Why do small volcanic ocean islands collapse? Lessons from Santa Maria Island, Azores Triple Junction

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Abstract

Volcanic ocean island collapse is a gravitational process, therefore mass is a key variable. Based on this premise, islands much smaller than Hawaii are believed to be not prone to collapse. Here we show that they can collapse, and more than once, like in Santa Maria Island (Azores), 170 times smaller than Hawaii, as inferred from onshore data and new high-resolution bathymetry. Santa Maria sits on oceanic sediments hundreds of meters thick, the top of which is unconsolidated, water saturated and, therefore, soft. Numerical simulations indicate that, if the volcanic edifice is strong, it does not collapse, even if its base is weak. However, a relatively weak edifice can collapse over a weak base. We conclude that small volcanic islands can collapse when both the edifice and its base are weak. Our numerical simulations also indicate that, if the basal detachment only partially occupies the base of the volcano edifice (outer soft sediment ring less affected by pressure and temperature), the flank will only partially collapse. This could be the case of the Hilina Slump in the Big Island of Hawaii, because the large size of the edifice can produce high-grade metamorphism in the sediments at the core of the edifice's base.

Introduction

Volcanic edifice collapse is a gravitational process; therefore, mass is a key variable, which raises the following question: if mass is critical, then why do small volcanic ocean islands (small mass) collapse, and sometimes catastrophically? We use Santa Maria, a small volcanic ocean island in the Azores ca. 170 times smaller than the Big Island in Hawaii, to address this problem. If (1) the early Santa Maria seamount is ca. 10 Ma (6 Ma above sea level), and (2) the oceanic crust below Santa Maria is ca. 40 Ma old (anomaly 18-20, cf. Luís and Miranda, 2008), then Santa Maria sits on an oceanic crust covered by ca. 30 Ma of marine sediments. If pelagic sediments have deposited around Santa Maria like elsewhere in the deep ocean in and around the Azores, at a rate of a ca. 30 mm/ka (Searle, 1977; Vlag et al., 2004) (no other islands existed at the time to produce volcaniclastic sediments), then Santa Maria would sit on a pile of sediments around 1,000 m thick (cf. Searle, 1977), which corresponds to about one third of the height of the volcanic edifice in Santa Maria (currently 2,500 m below sea level and 500 m above). What are the effects of such basement sediments on the evolution of a small volcanic ocean island, especially regarding edifice spreading and flank collapse? Is a soft basal ring capable of partial detachment, thus facilitating collapse of a full flank, including summit? Here we use numerical modelling to address this problem.

The Azores islands sit on a particular geodynamic setting, the Azores Triple Junction (ATJ, Fig. 1), where the North America, Eurasia and Nubia plates meet. Although not experiencing high magnitude earthquakes ($M < 7.0$), the Azores are frequently shaken by earthquakes along the main tectonic structures, i.e. the Mid-Atlantic Rift and the diffuse boundary between the Eu and Nu plates. Although with moderate magnitude, some earthquakes can be very destructive when they occur at shallow depth. Therefore, we must consider seismicity as a possible trigger of flank collapses.

The evolution of subaerial Santa Maria (Sibrant et al., 2015a; Ramalho et al., 2017; Marques et al., 2020; see Fig. 1B, C) started ca. 6 Ma ago with a basaltic subaerial shield volcano (Old Volcanic Complex), which collapsed to the east at ca. 5.1 Ma. A new basaltic shield volcano (Young Volcanic Complex) grew on the collapse scar, therefore initially submarine and later subaerial as it grew out of the water, which collapsed to the east at ca. 3.8 Ma. Immediately following the collapse, numerous Strombolian cones grew unconformable on the eastern concave scar facing east, from ca. 3.7 to 2.8 Ma, thus rapidly filling the collapse scar. Similarly to other volcanic ocean islands (e.g. Hildenbrand et al., 2003; Ramalho et al., 2013; Marques et al., 2020b), Santa Maria experienced considerable vertical motions (Marques et al., 2020a), witnessed by submarine lava flows currently outcropping at ca. 200 m above sea level. The topography of Santa Maria (Fig. 2A) shows a well-defined divide separating the contrasting topography between E (rugged and concave to the E) and W (structural surface gently dipping to the W, similarly to the lava flows of the two volcanic complexes) Santa Maria.

Work on flank collapses has concentrated on relatively large volcanic ocean islands, and all modelling work (analogue and numerical) has considered a full detachment of the volcano's base (Borgia, 1994); Merle & Borgia, 1996; van Wyk de Vries & Borgia, 1996; van Wyk de Vries & Matela, 1998). This does not seem realistic to us, because the core of volcanic edifices typically has a high geothermal gradient and high pressure that should transform underlying soft sediment into hard metamorphic rock. However, the effects of pressure and temperature on the rheology of sediments underlying the island should depend on island size. Therefore, in the present work, we used a small edifice and low viscosity rheology in a ring totally or partially occupying the base of the volcanic edifice.

Since 2012 many large landslides in the Azores have been reported by the MEGAHazards team (PI F.O Marques) based on extensive on and offshore observation and data (Hildenbrand et al., 2012, 2018; Marques et al., 2013b, 2018, 2020, 2021; Costa et al., 2014, 2015; Sibrant et al., 2014, 2015a, 2015b, 2016). Regarding Santa Maria, Marques et al. (2013b, 2020) and Sibrant et al. (2015a) recognized two flank collapses at around 5.1 and 3.8 Ma using only onshore observation and data. The main argument is that the summits and eastern flanks of the two main shield volcanoes are missing (only the western flank is well preserved; cf. Fig. 2B), which should thus comprise two debris deposits at the ocean bottom, which are conspicuous in the new high-resolution bathymetry presented here.

Given the above state-of-the-art, the novelty in the present study is two-fold: (1) the high-resolution bathymetry showing the distribution and flow of the deposits produced by the flank collapses; (2) numerical simulations showing how small islands can collapse.

New field data

Despite their age (ca. 2.8-3.6 Ma), most Strombolian cones in Santa Maria have their original shape well recognizable, and can thus be spotted on the 10 m resolution DEM. Confirmation on the field was carried out by observing the typical volcanic stratigraphy (alternating pyroclastic layers and lava flows dipping radially to a central crater), sometimes also with outcropping necks with massive lava. We detected ca. 130 cones, of which only 9 occur W of the divide (cf. Fig. S1). 120 is a minimum number of cones E of the divide, because the terrain is in many cases very difficult to access or densely vegetated with no outcrops. We can distinguish two main types of cones, according to their dimensions (Fig. S2): large cones (diameter at the base > 500 m; Fig. S2), and small cones (diameter at the base <200 m).

New high-resolution bathymetry

Santa Maria lies very close to the junction between the East Azores Fracture Zone (EAFZ), the scarp of which is taller than 1000 m, and the Terceira Rift. The bathymetry around Santa Maria shows the following main features (Figs. 3 and S3): (1) Santa Maria is only conical in the NW quadrant, elsewhere the contours are either straight or concave outwards; (2) the Terceira Rift lies only ca. 25 km east of Santa Maria; (3) south of Santa Maria, the EAFZ is filled with thick sediments; (4) the EAFZ scarp is blanketed by thick sediments ca. 50 km ESE of Santa Maria; (5) these sediments comprise a hummocky terrain with lobes convex outwards (to ESE); (6) a tongue of sinuous sediment lies inside the EAFZ, indicating flow of fine debris into the EAFZ and over a thick older deposit; (7) SSW of Santa Maria, sediments partially blanket the tall scarp of the EAFZ (Figs. 4 and S6); (8) inside the EAFZ SSW of Santa Maria (Figs. 4 and S6), the thick sediment front is conspicuous, with younger lobes overlying an older and thicker deposit; (9) topographic profiles along critical directions show the shape of the topography where we infer the existence (convex upward) or absence (concave upward) of debris deposits (Figs. S4 and S5).

Given that the Terceira Rift is younger than the Santa Maria's flank collapses, part of the deposits SE of Santa Maria are currently inside the Terceira Rift, whose bounding fault in the S has displaced the deposits into the rift.

Numerical modelling

Our main goal was to investigate the effects of partial or total detachment at the base of the volcanic edifice, which differs from previous work (e.g. Borgia, 1994); Merle & Borgia, 1996; van Wyk de Vries & Borgia, 1996; van Wyk de Vries & Matela, 1998), where a fully detached base was used. Our argument for this critical difference is that pressure (edifice load) and temperature (geothermal gradient) increase towards the centre of the base of the edifice, which can transform soft sediments (detachment) into hard medium- to high-grade metamorphic rocks (strong coupling with volcanic rocks) depending on the pressure and temperature conditions, which in turn depend on edifice size and geothermal gradient within the edifice.

The numerical results for a viscosity of 10^{22} Pa s and a friction angle of 15º (Fig. 5) show that: (1) the island collapses only where there is basal decollement (lefthand side of the edifice), otherwise there is no collapse (righthand side); (2) a main detachment forms where most of the outward motion is accommodated; (3) strain within the collapsing edifice is accommodated by a number of small synthetic and antithetic faults; (4) when the soft layer occupies the whole radius, the entire flank, summit and part of the opposite flank collapse; (5) when the soft layer only partly occupies the base, only partial flank collapse is observed within relevant time.

Discussion

Onshore observations

The great number of Strombolian cones on the eastern concave surface of Santa Maria lie on the wrong surface (unconformity), because they should lie on a convex surface of a typical volcanic shield if there had been no collapse (Fig. 6). The mentioned cones are responsible for the partial filling of the collapse scar, therefore the original scar is not so obvious on the bathymetry. We note that the eruptive style changed from dominant shield volcano to numerous asymmetrically distributed Strombolian cones that grew unconformable on the eastern concave scar facing east, at around 3.6 Ma, thus rapidly filling the collapse scar.

Volumes

To estimate the volumes of the two collapses, we use the procedure reported in Marques et al. (2019): we approximate the shape of the collapse to a spherical cap, because the collapse fault is curved along both dip and strike. Then we calculate the volume of a spherical cap assuming values of the radius of the approximated circumference (ca. 7 km, measured as shown on the sketch in Fig. S7) and the height of the spherical cap (ca. 1.4 km), and we obtain ca. 110 km^3 for each of the collapses. Given that the volume of the volcanic edifice is ca. $1.26x10^3$ km^3 (20 km radius, and 3 km height), we infer that ca. 10% of the edifice collapsed in each event. The estimated Santa Maria volume is ca. 170 smaller than the volume estimated for the Big Island in Hawaii, i.e. about 213,000 km^3 (Robinson and Eakins, 2006), which has been the argument to claim that small islands like Santa Maria should not show large-scale collapses.

We did not attempt to estimate the volume of the debris deposits at the ocean bottom because the original topography is complex, and we do not have yet seismic surveys that allow determining the thickness of the deposits. From the great aerial extent of the debris deposits, we infer significant entrainment of sediments deposited earlier (in the previous 30 Ma). The debris deposits of both Santa Maria collapses predate the opening of the Terceira Rift, which means that they are affected by the opening of the new rift, and therefore the deposits were larger than they currently seem at first sight.

Collapse triggers – a volcanic edifice can collapse under its own weight, especially if it sits on soft basement rock, but it can do so slowly (e.g. the Hilina Slump in the Big Island, Hawaii; e.g., Moore et al., 1994; Smith et al., 1999; Owen et al., 2000). What the new bathymetry indicates is that the collapse was catastrophic at some point, because the debris travelled far from the source (at least 100 km, i.e. 5 times the radius of Santa Maria at the base). Note that the flank collapses in Santa Maria predate the jump of the Nubia-Eurasia plate boundary from the East Azores Fracture Zone to the Terceira Rift around 1.5 to 2.0 Ma. The collapses apparently occurred to the east (mostly) and to the south, and this could be due to the topography underlying Santa Maria and the buttressing offered by the volcanic ridge in the west.

Numerical modelling

The present numerical simulations indicate that: (1) partial basal detachment produces partial flank collapses, like the Hilina Slump in the Big Island, Hawaii. From this we infer that the pressure and temperature induced by the Hawaiian edifice transformed the soft sediment into strong rock hampering full detachment at the volcano's base. (2) To have a full flank collapse, like in Santa Maria, a full radius at the volcano's base must detach. From this we conclude that the pressure and temperature induced by the Santa Maria edifice could not transform the soft sediment into strong rock that could hamper the inferred full flank collapse. (3) A viscosity in the order of 10^{23} Pa s prevents collapse in relevant time, and viscosity in the order of 10^{21} Pa s makes the volcanic edifice rapidly collapse into a flat pancake. From this and the gathered natural data, we infer that a viscosity in the order of 10^{22} Pa s realistically approximates the behaviour of a volcanic edifice like Santa Maria. We could make collapse velocities more similar to nature by lowering a bit the viscosity, but a full parameter investigation is out of the scope of this study.

Conclusion

With the new high-resolution bathymetry, we found that the missing flanks are deposited at the bottom of the ocean, which confirms the onshore data and earlier interpretations, and better helps to estimate the dynamics of the debris-avalanches (runout distance, flow, area covered by slide deposits, size of debris, type of collapse – slow or catastrophic). Previous onshore and new bathymetric data on and around Santa Maria Island concur toward the same conclusion: the island has experience two major flank collapses, the debris of which lie at the ocean bottom south and southeast of the island. Given that the collapses occurred some millions of years ago, it is difficult to discern between the deposits resulting from the two collapses. However, from the distance travelled by large blocks and volume of entrained sediments (at least 100 km away from an island that is < 20 km wide and 3.5 km high), we infer that both collapses were catastrophic. Given that Santa Maria lies very close to the East Azores Fracture Zone (only a few km apart), which was active at the time of the collapses, the catastrophic collapses may have been triggered by shallow earthquakes occurring nearby in the East Azores Fracture Zone.

The numerical simulations here presented indicate that, if the volcanic edifice is strong, it does not collapse, even if its base is weak. However, a relatively weak edifice can collapse over a weak base. We conclude that small volcanic islands can collapse when both the edifice and its base are weak. From the numerical results, we infer that Santa Maria's edifice is not hot and big enough to induce pressure/temperature conditions that could transform soft sediment into hard metamorphic rock, thus hampering collapse. This weak layer promotes detachment at the base, which facilitates deep flank collapses as indicated by the missing flank, the volume of the ocean bottom debris deposits, and the numerical simulations here presented. This would explain why the Azores (small islands) and Canary Islands (bigger but still relatively small) show so many large-scale flank collapses and ongoing slumps: they both sit on soft sediment. Our numerical simulations also indicate that, if the basal detachment only partially occupies the base of the volcano edifice (outer soft sediment ring less affected by pressure and temperature), the flank will only partially collapse, which does not seem to be the case in Santa Maria.

This could be the case of the Hilina Slump in the Big Island of Hawaii, because the large size of the edifice can produce high-grade metamorphism in the sediments at the core of the edifice's base.

Confirmation that the collapses have actually occurred increases both hazard and risk, because the number of recognised collapses increases, and so does the frequency, thus bringing closer the time scales of collapses and human life.

Declarations

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Data Availability Statement

The data that support the findings of this study are available from the Task group for the Extension of the Continental Shelf (EMEPC) but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of the EMEPC. Supplementary datasets generated and/or analysed during the current study are available on the EMODnet repository at https://portal.emodnet-bathymetry.eu/?menu=19

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Figures

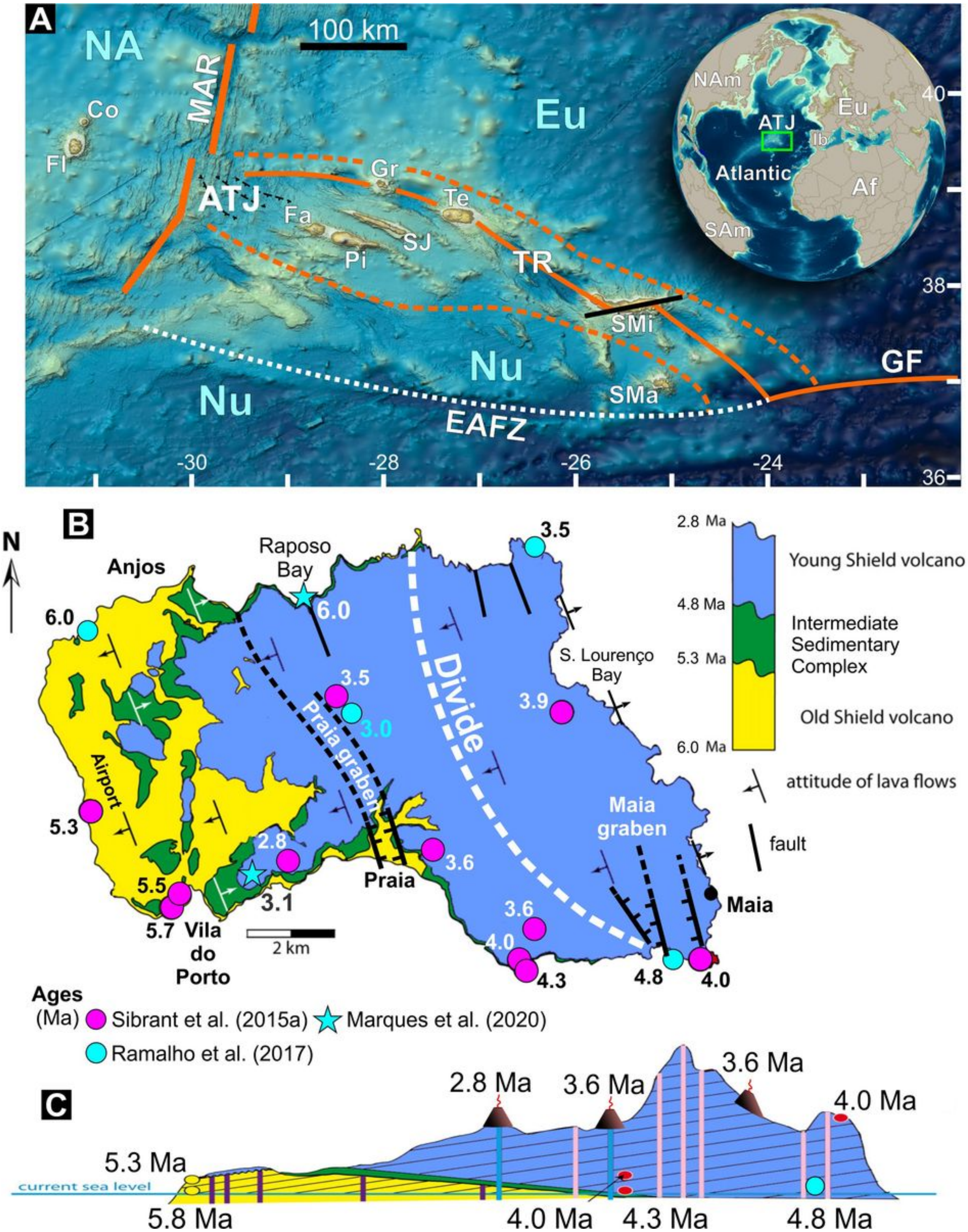

Figure 1

A – Tectonic setting of the Azores Triple Junction (ATJ) with the main tectonic and volcanic elements: 3 lithospheric plates, North America (NA), Eurasia (Eu), and Nubia (Nu); the Mid-Atlantic Rift (MAR); the Terceira Rift (TR); the East Azores Fracture Zone (EAFZ), the former boundary between the Eu and Nu plates; the Gloria Fault (GF), a dextral transcurrent fault linking the TR with Gibraltar. The Azores archipelago comprises 9 islands, from W to E: Flores (Fl), Corvo (Co), Faial (Fa), Pico (Pi), S. Jorge (SJo), *Graciosa (Gr), Terceira (Te), S. Miguel (SMi) and Santa Maria (SMa). Dashed orange line delimits the diffuse plate boundary between Eu and Nu. Black line represents the S. Miguel transform fault. B – Simplified Santa Maria geological map with main ages, faults, and attitude of lava flows. Note the curved divide concave to the E. C – geological profile along the S coast, which is similar to what is observed in the N coast (cf. Fig. 2B). Background image from EMODnet (https://portal.emodnet-bathymetry.eu/), and globe insert in A from Google Earth.*

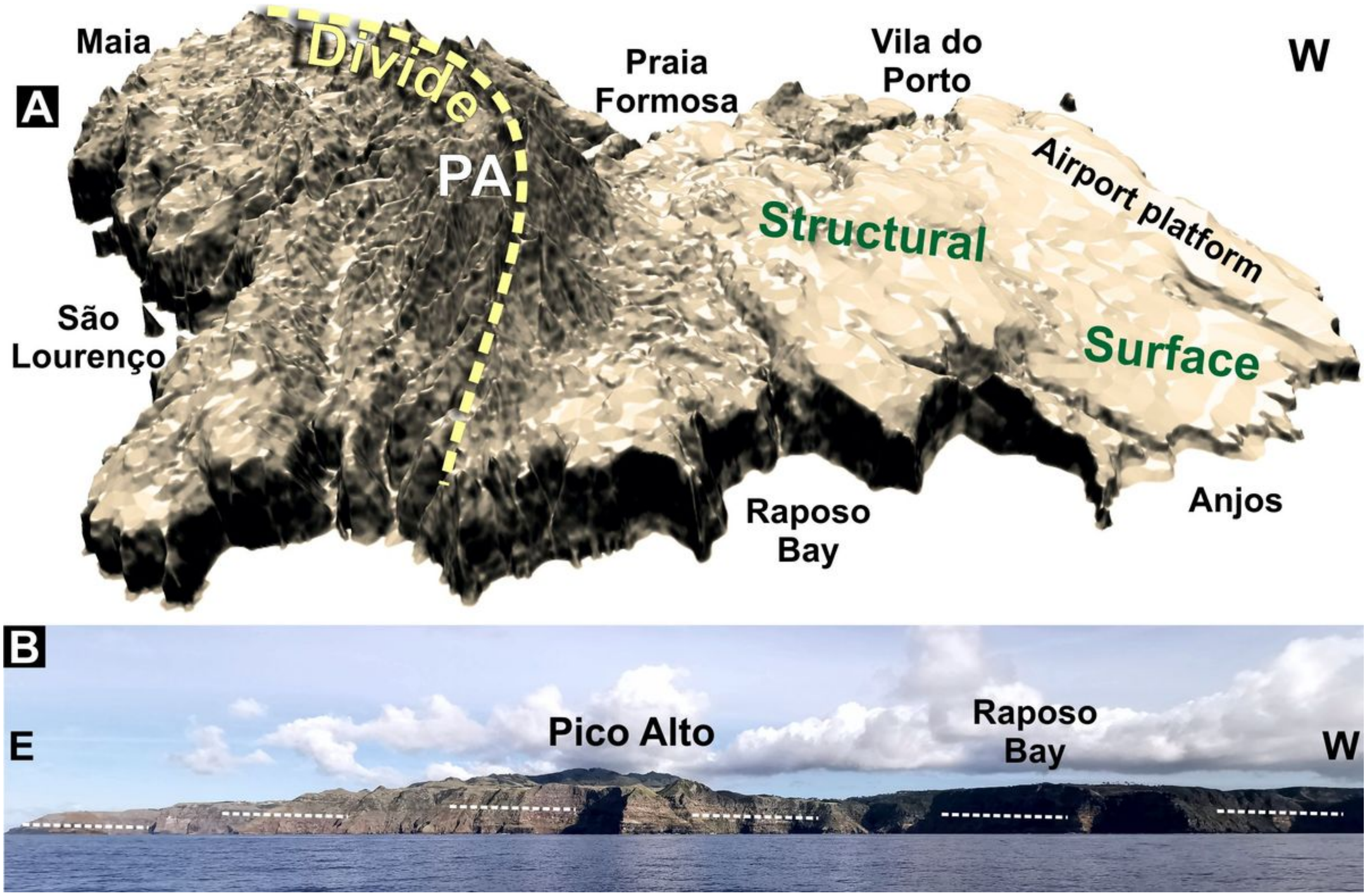

Figure 2

A – 3-D shaded relief viewed from N and showing the position of the divide and the contrasting topography between E (rugged and concave to the E) and W (structural surface gently dipping to the W, similarly to the lava flows of the two volcanic complexes) Santa Maria. B – Panorama photograph of the entire northern seaboard with lava flows gently dipping to the W (highlighted by dashed white lines), similarly to the southern seaboard.

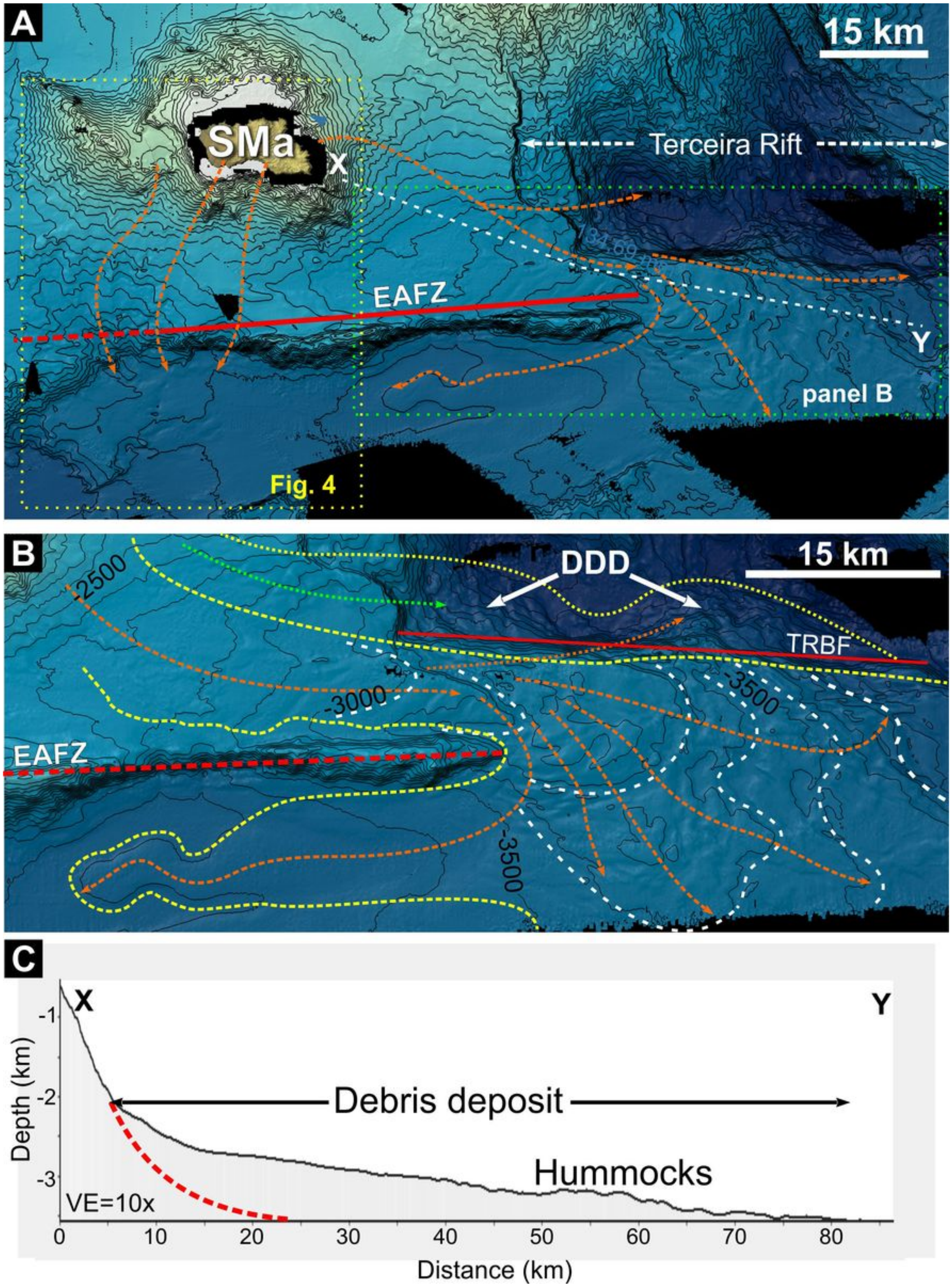

Figure 3

A – contoured shaded relief of Santa Maria with interpreted debris flow lines represented by arrowed orange dashed lines. The East Azores Fracture Zone (EAFZ) is marked by red dashed line. Green dotted rectangle – location of panel B. Yellow dotted rectangle – location of Fig. 4. B – Interpreted closeup of the region marked by green dotted rectangle in A, where the blanketing of the East Azores Fracture Zone (EAFZ) scarp (> 1000 m tall) is conspicuous. Dashed white lines outline the lobes on the bathymetry, *which we infer to be due to debris flow to the ESE (dashed orange arrows). Given that the debris deposits should be older than the Terceira Rift, then they should be displaced by the main fault (red line) bounding the Terceira Rift in the S (TRBF). In fact, two lobes are observed inside the Terceira Rift that could correspond to displaced debris deposit (DDD inside the dotted yellow line). The dashed yellow line delimits the inferred main debris deposit. Note that the slope E of Santa Maria is to the S, and therefore the debris had to travel to the SE, where they blanket the EAFZ scarp. C – topographic profile (X-Y white dashed line in A) showing the upward convex cross-section shape of the debris deposit, including a hummocky region in the frontal part. Note that after 4 Ma of sedimentation, the size and shape of the blocks is still well recognizable. Red dashed line marks the hypothetical base of the deposit.*

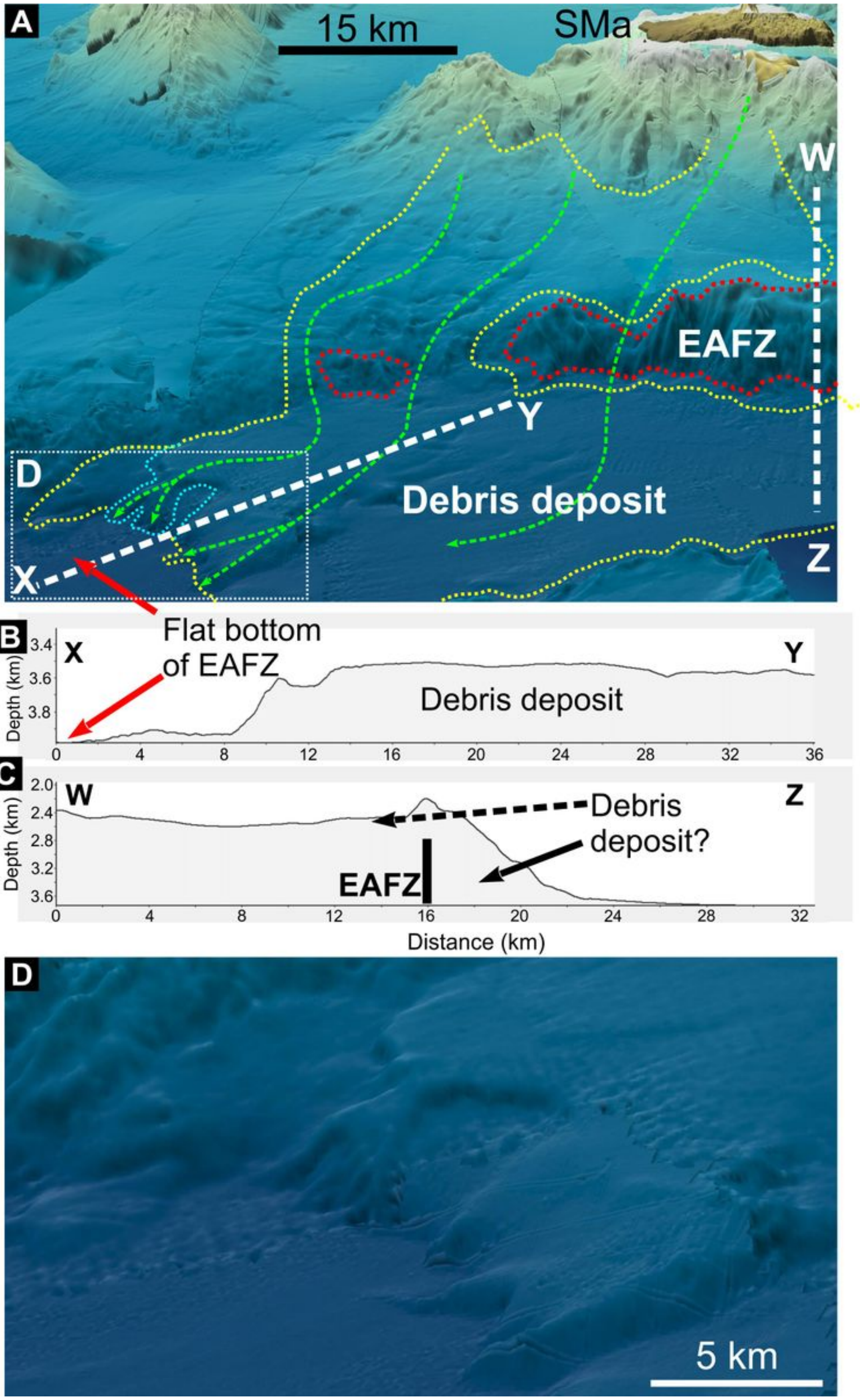

Figure 4

A – Interpreted shaded relief of SSW Santa Maria (SMa). Red dotted line marks the uncovered scarp of the East Azores Fracture Zone (EAFZ). Green dashed lines represent flow. Yellow dotted line marks the boundaries of the deposit. Cyan dotted line marks the shape of the younger sediment lobes. B and C – topographic cross-sections showing positions of debris deposits. D – zoom showing younger lobes on older deposit (marked by white dotted rectangle in A).

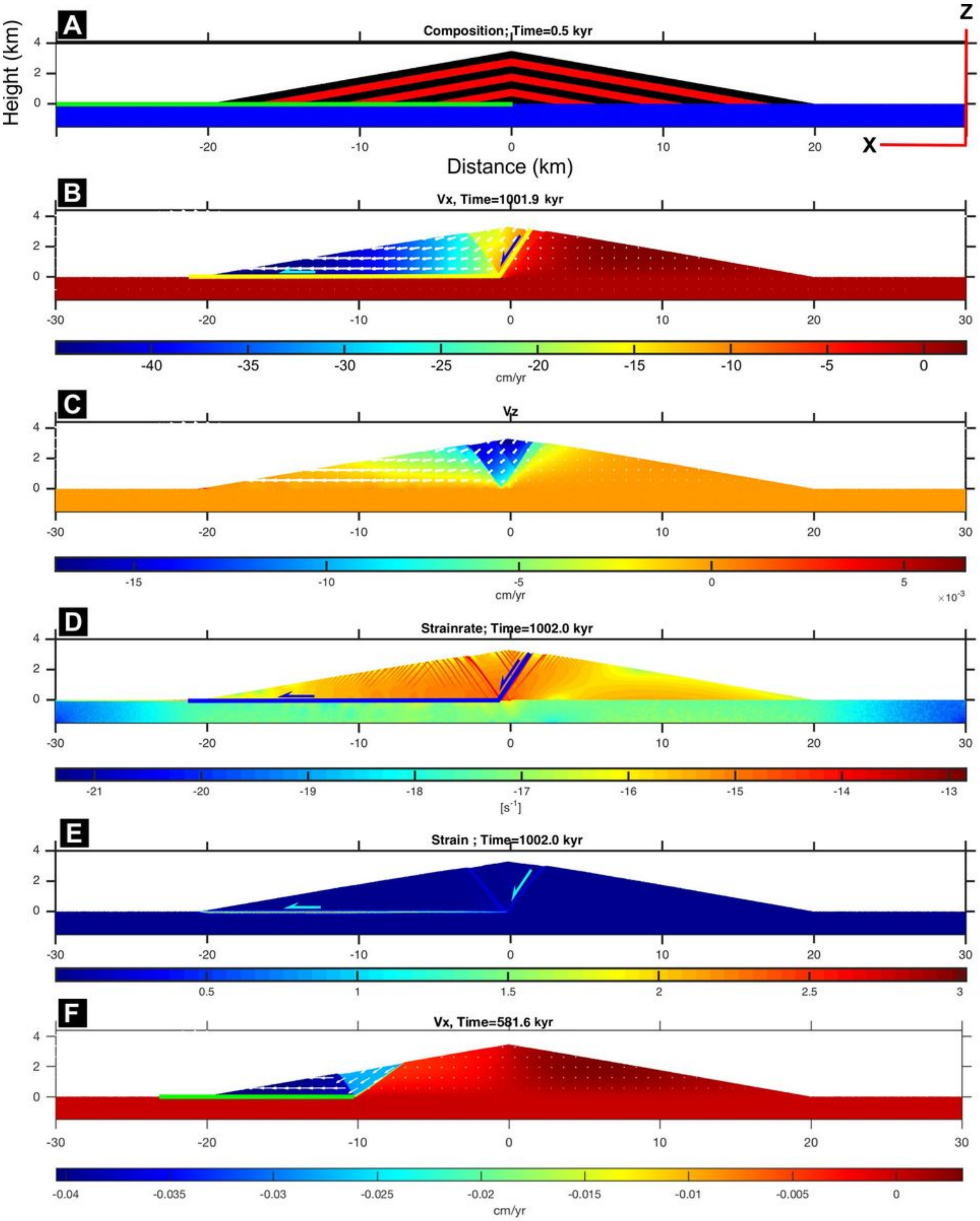

Figure 5

Model setup and main results. A – initial model setup for full radius detachment; reference frame on the right-hand side. B and C – velocity maps with the horizontal (Vx) and the vertical (Vz); note that maximum Vz occurs at the volcano's summit, and the maximum Vx lies at the rim of the base. D and E – respectively strain rate and strain maps to show main faults along which the collapse occurs. F – partial flank collapse following partial detachment at the base.

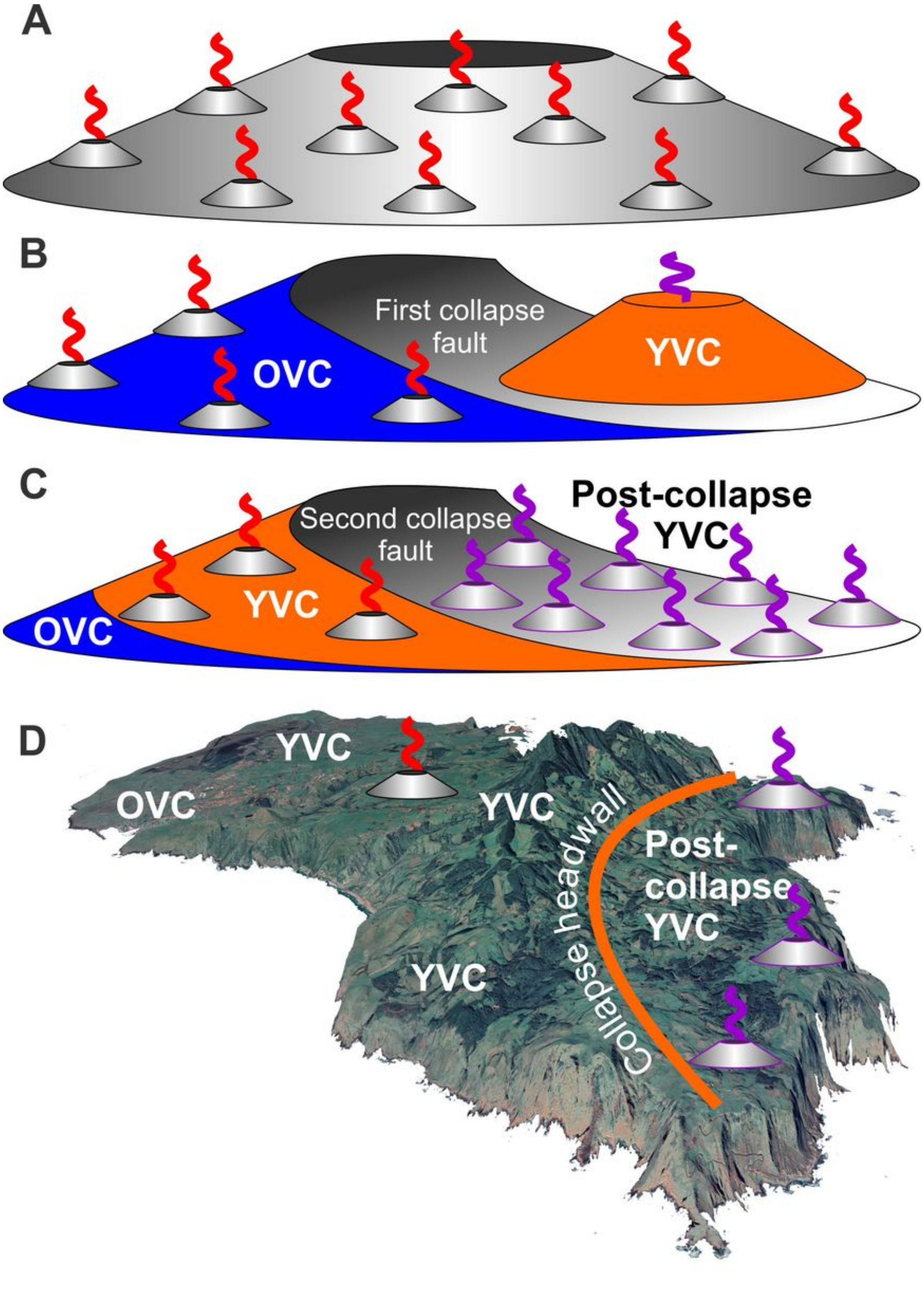

Figure 6

Sketches to illustrate the possible relations between main volcano and parasitic cones in the cases of absence (A) or presence of flank collapse (B to D). A – conformable parasitic cones sitting on a convex surface of a shield volcano is the most common case. B – old shield volcano (OVC) and new shield volcano (YVC) growing on the collapse scar. C – young shield volcano with few Strombolian cones on the convex surface (conformable), and many Strombolian cones on the concave ("wrong") surface *(unconformable), from which we infer a flank collapse removing the summit and eastern flank prior to emplacement of the younger Strombolian cones. D – 3-D shaded relief of Santa Maria viewed from SE showing the position of the main volcanic complexes, of the scar of the collapse headwall, and of the conformable (cones with red sinusoid) and unconformable (cones with red sinusoid) parasitic cones. If there had been no collapse, all parasitic cones would lie on a conical surface convex outward, which is clearly not the case.*

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