parts: an upper slope volcanic zone (western segment) and a mid- to lower-slope zone (eastern segment). The eastern segment trends N130°E and is made of many constructional features similar to mafic submarine eruption features observed elsewhere: cones up to 2 km-wide and 500 m-high, probably monogenetic; high backscatter zones with smooth bathymetry, which could correspond to recent lava flows; elongated ridges with steep slopes and varying orientations, which could result from dykes in more sedimented areas (Figure 1 and extended data Figure 2d,e).

The western segment is made of volcanic features having more complex morphologies and emplaced along different directions (Figure 1b and extended data Figure 2b,c). The main features are: i) Two N40°E and N120°E trending sets of cones and lava flows, with high backscatter, northeast and southeast of Petite-Terre, respectively. These sets converge to prolong the onshore maar craters of Petite-Terre and may have emplaced along pre-existing fractures or faults; ii) a horse-shoe shaped edifice (the Horseshoe) with a 3.5 km wide cone, steep slopes and a large collapse-induced scar. East of the Horseshoe, several smaller cones and volcanic features are aligned E-W, suggesting eruptive fissures. Large lava flows characterized by high backscatter and rough bathymetry likely originate from this fissure system. iii) a 4 km-wide circular structure (the Crown), whose rim is crowned by seven 1 km-wide, 100-150m high volcanic cones. Their arrangement suggests typical post-caldera domes. West of the Crown, submarine canyons and slope failure scars all terminate at a N-S trending slope break that may be controlled by faulting. The Crown appears to be located in a
larger 10 km wide flat depression, which is bounded by faults and fissures and could be the remnant of an ancient caldera collapse.

The new volcanic edifice and the eruptive plume

The NVE is located at the eastern tip of the eastern segment of the Mayotte ridge (Figures 1b). In May 2019, its summit rose to 2580 m bsl. The highest and central part of the NVE resembles a pyramid with steep and smooth slopes (Figure 2a and extended data Figure 3). Radial ridges, up to 5 km long and 300 m thick, develop from the central part. The ridges display hummocky morphology similar to that observed along mid-ocean volcanic ridges and active seamounts and probably correspond to coalesced pillow lava mounds. Beyond and in-between the hummocky ridges, flat areas up to 100 m thick, with high backscatter, could indicate channelized lava flows or sheet flows emplaced at high effusion rates. We calculate the volume of material corresponding to the 2014-2019 seafloor depth difference to be at least 5.0 ± 0.3 km$^3$. Popping fragments of very fresh basanitic pillow lavas (SiO$_2$ 47 wt%, Na$_2$O + K$_2$O 7.1 wt%, MgO 5.7 wt% 28) were dredged on the northeastern flank of the NVE, near its summit (see Figure 2a for sample location and supplementary material S1). The lavas, similar to other basanites sampled in northern Mayotte are aphyric with rare microphenocrysts of olivine (Fo70) and Ti-magnetite.

A ~1900-m high, vertical acoustic plume, rising through the water column from the summit of the NVE to ~800 m below the sea surface, was imaged several times during the cruise using the ship-borne multibeam echosounder (Figure 3, supplementary movie 1). A vertical CTD/rosette cast to 3137m depth above the northern flank of the NVE, 1000m away from the acoustic plume, showed strong geochemical signatures. High volatile concentrations (H$_2$ = 550nM, CH$_4$ = 831 nM, CO$_2$ = 34 µM), high turbidity and high total alkalinity values were associated with temperature and pH anomalies (respectively 0.2°C and 1 pH unit) and supplementary material. Such chemical anomalies are characteristic of submarine eruptions.
and may reflect magma degassing \(^3\), molten lava interaction with seawater \(^3\) or fluid/water discharge from subsurface storage zones in the crust or sedimentary cover \(^3\). The height and the strong backscatter signature of the acoustic plume suggest that a mixture of solid particles (pyroclastic/hyaloclastic jet \(^3\)) and/or differentiated fluid phases (droplets, hydrate-coated bubbles or free gas \(^3\)) are driven upward through the water column from the summit of the NVE \(^3\). High turbidity measured, below 2500 m, on the northern flank of the NVE, likely indicates the presence of these particles \(^3,3^6\). Both the multiple observations of this vertical acoustic plume at the summit of the NVE and the high H\(_2\) concentration 1 km away indicate that the eruption was likely on-going in May 2019 \(^3\).

In the upper slope zone, 30 km far from the volcano, two, ~1000-m high acoustic plumes were detected in the water column, above the Horseshoe edifice (Figure 1 and extended data Figure 5, movie 2) but no significant change in the seafloor morphology and reflectivity was detected there.

**The seismicity and VLF events relocated by OBS data**

The combined land-OBS network of seismic stations (supplement Figure S2.1) detected 17000 events between February 25 and May 6, 2019. We manually relocated about 800 of the largest earthquakes onboard (see method and supplementary S2). Ninety-four percent of the earthquakes cluster in the upper slope volcanic zone (western segment of the Mayotte ridge), 40 km west of the NVE and 5 to 15 km east of Petite-Terre (swarm 1, Figure 1). Almost all of the remaining events lie in a secondary swarm beneath the northwestern tip of the eastern segment, 30 km from Petite-Terre and 20 km from the NVE (swarm 2, Figure 1). A few events are also scattered along this segment. Despite a full search of the OBS-land catalog for events beneath the NVE, we found none. The earthquakes are very deep, ranging from 25±5 to 50±5 km. All P-S arrival delays recorded by an OBS deployed for 48h above the main
swarm were greater than 3 seconds, indicating no events less than 20 km depth (Figure 4, extended data Figure 6b, method and supplementary material S2). The combined land-OBS network dataset do not show any evidence for seismicity migration, but it only represents a two-month “snapshot” of the activity. To extend the observation time window, we carefully relocated 139 earthquakes recorded by the land stations between the beginning of the crisis (May 2018) and the first OBS deployment (February 2019). All the events were beneath the volcanic ridge (extended data figure 6a). During the first weeks of the crisis, these events were mainly located beneath the northwestern tip of eastern ridge segment between 30 and 50 km depth. In the last two weeks of June, a few events occurred between 30km-depth and the surface, and closer to the NVE.

In addition to the high frequency seismicity, VLF events were recorded by the OBSs wideband hydrophones. Their waveforms are similar to those of the globally detected November 11 2018 event (exponentially decaying monochromatic signals of approximately 2000s duration, with dominant period of ~15 s and polarized Rayleigh waves), suggesting repeated excitation of the same radiating source. We located 84 VLF events using waveform cross-correlation (see method and supplementary material S2), all of them are most probably above seismic swarm 1 (Figures 4 and extended data Figure 6b), at a mean depth of 22 ± 15 km.

**GNSS data and APG modeling**

The GNSS network includes nine stations on Mayotte Island and two far field stations at Diego Suarez and Grande Glorieuse islands. The geometry is not optimal, preventing geodetic inversions for complicated structures or media. We performed Bayesian inversions of the data using a point source in an elastic half-space with two distinct analytical formalisms: an isotropic point source and a point compound dislocation model (pCDM see method,
**supplementary material S3, extended data Figure 7).** In both cases, the results indicate ~5 km³ deflation of a deep reservoir (> 30 km). The simplest and most robust model indicates the deflation of ~ 40 km deep isotropic source below the eastern segment of the Mayotte ridge. An increase in absolute seafloor pressure measured by all APGs on the OBS frames, interpreted as seafloor subsidence, is compatible with these models (see method, *supplementary S3, extended data Figure 7d*).

**Magma reservoirs and chronology of the eruption**

Most of the seismicity and the GNSS sources models are deep and lie in the lithospheric mantle beneath the Moho, which is estimated to be ~17 km deep beneath Mayotte. Seismicity this deep is rarely documented in a volcanic context, especially in the form of dense swarms during eruptions. Mantle seismicity has been detected beneath Kilauea, Loihi and La Réunion volcanoes, where it has been interpreted as failure of the brittle lithosphere induced by magma migration through long-lived tectonic structures or by the islands’ loading.

The distribution of the seismicity in the first weeks of the crisis suggests a dyke migration from the mid-slope zone to the NVE, along the eastern segment of the Mayotte ridge. This is supported by the migration of the Centroid Moment Tensor solutions depths (CMT project) of the largest earthquakes towards the surface (*extended data Figures 6c and 8*) and agrees well with. The earthquakes show strike-slip focal mechanisms compatible with a least compressive principal stress orthogonal to the eastern segment of the ridge (*extended data Figure 8*). Similar stress trends have been observed during dyking events beneath the Izu peninsula in Japan and in Iceland but at much shallower depths, where they were interpreted as seismic shear faulting caused by stress transfer to the surrounding vertical faults in response to dyke opening and propagation.
During the first six weeks of the crisis, the magma migrated 20 km laterally along the eastern segment of the Mayotte ridge, then upward (Figure 4 and extended data Figure 8). The building of the NVE may have begun in July 2018 once the dyke reached close to the surface allowing for high magma flow rates and rapid ensuing growth. On the basis of this assumption, we estimate a minimum mean lava flow rate of $\sim 180 \text{m}^3\text{s}^{-1}$ between the start of the eruption on the seafloor and our survey (~11 months). The local stress probably decreased considerably once the magma path to the NVE was opened, as is observed during many eruptions involving dyke propagation, which would explain why no earthquakes were detected beneath the NVE during the OBS deployment, which started in late February 2019.

After the dike reached the near surface, seismicity resumed beneath the mid- and upper-slope volcanic zones (Figure 4 and extended data Figures 6a,b and 8) and its pattern appears to be constant since September 2018. This stationary seismicity could be caused by stress perturbation along pre-existing structures and/or fluid (gas, magma or water) motions. The swarm 1 earthquakes cluster beneath a 10 km-wide circular area that coincides with the ancient caldera structure inferred from our high-resolution bathymetry (Figure 1c and extended data Figure 6b and 8). This seismicity could indicate activation of pre-existing subvertical faults above a deep (> 55 km) depleting reservoir (R1,4), as has been observed during caldera collapse events but these faults would be much deeper than at any caldera structures documented elsewhere. Analog models for collapse of a caldera with a high-roof aspect ratio (thickness/width $\gg 1$) indicate reverse fault motions during an initial downsag stage, in accord with the focal mechanism of the May 14, 2019 Mw4.9 swarm 1 region earthquake (Figure 4 and extended data Figure 8) and 45.

The VLF events, located above swarm1, may be generated by the resonance of a fluid-filled (magma, gas or hydrothermal) shallower cavity or a fluid-filled crack, most probably at the base of the crust. The characteristic frequency and duration of these events are very different
from VLF events typically observed in volcanic zones. Simple up-scaling of fluid resonance models imply a size of several kilometres for this shallower reservoir (R3, Figure 4). The excitation mechanism could be rapid slip and related strain on faults close to the reservoir or episodic collapse of a piston at the base of this shallow reservoir. The acoustic plumes emanating from the overlying Horseshoe edifice may result from actively degassing of this shallower reservoir.

Both the distribution of seismicity over time and the surface deformation models suggest the drainage of an exceptionally deep reservoir by a dyke that propagated from the base of the brittle lithosphere to the eastern portion of the Mayotte ridge, possibly intersecting another vertical storage zone below seismic swarm 2 before reaching the surface (R2, Figure 4 and extended data Figure 9). Within the uncertainties the GNSS isotropic model may reflect the drainage of this reservoir R2 in the brittle lithosphere. The deeper reservoir R1 may have slowly recharged from the asthenosphere before reaching tensile failure in May 2018.

**Magma roots and paths.**

The eastern segment of the Mayotte ridge, along which the dike propagated, has the same orientation as many other volcanic features over a range of scales (quaternary dykes, volcanic vent alignments, ridges and volcanic rift zones) in the northeastern part of Mayotte Island and in and around the other Comoros islands (Figure 5 and extended data Figure 9). The left-lateral en-echelon arrangement of these features resembles that of extensional tectonic structures in a context of oblique extension (i.e in segmented and diffuse strike-slip fault systems or highly-oblique rifting. We infer that the Mayotte ridge results from the interplay between volcanism and tectonics. The location and orientation of the volcanic features may be in part controlled by the pre-existing Mesozoic fracture zones but they probably also emplace along new tectonic structures. These tectonic structures are extensional (fissures or step-overs) and open as a result of volcano-tectonic interactions in a wide E-W
striking zone, to transfer the strain between the N-S striking offshore branches of the East African rift and the grabens of Madagascar (Aloatra and Ankai). In this context, high strain rates or highly damaged zones may develop (Figure 5a inset) in between the main en-echelon extensional structures. Such zones may constitute high-permeability zones where large magmatic reservoirs can develop. The main Comoros volcanic islands may have grown above such zones.

Between Mayotte and Madagascar, the lithosphere-asthenosphere boundary (LAB) is a sharp limit between a high-velocity 150 Ma lithosphere and a low-velocity asthenosphere, at about 70 km depth. The low-velocity asthenosphere is interpreted as hot material spreading beneath the Mascarene basin and beyond. Heating of the base of the oceanic lithosphere damaged by extensional tectonic and loaded by Mayotte island may favour the ponding and withdrawal of large volumes of buoyant melts. Pore pressure increase in these zones may in turn favour failure of deep reservoirs and faults inside the brittle lithosphere.

The largest eruption ever documented in submarine domain

The NVE extruded volume (as of May 2019) is 30 to 1000 times larger than that reported for other deep-sea eruptions. As is the case for many submarine eruptions, it is difficult to evaluate the dense rock equivalent (DRE) volume. Taking an upper bound of 50% for the DRE factor, compatible with the 40% vesicularity of our sample, the DRE erupted volume could be as large as 2.5 km$^3$, which is larger than the 1.2 to 1.5 km$^3$ Havre silicic eruption, up to now considered to be the largest documented submarine eruption. It would be 2.5 times larger than the Bardabunga eruption (Iceland’s largest eruption of the last two centuries) and only 6 times less than Iceland’s 1783-1784 Laki eruption, considered to be one of the largest basaltic eruptions witnessed by humanity. The volumes and flux of emitted lava during the Mayotte magmatic event are comparable to those observed during eruptions at Earth's largest hot spots (Hawaii, Iceland, and one quarter of that emplaced...
yearly over the entire mid-ocean ridge system (mean estimate from spreading rates over the last 80 Ma\(^88\)). It thus represents a considerable input in terms of CO2 flux\(^89\).

Future scenarios could include a new caldera collapse, submarine eruptions on the upper slope, or onshore eruptions. Large lava flows and cones on the upper slope and onshore Mayotte indicate that this has occurred in the past. Since the discovery of the NVE, an observatory has been established to monitor activity in real time (REVOSIMA \(^90\)) and return cruises are ongoing to follow the evolution of the eruption and edifices.

Acknowledgements

We thank captain A. Eyssautier and the officers and the crew of the R/V Marion Dufresne (TAAF/IFREMER/LDA), GENAVIR’s coordinator, M. Boudou D’hautefeuille, and the shipboard operations engineers. We thank the captain and crew of the M/V Ylang (SGTM company). We thank the French Ministries of Environment, Research and Overseas, CNRS/INSU, IPGP, IFREMER, BRGM and the Prefect of Mayotte for funding and support. We thank our colleagues F. Tronel, A. Roulle, E. Dectot, A. Colombain, C. Doubre, Daniel Sauter, Antony Dofal and Antoine Villié for assistance in the field, previous data acquisition, processing and model development. We thank Olivier Desprez de Gesincourt, L. Testut and T. Tranchant for loan and data processing of the seafloor pressure sensors. We thank the French National Marine Hydrographic and Oceanographic Service (SHOM) for providing us with previous data from the area. We thank G. Barruol for discussions. This is IPGP contribution number XXXX.

Method Summary

Ship-borne Multibeam data was acquired using a Kongsberg EM122 1°x1° during the 2014 and 2019 \(^91\) cruises. Both data sets were processed with the GLOBE software to provide
30-m grid spaced digital terrain models and seafloor backscatter imagery and to calculate depth differences, surface and volumes. The 3D acoustic water column data from the 2019 cruise were processed using SonarScope (@Ifremer) and GLOBE softwares. **Water column measurements:** A CTD-Rosette Seabird 911+ CTD (Conductivity; Temperature; Depth) equipped with an altimeter, an Aanderaa oxygen optode and a Seapoint Turbidity Meter was mounted on a carousel with 16 ®Niskin sampling bottles (8L) to measure and sample throughout the water column. Sub-sampling was performed for onboard analyses (pH, alkalinity and total CO2 by pH electrode and titrator) and for onshore analyses (CH4 analysis by the purge and trap method and H2 and CO2 analysis by the Headspace method). **Seismology:** 800 earthquakes identified from the onshore catalog were selected in descending magnitude order and manually picked onboard. The seismic network used during the two month deployment included OBSs, onshore local and regional stations (up to 500km distance). The events were relocated with NonLinLoc and an hybrid velocity model based on trials with 6 different velocity models, achieving final location accuracies better than 5km. Eighty-four very low frequency (VLF) earthquakes were detected between February 25 and April 24, 2019, using an amplitude trigger on ocean bottom hydrophones recordings, filtered between 0.05 and 0.10 Hz, followed by a selection of events with a clear peak frequency and a final visual inspection. VLF earthquakes were located using spatial 3D back-projection of station-pair cross-correlation functions, assuming a constant surface-wave speed of 3.5 km/s. A well-constrained epicentral location was obtained for 81 events. **Geodesy:** We inverted the surface deformation recorded by 6 permanent GNSS (Global Navigation Satellite System) receivers installed in Mayotte, Grande Glorieuse and Madagascar. We used both an isotropic model and a triple volumetric discontinuities (pCDM source) in a homogeneous elastic half-space, isotropic material with Poisson's ratio of 0.25 to model the pressure source in depth. Seafloor pressure data (30s sample interval) were pre-processed using harmonic
analysis to remove the tides and low-pass filtering to remove residual oscillations interpreted as internal waves.

**Author contributions**

NF, SJ, WC, CD, IT, EJ, JMS, ALe, FP, RD, AG, CA, OF, PK, ALa, JPD, LG, JG, VG, PP, ER participated on the MAYOBS1 cruise (NF, SJ and WC as PI), acquired and processed the geophysical and seismological data. CSa, ALa and PB detected and located the VLF events. AP was in charge of the GNSS installation in Glorieuse island and processed and modeled the GNSS data with FB and RG. VB was in charge of the OBSs APGs and processed their data. SB participated in the first OBS deployment on the Ylang vessel with WC and RD. DB, ALM and JVW were responsible for the installation of new seismological and GNSS stations in Mayotte and of data acquisition onshore. JPD, VG, ER, CC performed the geochemical analysis and interpretation of the water column data. CSc and AG processed the EM122 acoustic data. CD and AG performed the depth changes calculation. CSc provided the interpretation of the water column acoustic data. PBa and YF furnished the rocks sample descriptions and petrological analysis. NF, SJ, CD, PBa, YF, IT, FP, JVW, EJ provided the geological interpretation. NF wrote the paper with the contribution of all other authors. JMS, EJ, CSa, ALe, GL, CA, VB, AG, AP, FB, RG, ER, CC, CSc wrote the supplementary method and method online.

**Data availability statement**

The authors declare that most of the data supporting the findings of this study are available within the paper and its supplementary information files. GNSS data are available on the website «http://mayotte.gnss.fr». Ship-borne geophysical data from the MAYOBS1 cruise can be obtained through the French national oceanographic data center SISMER (http://en.data.ifremer.fr/SISMER) but restrictions apply to the availability of these data. The
compilations of older bathymetric and topographic data are available on the SHOM Website (http://www.shom.fr.)
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FIGURE CAPTIONS

**Figure 1:** The volcanic ridge offshore Mayotte. a) Westward view of Mayotte island and insular slope (vertical exaggeration 3) with MAYOBS1 cruise multibeam EM122 bathymetry (resolution: 30m) superimposed on a previous bathymetry-topography compilation. The volcanic Mayotte ridge extends from the onshore Mamoudzou-Petite Terre volcanic zones to the new volcanic edifice (NVE). Green arrows and stars: location of acoustically-detected plumes above the Horseshoe, the NVE and the degassing area on Petite-Terre island. Left inset: geographic setting and surface horizontal displacements (with plate velocity removed) recorded by Global Navigation Satellite System (GNSS) stations in Mayotte, Grande Glorieuse and Madagascar (Diego Suarez). Black points: seismic stations (details and name in Supplementary material). Dashed grey lines: NNW-SSE to N-S striking Mesozoic fracture zones resulting from the Gondwana break-up. b) MAYOBS1 multibeam bathymetry superimposed over slopes (dark zones: steep slopes) and geological interpretations. Volcanic structures are indicated in purple (mainly cones) and pink (lava flows and elongated features). In yellow: Upper slope’s highly reflective patches (backscatter data). The NVE is indicated in red (central part with steep slopes) and orange (radial ridges and flat flows). Green stars: degassing areas detected acoustically (on the Horseshoe) and visually (on Petite-Terre). Red lines: fissures and faults, dashed lines for inferred faults. Area filled with small black dots: bathymetric depression. White boxes: location of Fig.2a and Extended data Fig. 3. Inset, as in b with Mayotte ridge segments underlined by red and purple colored patches, pink dots: seismicity recorded during the Ocean Bottom seismometer (OBS) deployment and relocated on board; yellow diamonds: location of the Very Low Frequency earthquakes. c) MAYOBS1 multibeam backscatter map (white = higher reflectivity). Shallow bathymetry and topography are the same as in a). Pink dots and yellow diamonds as in b) inset. Black and white boxes: location of extended data Figure 3, respectively.

**Figure 2:** The new volcanic edifice (NVE) offshore Mayotte. a) 30 m resolution bathymetric maps from shipboard EM122 multibeam, illuminated from N290°E. Left panel: SHOM bathymetry collected in 2014. Right panel: MAYOBS1 bathymetry collected in May 2019. Red circle: position of dredge DR01. b) Depth changes between 2014 and 2019. The change in topography is estimated to be significant when larger than 10 m.
Figure 3: a) Southward 3D view of the NVE and the water column acoustic plume observed one hour before the Conductivity-Temperature-Depth (CTD) rosette on May 16th 2019 (White dot and blue patch) deployed, 1 km far from the summit the volcano (see Extended data Figure 4). Right inset: Processed polar echogram from one EM122 multibeam ping on May 16th (13:33 UT), horizontal and vertical-axes (both in meters) correspond respectively to the cross-track distance and the water depth. See also Acoustic plume movie 1.

Figure 4: Conceptual model of the submarine eruption offshore Mayotte eruption: Bathymetry as in Figure 1b, no vertical exaggeration. Red zones on the seafloor: N130°E volcano-tectonic ridges (Jumelles ridges) and segments including Mayotte ridge eastern segment. Dashed white lines: inferred ancient caldera with degassing zones above. In cross-section: red and reddish zones: magma storage zones (mush or magma chambers) and magma pathways involved in the 2018-2020 Mayotte volcanic crisis and seafloor eruption. Yellow layer: sediments. Dashed lines: subvertical faults beneath inferred caldera possibly reactivated by the deflation of a deep reservoir. White arrow: possible downsag at an initial stage of caldera collapse. Pink dots: 800 earthquakes between 25 February and May 6 2019 located using OBSs and land stations. Other dots: 139 earthquakes from before the OBS deployment, picked on land stations and relocated using a new model based on the OBS+land data: colored dots are from the first 6 weeks of the crisis and white dots from the remaining 8 months before the OBS deployment. Yellow diamonds: Very Low Frequency (VLF) earthquakes, constrained by the OBS+land network. Blue and red triangles: water and magma movements, respectively. Blue patch: Location, with 3 sigma uncertainties, of the most robust isotropic source deformation model. Moho depth from 40. Lithosphere/asthenosphere boundary depth from 77.78.

Figure 5: Regional volcano-tectonic setting of the submarine eruption offshore Mayotte. a) Volcano-tectonic setting of the new volcanic edifice (NVE). Bathymetry compiled from MAYOBS1 cruise 18, PTOLEMEEE Cruise 95, and the General Bathymetric Chart of the Oceans (https://www.gebco.net). Global topography from SRTM GL1
Volcanic cones and ridges (purple) from 13,96,16,14 and this study. Dots and diamonds are earthquakes as in Figure 4 and Extended data Fig. 6 and 8. Beach balls: focal mechanisms for M>5 earthquakes 97. Dotted white arrow: dyking event along the N130° E trending eastern segment of the Mayotte volcanic ridge. Red ellipse: inferred main volcano-tectonic ridges (Mayotte, Jumelles…). Purple ellipses: highly damaged zones in between the en echelon ridges (see sandbox model in Inset). Thick black arrows: local extension direction. Inset: sandbox model from 73 illustrating the possible arrangement of the main volcano-tectonic structures in Comoros (see also Extended data Figure 9). b) Geodynamic setting of the East African Rift systems. Bathymetry from GeoMapApp (www.geomapapp.org), main tectonic structures and extensional zones in Africa and Madagascar adapted from 98,73,74,99,100,101,72 and references therein. Purple patches: Quaternary volcanism in Madagascar from 73. Red dots: M> 2.5 earthquakes 4 with focal mechanisms from the Global Centroid-Moment-Tensor Project 97 for the M>5 earthquakes. Arrows: GNSS horizontal motions 98. Small purple ellipses in the Comoros as in a) with double dark red arrows: the volcanic ridge east of Mayotte and extension direction. Inset: Simplified tectonic map of the East African Rift system: Yellow highlights: most active rifts and grabens; Red ellipse: Transfer zone of the Comoros with direction of lateral motion.
Extended data. Figure 1: 3-D westward view of submarine volcanic features located east of Mayotte, 3x vertical exaggeration. Bathymetry from MAYOBS1 30-m resolution DTM and previous bathymetry-topography compilation\(^{16,94}\) a) bathymetry (b) Backscatter seafloor reflectivity (white is highest reflectivity) from MAYOBS1 cruise.

Extended data. Figure 2: Volcanic features offshore Mayotte. a) 30-m resolution EM122 multibeam bathymetry (MAYOBS 1 cruise) superimposed on a previous bathymetry-topography compilation\(^{16,94}\) with locations of Fig2.b,c,d indicated. b), c) Interpreted MAYOBS1 shipboard bathymetry and backscatter of the upper slope east of Mayotte (location in a). Cones, lava flows and canyons as in Figure 1b. Black dots: bathymetric depression. Dashed red lines: possible pre-existing caldera structure. d) Interpreted bathymetry of the lower slope east of Mayotte (localisation in a). e) zoom on d) showing monogenetic cones and lava flows.

Extended data. Figure 3: New volcanic edifice. a) 2014 EM122 multibeam seafloor backscatter\(^{19}\). b) 2019 reflectivity (MAYOBS 1 cruise)\(^{18}\). c) Depth changes between the 2014 and 2019 surveys, superimposed on 2019 reflectivity. The white areas of the 2019 backscatter map exceeding the bathymetric difference map indicate the extent of new volcanic material.

Extended data. Figure 4: CTD (conductivity temperature-depth)-Rosette measurements. a) Nephelometry and b) temperature vertical profiles. c)-g) sample analyses from 8L ®Niskin bottles. c)-e) Gas concentrations(CH\(_4\), H\(_2\), CO\(_2\)); .f) pH, g) total alkalinity and total CO2.

Extended data. Figure 5: Acoustic plumes over the Horseshoe volcanic structure. a) Southward 3D view of the horseshoe morphology and two water column acoustic plumes observed on the western internal flank. b) Processed polar echogram from one EM122 multibeam ping of the data set displayed in (a) acquired on May 18th (0541 UT) horizontal and vertical-axes correspond respectively to the cross-track distance and the water depth, in meters) – see also Acoustic plume movie 2.
**Extended data. Figure 6**: Top: map views, bottom: cross-sections (A-A’) projection along azimuth N115°E; (B-B’) along azimuth N45°E. a) Earthquakes recorded by onshore seismological stations before the deployment of the Ocean bottom seismometers (OBS). Colored circles are events occurring in the first six weeks of the crisis, white circles are earthquakes in the intervening 8 months. b) Earthquakes recorded by the OBS+land stations between February 25 and May 6 2019 (pink dots). Yellow diamonds: location of the Very Low Frequency (VLF) events located in this study (see supplementary information). c) Focal mechanisms of the largest earthquakes from the Harvard CMT catalog (https://www.globalcmt.org/), with color scale as in a).

**Extended data. Figure 7** - Global Navigation Satellite System (GNSS) data modelling and seafloor subsidence estimated from seafloor pressure variations. a) Map shows the locations of the stations used. Arrows with colors with names: GNSS velocity vectors (mm/yr) and station names. Coloured numbers: vertical deformation (mm/yr). Inset: yellow dots locate pressure sensors on ocean bottom seismometer stations (see Fig.S2.1 for names), red arrows: Mayotte GNSS velocity vectors (mm/yr), white arrows: far field GNSS velocity vectors. b) GNSS Time series with relative displacements recorded on the east (top), north (middle) and vertical (bottom) components of the stations between January 2018 and January 2020. c) Best fit-models with 1σ uncertainties of the GNSS data for one isotropic point source and a triple volumetric discontinuity pCDM source. d) Top panel: Pressure recorded by Seabird SBE37 gauges at the six ocean-bottom seismometer stations (Yellow dots inset Figure 7a and Fig. S2.1) de-tided and converted to vertical motion.Middle panel: vertical deformation estimated at each seafloor instrument location, using the best isotropic source model obtained from the GNSS data for the March 1st to May 1st 2019 period. Lower panel: residual signal after subtracting the model-predicted trend from the seafloor pressure variations. This residual probably contains instrumental drift (especially in the first 2 weeks of the deployment) but may also include some mis-modelled seafloor deformation. The residuals at stations MOSE and MONE (see location on Figure S2.1) exhibit slight negative and positive trends, respectively which could indicate that the volcanic source is located a bit further south than that modelled using the GNSS data, assuming that instrumental drift is not the dominant factor.
**Extended data. Figure 8:** Conceptual model for the Mayotte seismo-volcanic event. Circles and diamonds are events as in Extended data - Figure 6. Focal mechanisms of main earthquakes are from Harvard CMT catalog (https://www.globalcmt.org/) with the same color scale as the May 10 to June 30, 2018 events, Yellow circle and blue patch: Location, with 3 sigma uncertainties, of the most robust isotropic source deformation model. a) Map view: The redish ellipse: Mayotte ridge, dashed circular area: old caldera structure in the morphology b) Cross-section (projection along azimuth 115 degree). Symbols as in a). Red lines: magma migration (dykes). Red ellipses and circle: magma reservoirs or mushes. Pink arrow: possible downsag along caldera structures. Redish zone: Eastern segment of the Mayotte ridge.

**Extended data. Figure 9:** Regional volcano-tectonic setting of the submarine eruption offshore Mayotte. a) Volcano-tectonic setting of the new volcanic edifice (NVE). Bathymetry compiled from MAYOBS1 cruise, PTOLEME cruise, and the General Bathymetric Chart of the Oceans (https://www.gebco.net). Global topography from SRTM GL1 (https://catalog.data.gov/dataset/shuttle-radar-topography-mission-srtm-gl1-global-30m). Volcanic cones and ridges (purple) from and this study. Beach balls: focal mechanisms for M>5 earthquakes. Dotted white arrow: dyking event along the N130° E trending eastern segment of the volcanic ridge. Pink ellipse: inferred main volcano-tectonic ridges. Purple ellipses: highly damaged zones in between the en-echelon ridges (see sand box model Inset of Figure 5). Thick black arrows: local extension direction.
Figure 1
Chronology

1. Deep asthenospheric reservoir drainage (before May 10, 2018)
2. Slow refilling of the deep reservoir (before May 10, 2018)
3. Reservoir failure/Dyking (May-June 2018)
4. Start of the eruption (July 2018)
   - Lithospheric reservoirs drainage
5. Reactivation of faults beneath ancient caldera? (Sept 2018)
   - Fluid movement (magma/water)?

Seismicity time scale

MAYOBS1 data
(26/02/19 - 6/05/2019)
- VT
- VLF

Before OBS deployment
- 07/18-02/19
- 28/06/2018
- 21/06/2018
- 14/06/2018
- 10/05/2018
- 24/05/2018
- 31/05/2018
- 17/05/2018
- 10/05/2018

Magnitude drainage
- 5.5
- 5
- 4.5
- 4
- 3.5
- 3
- 2.5
- 2
- 1

20 km

Figure 4