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

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Supplementary Material

Methods

For the present work, we used: (1) field work to map volcanic cones on the E half of the island, where they occur on an eastward concave surface E of the divide (Fig. 1B), and to measure the attitude of lava flows, which allows confirming the position of Strombolian cones and recognizing where flanks are missing; (2) high-resolution bathymetry to identify debris deposits; and (3) numerical modelling to address the mechanics of gravitational failure of volcanic edifices that can lead to flank collapses in small islands.

Bathymetric data used in this study were compiled from different sources. The high-resolution bathymetry data were acquired by EMEPC using an EM120 MBES onboard the research vessels N.R.P.

Almirante Gago Coutinho, N.R.P Dom Carlos and R/V Kommandor Jack, between 2006 and 2014, within the scope of the Portuguese project for the Extension of the Continental Shelf. MBES data were processed using CARIS HIPS&SIPS™ software. We also searched the European Marine Observation Data Network (EMODnet) bathymetry repository for high resolution data, which we downloaded from EMODnet bathymetry Portal in xyz format. The MBES bathymetry data were used to generate digital terrain models (DTM) at spatial resolutions from 100 to 150 m. The multi-resolution DTMs were also used to generate regional sun-shaded image renders and perspective views, and to extract bathymetric profiles using Fledermaus™ software to interpret the submarine landscapes. Bathymetric full-coverage images show the multi-resolution MBES data overlapped on GEBCO 2019bathymetric data available for this area with a spatial resolution of 15 arc seconds.

The numerical models were executed with the 2-D Finite Element Method code MVEP2 (Kaus, 2010; Thielmann and Kaus, 2012), which allows the generation of failure without a prescribed weakness point. We ran models that included a 100 m thick weak layer totally or partially underlying the volcanic edifice, which was 40 km wide and 3.5 km tall as in Santa Maria. We assumed viscoelastoplastic rheology with strain weakening for the volcanic edifice, because the rocks comprising the edifice are not homogeneous solid rock; they are pervasively fractured basalt intercalated with porous pyroclast, so relatively weak as a whole. For the rationale of using a viscous rheology to simulate the volcanic edifice we refer the reader to Borgia (1994).

For simplification, the density (ρ) was kept constant at 2700 kg/m^3 for all phases, although in nature the density of sediment is generally lower than that value (ρ = 2100-2200 kg/m^3 for 0-1700 m thick deposits; Olson et al., 2016, and references therein); cohesion, C, was kept at 1 MPa for the volcanic edifice and basal weak layer, because the former is pervasively fractured and/or porous, and the latter is unconsolidated and soft sediment. We considered for the weak basal layer: viscosity, $\eta = 10^{18}$ - 10^{19} Pa s, values within the range published for clay material; and angle of internal friction, ϕ = 15°, close to the value used by del Potro and Hürlimann (2009) (ϕ =16°), but the clay material could be even weaker if under fluid overpressure (Morrow et al., 1982). We ran simulations varying η and ϕ of the volcanic edifice ($10^{21} - 10^{23}$ Pa s, 15°-30°, respectively).

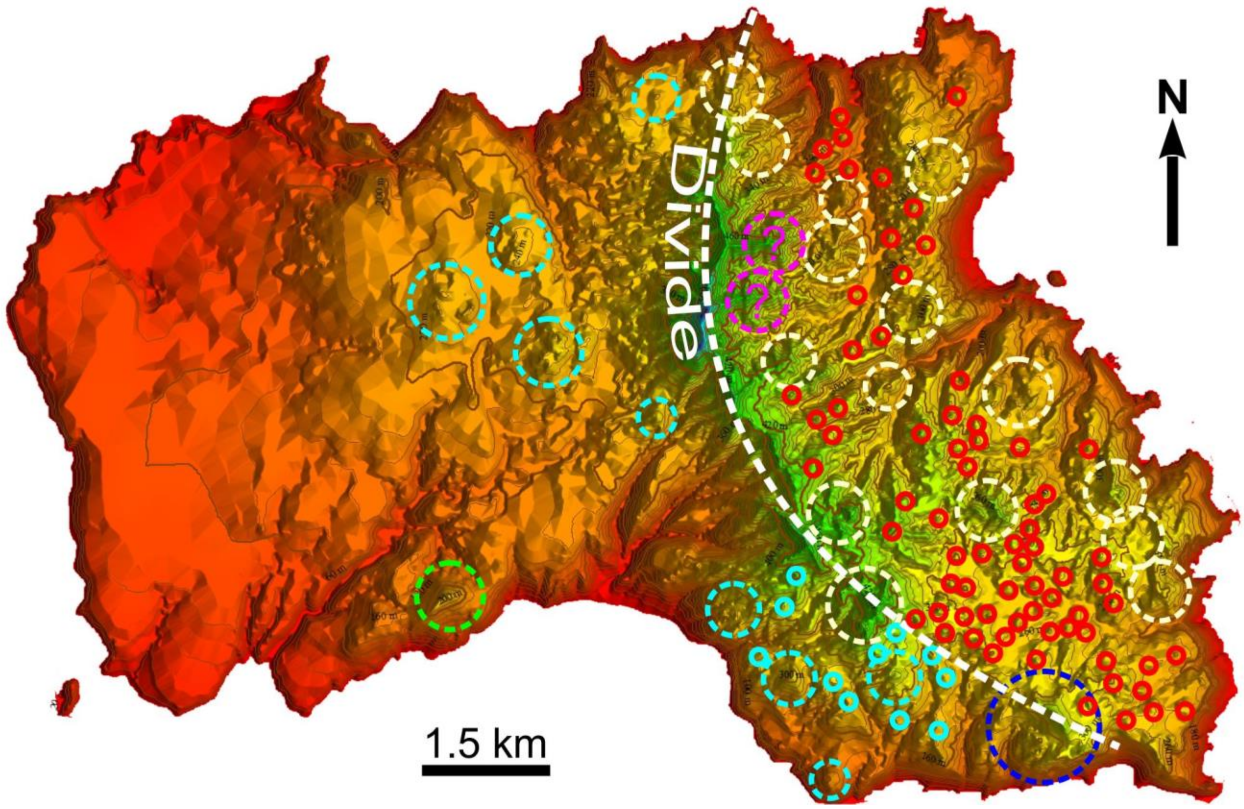

Figure S1. Shaded relief with volcanic cones plotted as circles. Large cones W and E of the divide (white dashed line) are marked by dashed cyan and white, respectively. Small cones W and E of the divide are marked by cyan and red small circles, respectively. Blue dashed circle marks the large cone shown on the photo in Fig. S2A. Magenta dashed circles with question mark inside represent interpreted large cones not confirmed in the field. Not all identified small cones are plotted for the sake of clarity.

Figure S2. A – Large Strombolian cone in SE Santa Maria, with secondary smaller cones, viewed from NW and marked by dashed blue circle in Fig. S1. The main cone is ca. 1.5 km in diameter at the base and sits unconformably on the concave surface of the younger shield volcano. B – Large Strombolian cone in SW Santa Maria (marked by dashed green circle in Fig. S1), ca. 1 km in diameter at the base and sitting conformably on the convex surface of the younger shield volcano.

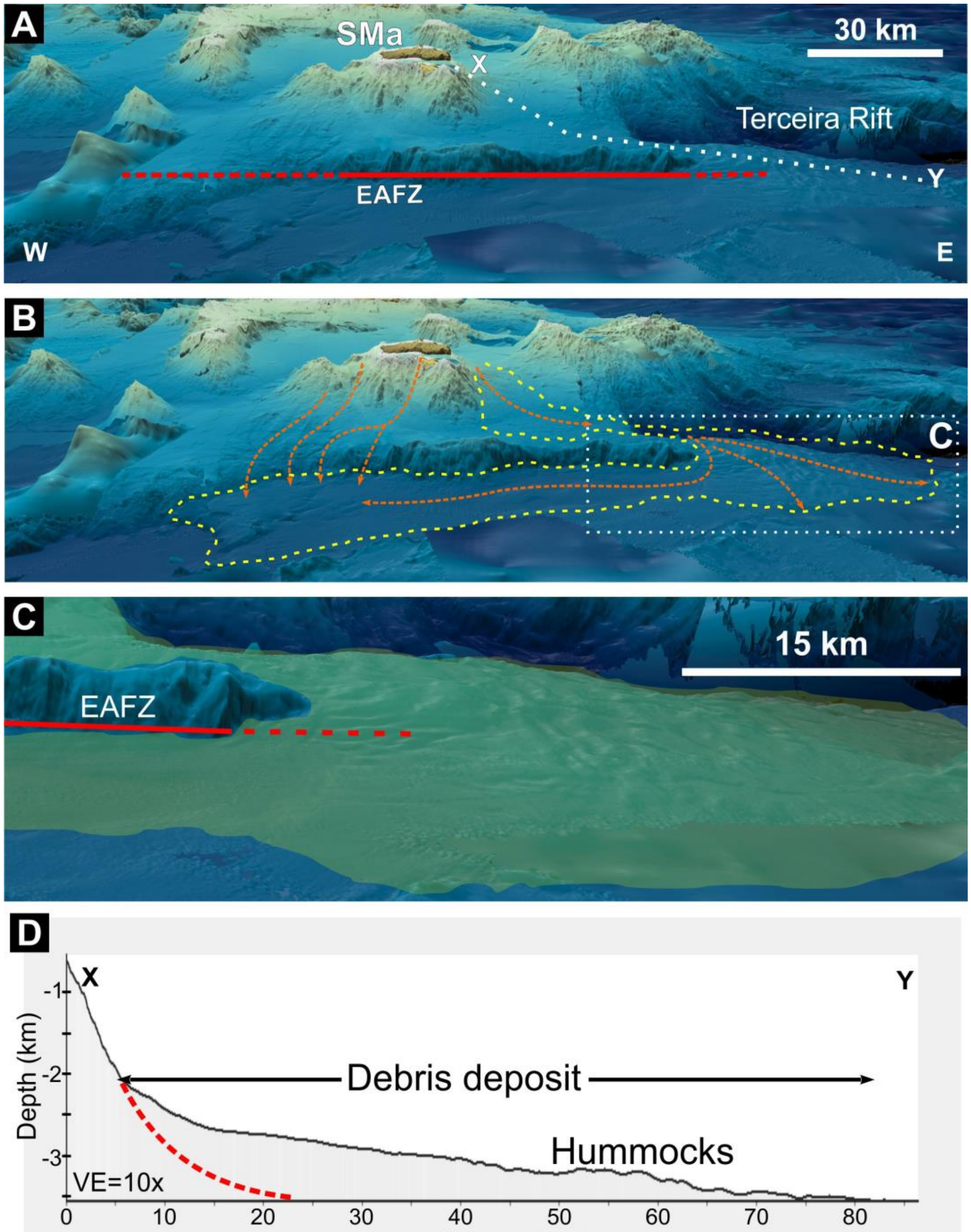

Figure S3. A – uninterpreted 3-D shaded relief around Santa Maria (SMa), oblique view from the south. B – interpreted distribution of the debris deposits, in which the dashed yellow line and the dotted green lines mark the limits of the deposit and the flow, respectively. C – 3-D zoom of the dotted rectangle drawn in B, in which the deposit is represented by a green shade. D – cross-section along the X-Y dotted line drawn in A, showing the upward convex shape of the deposit and a hummocky terrain in the frontal part. EAFZ – East Azores Fracture Zone.

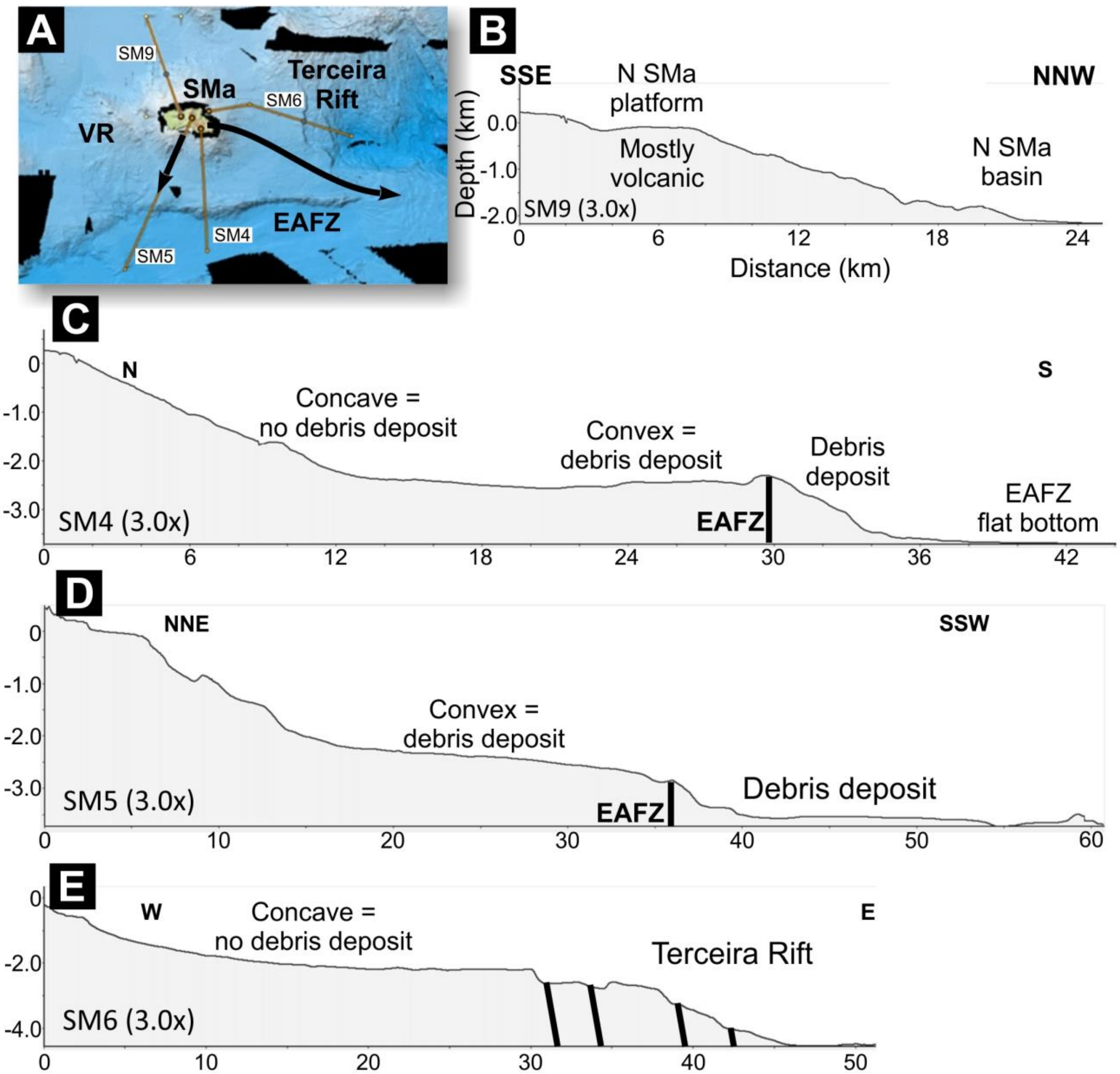

Figure S4. Topographic profiles along critical directions to show the shape of the topography where we infer the existence (convex upward) or absence (concave upward) of debris deposits. Black arrows mark the position and flow of the landslides inferred from on and offshore data. Note that, outside these areas of debris avalanches with upward convex profiles, the topographic profiles are concave upwards. VR = volcanic ridge; EAFZ = East Azores Fracture Zone; N SMa basin = north Santa Maria basin.

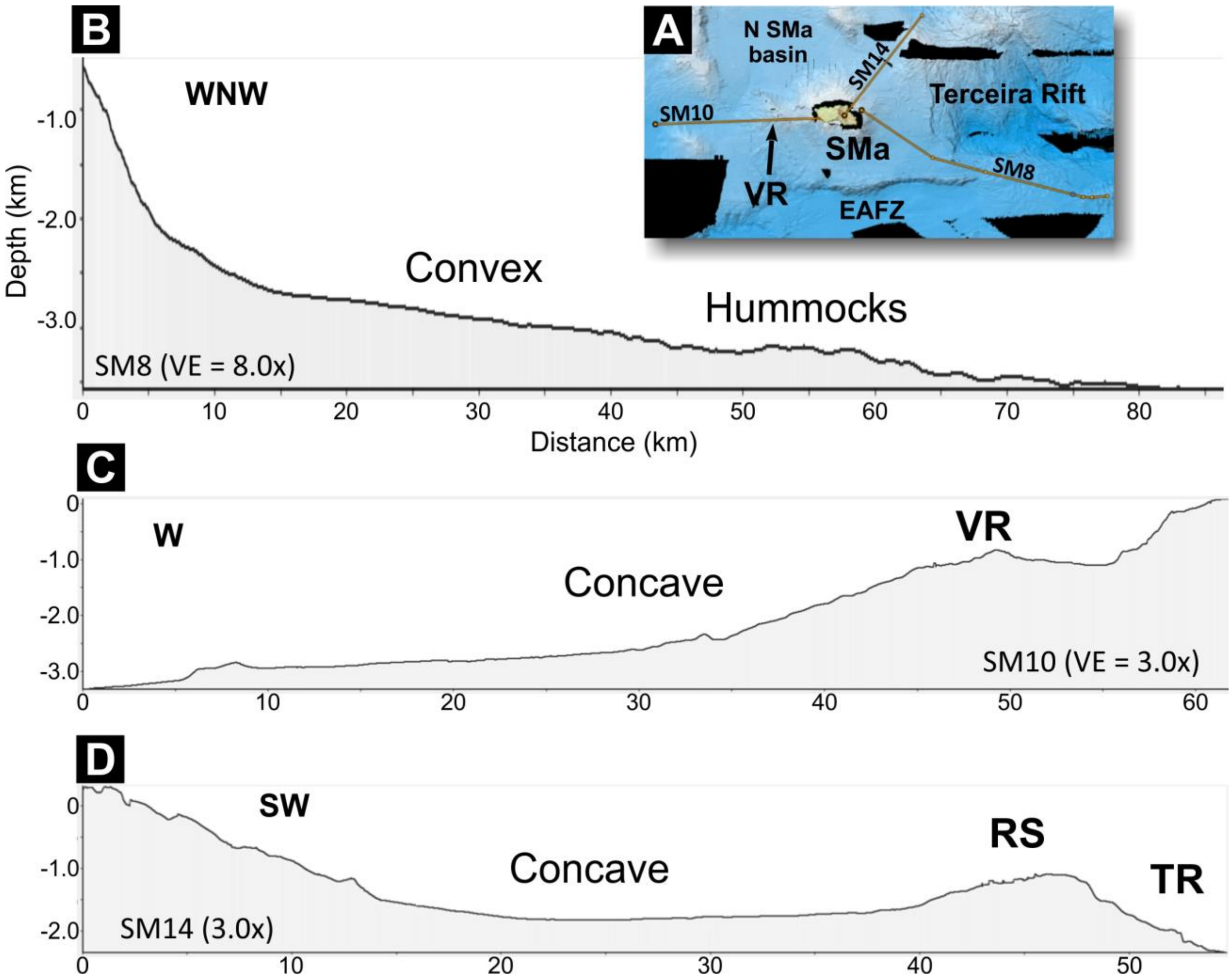

Figure S5. Topographic profiles along critical directions to show the shape of the topography where we infer the existence (convex) or absence (concave) of debris deposits. EAFZ – East Azores Fracture Zone; VR – volcanic ridge; TR – Terceira Rift; RS – rift shoulder.

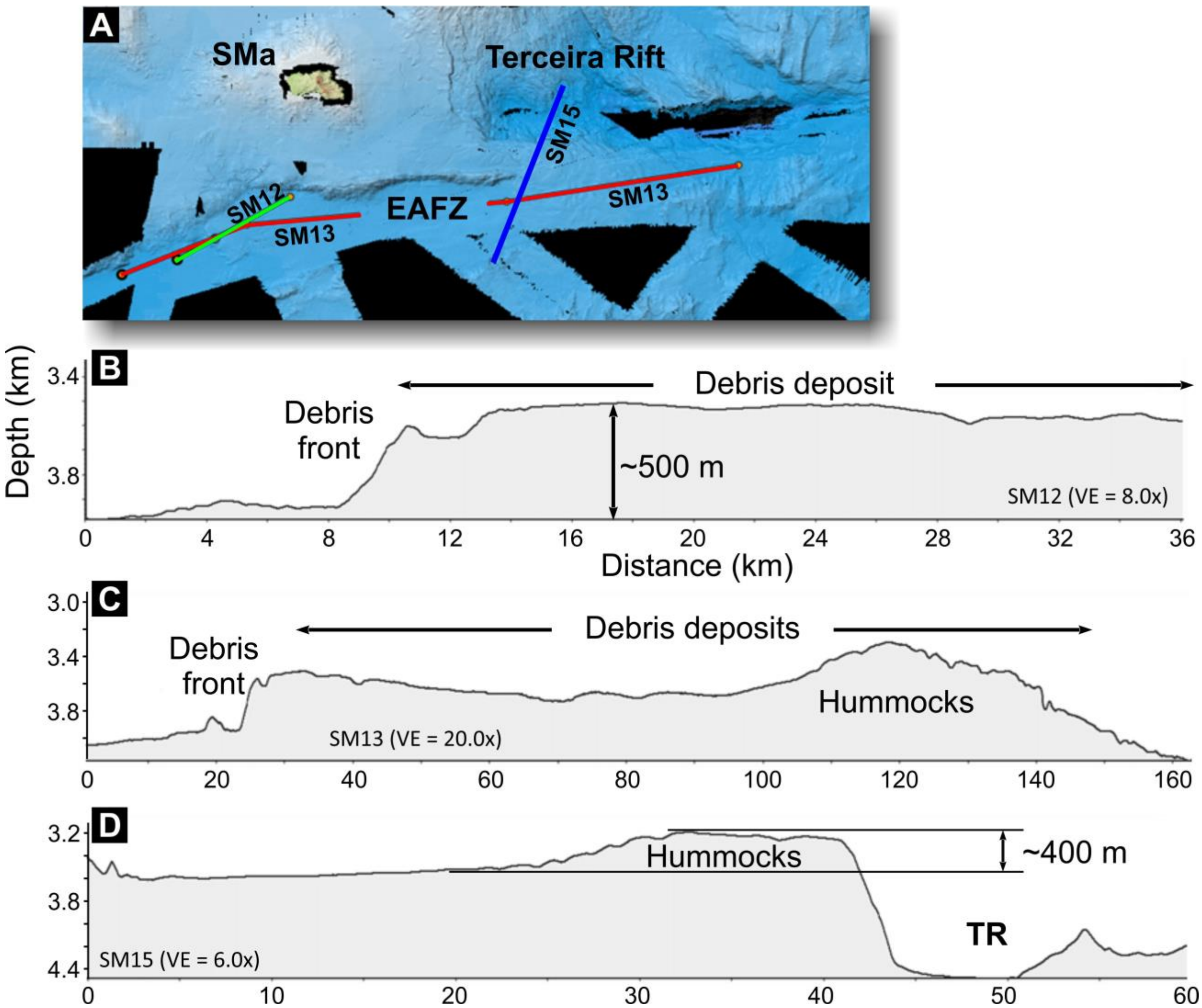

Figure S6. Topographic profiles inside the East Azores Fracture Zone (EAFZ) to show the inferred debris deposits and their local thicknesses. SMa – Santa Maria Island; EAFZ – East Azores Fracture Zone; TR – Terceira Rift.

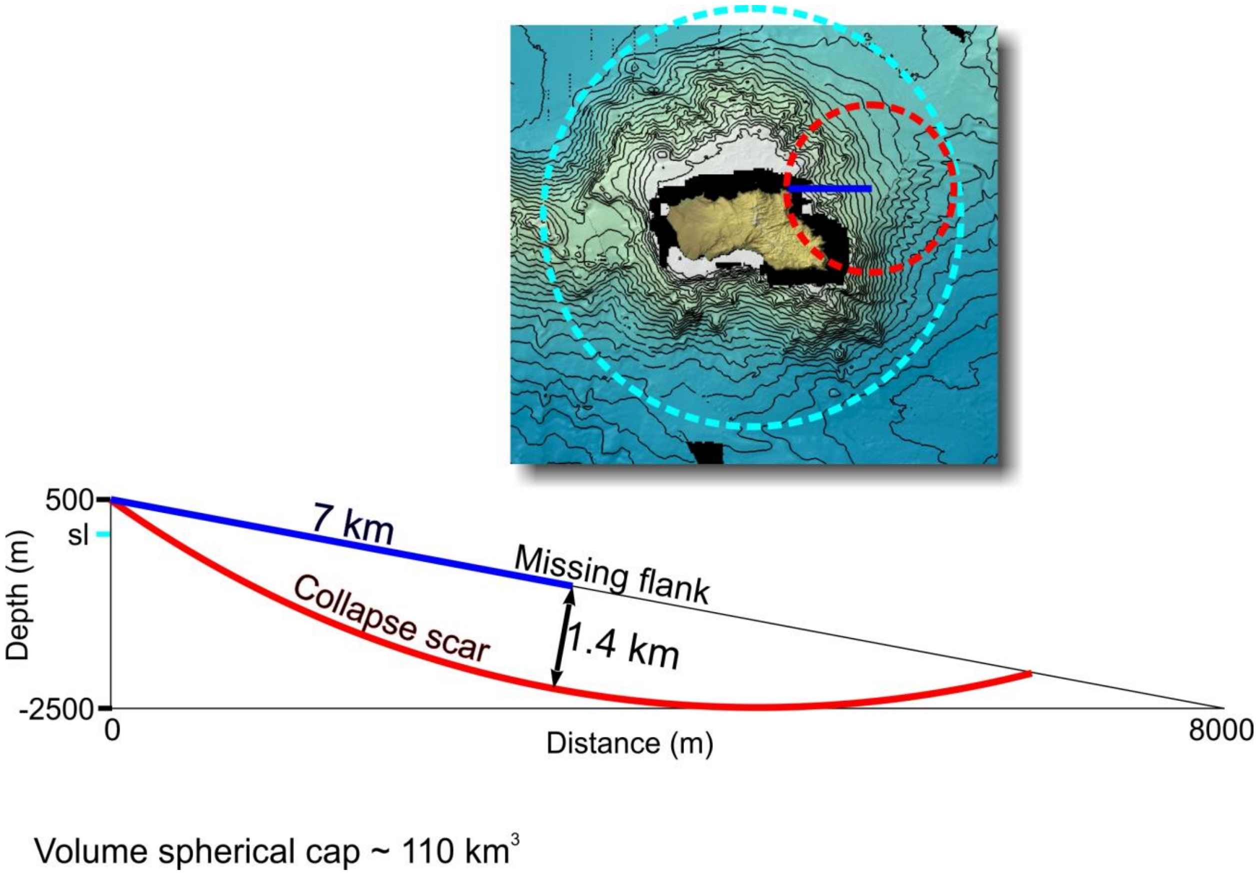

Figure S7. Sketch to illustrate how one can find the volume of a spherical cap, which we take as good representation of the volume of rock involved in each collapse. The volume was calculated here: https://www.omnicalculator.com/math/sphere-volume. *sl – sea level.*