Geology

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Notes

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A. Hildenbrand[1,2,*], F.O. Marques[3], J. Catalão[4], C.M.S. Catita[4], and A.C.G. Costa[1,4]
[1]Univ Paris-Sud, Laboratoire IDES, UMR8148, Orsay, F-91405, France
[2]CNRS, Orsay, F-91405, France
[3]Universidade Lisboa, 1749-016 Lisboa, Portugal
[4]Universidade Lisboa and IDL, 1749-016 Lisboa, Portugal

ABSTRACT

We report evidence for ongoing lateral slump of part of the southeastern flank of the Pico volcanic ridge in the Azores. Data from a high-resolution digital elevation model, field work, GPS, and radar interferometry show that: (1) the slumping sector is several cubic kilometers in size; (2) the structure involves several curved scars with normal fault kinematics; (3) the central part is undergoing little horizontal displacement toward the southeast (1.6 ± 1.3 mm/yr), but significant downward movement (5–12 mm/yr); and (4) the outer part of the southeastern flank of Pico is subsiding faster than the inner parts; this likely reflects recent individualization of a steep seaward-dipping fault in the moving mass. The slump shares similarities with active slumps recognized elsewhere, although the studied area may represent only the proximal part of a much larger complex potentially affecting the deep submarine base of the island. Displacement of the subaerial part of the southeastern flank of Pico seems to be accommodated by the movement and rotation of large blocks along listric normal faults.

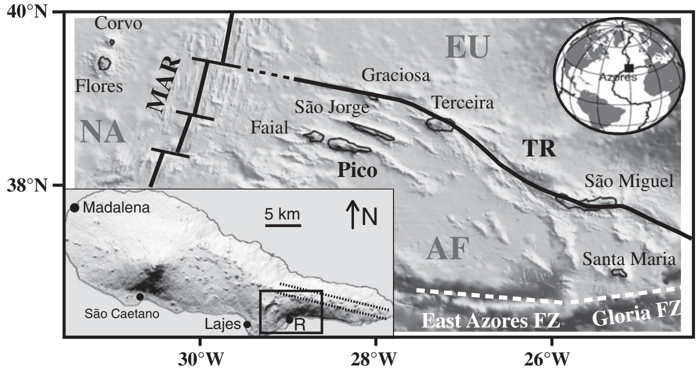

Figure 1. Location of Azores volcanic archipelago near triple junction between North American (NA), Eurasian (EU), and African (AF) plates. Bold lines show Mid-Atlantic Ridge (MAR) and Terceira Rift (TR). FZ—fracture zone. Inset: Shaded relief map showing main morphology of Pico Island. Dotted lines highlight axis of main N110° rift zone. Two main landslide failures affect southern flank of island. Rectangle shows geographical extension of studied southeastern collapse area (Fig. 2). R is Ribeiras town.

INTRODUCTION

The growth of volcanic islands is generally punctuated by large lateral flank failures, which can trigger destructive tsunamis (Keating and McGuire, 2000; McMurtry et al., 2004). Giant sector collapses have been recognized around numerous islands worldwide, e.g., in Hawaii (Lipman et al., 1988; Moore et al., 1994; Morgan et al., 2000), French Polynesia (Clouard and Bonneville, 2004; Hildenbrand et al., 2006), the Canary Islands (Krastel et al., 2001; Walter and Schmincke, 2002; Boulesteix et al., 2012), Reunion Island (Duffield et al., 1982; Gillot et al., 1994), and the Caribbean arc (Le Friant et al., 2003; Samper et al., 2007). A number of triggering factors have been proposed over the past 20 years (e.g., McGuire, 1996; Elsworth and Day, 1999; McMurtry et al., 1999, 2004; Klügel et al., 2005; Quidelleur et al., 2008), including concentration of dikes along rift zones and associated fluid pressurization by heating and/or compression of groundwater trapped between dikes, ground shaking by large regional earthquakes, gravitational spreading of the volcanoes along weak geological layers, or sea-level variations associated with climatic changes.

Contrasting types of sector collapse have been distinguished (Moore et al., 1994): (1) slow-moving rotational landslides along a deep-sea detachment fault, often called slumps; and (2) catastrophic landslides produced by the rapid detachment of the island flank, which may release fast-moving debris avalanches. These two kinds of processes are not mutually exclusive; part of a slump may suddenly collapse and trigger a tsunami (e.g., Tilling et al., 1976; Moore et al., 1994).

The Azores archipelago, in the Atlantic Ocean, comprises nine active volcanic islands and numerous linear submarine ridges developed close to the triple junction between the North American, Eurasian, and African lithospheric plates (Fig. 1), in an area characterized by important regional deformation and recurrent high-magnitude earthquakes (Borges et al., 2007). The islands are marked by a multistage evolution, including fast-growing phases and multiple destruction events, such as vertical caldera collapse, lateral landslides, and rock fall of various sizes (Mitchell, 2003; Calvert et al., 2006; Hildenbrand et al., 2008; Silva et al., 2012).

Pico Island is a narrow and steep volcanic ridge, formed by magma concentration along the N110° trend (Fig. 1). The oldest volcanic units are exposed in the central and eastern parts of the island, whereas more recent volcanic activity produced the Pico volcano, which occupies the western third of the island (Woodhall, 1974; Nunes, 1999).

Due to its steep topography, Pico Island is particularly sensitive to flank instability. The southern flank of the ridge shows several curved structures that are concave toward the ocean (Fig. 1), previously interpreted as reflecting early caldera development, faulting, or ancient lateral collapse (Woodhall, 1974; Nunes, 1999; Mitchell, 2003; Nunes et al., 2006). Knowledge of the geometry, volume, and kinematics of these structures, and understanding of their recent evolution and susceptibility to further movement, are critical for risk and hazard assessment, but remain poorly constrained. Our study focuses on the unstable southeastern part of the ridge; data from a high-resolution digital elevation model (DEM), field work, GPS, and radar interferometry show that part of the flank is currently being displaced toward the ocean, accommodated by the motion of large blocks that may eventually detach, with catastrophic consequences.

SLUMP GEOMETRY AND KINEMATICS

Using cartographic data and maps generated in 2005 by the Portuguese Army Institute (scale 1:25,000), we developed a DEM with 10 m spatial resolution and a vertical accuracy of 2 m. It was used to produce a shaded relief map (Fig. 2A), a slope map, and topographic cross sections

*E-mail: anthony.hildenbrand@u-psud.fr.

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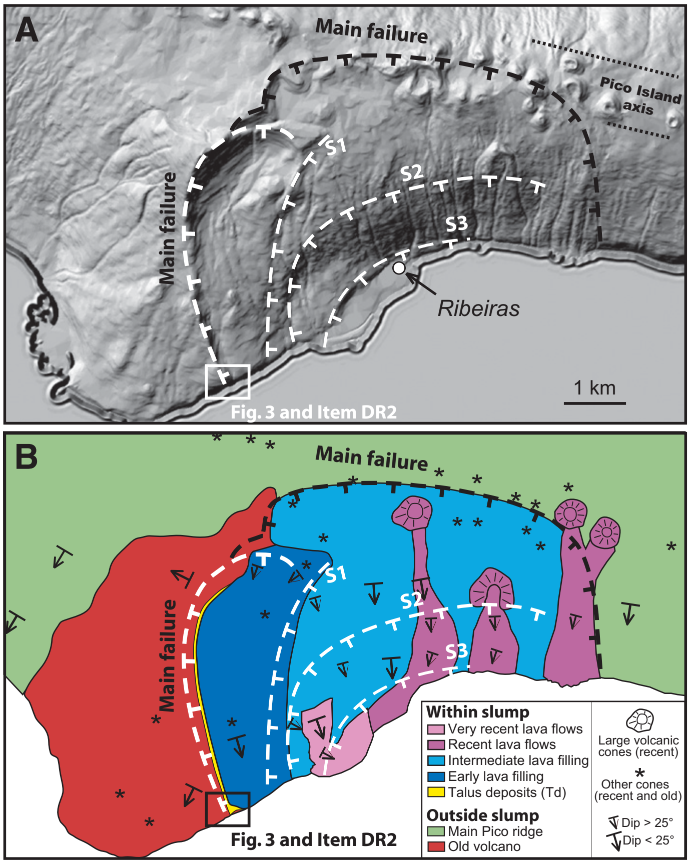

Figure 2. A: Main morphostructural units within southeastern slump area. Main scars here recognized are highlighted by white dashed lines. Black line indicates inferred continuation of main structure extending to southern part of axial rift zone. B: Simplified geologic map of studied area. Modified after Nunes (1999).

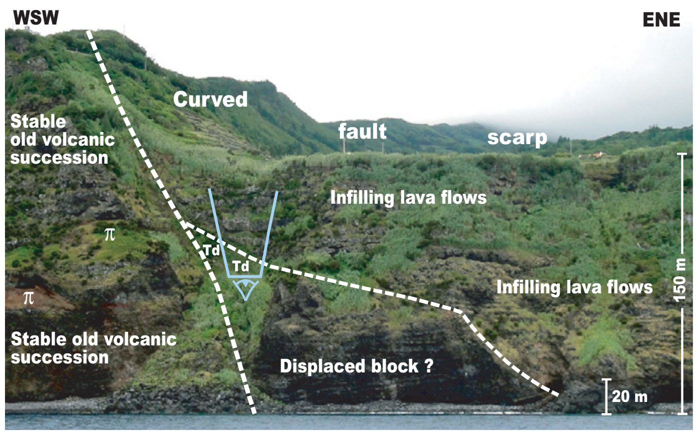

Figure 3. Photograph taken from sea showing geometric relationships between main geological units exposed along southern end of main collapse rim at shore level. Td—talus deposits; pi symbols—levels of Strombolian fallout deposits; blue outline and symbol show point of view from which photo exposed in Item DR2 (see footnote 1) was taken (upward).

(Fig. DR1 in GSA Data Repository[1]), which, together with geologic data (Figs. 2B and 3), provide important new constraints on the geometry of the failure.

1. The main collapse rim is exposed as an arcuate scarp open to the southeast. It forms a 300-m-high prominent headwall with steep slopes dipping as much as 60°. The northern part of this structure has been partly covered by recent lava flows, but discontinuous unburied segments can be identified, suggesting an overall horseshoe-shape geometry.

2. The inner portion of the collapse sector is marked by a morphological plateau with gentle slopes. The upper part of the plateau is composed of recent lava flows erupted from small cones developed at the base of the main failure.

3. The plateau is interrupted by slope breaks; from west to east, three main scarps can be identified (S1, S2, and S3, Fig. 2; Item DR1 in the Data Repository). S1 occurs along a lineament roughly parallel to the southern end of the main failure. Its northern end is apparently connected with the main scar. S2 extends over a large area as an arcuate structure affecting the outer part of the plateau. It has a geometry typical of lateral failures, starting with a north-south rim at sea level, then bifurcating eastward and becoming almost parallel to the main axis of the island. This scarp is characterized by a steep seaward dip of as much as 45°. Farther east, the slope is smoothed by recent lava flows erupted from volcanic cones located along the main rift zone, and from parasitic cones developed within the collapse sector. The S3 scarp has been previously interpreted as fossil coastal cliffs (Nunes, 1999); however, it defines a clear embayment partly covered by recent lava flows, which cascaded down to the sea and formed a lava delta.

The architecture and kinematics of the slump are further constrained by field data (Fig. 3; Item DR2). The in situ old volcanic sequence is exposed along coastal cliffs as a pile of thin lava flows, including red levels of Strombolian fallout deposits (π symbol in Fig. 3). This succession is interrupted by a main scarp making up the western rim of the slump (Fig. 3). To the east of this major discontinuity, a different volcanic succession crops out. It likely defines the top of a large downthrown block, which would therefore indicate a minimum vertical offset of ~300 m. This large block is overlain by a thick layer of poorly sorted talus deposits (Td in Fig. 3), including angular lava blocks exceeding 1 m in size, that imply rapid infilling of a steep-sided canyon by large blocks probably shed from the main slump scar. The talus unit is covered by a suite of thick volcanic lava flows wedging out toward the main fault scarp (Fig. 3; Item DR2). All the field data suggest that the main collapse rim has acted as a major fault with normal kinematics. Gradual downward movement resulted in the persistence of a narrow drainage system, which was filled by lava flows and significant amounts of debris. Recent movement can also be suspected from the active development of a narrow debris fan remobilizing the talus deposits along the main scar (Fig. 3).

SLUMP MONITORING BY GPS AND RADAR INTERFEROMETRY

In the framework of the research projects SARAÇORES (Deformation Partition in Azores using interferometric SAR Images; Catita et al., 2005) and TANGO (TransAtlantic Network for Geodesy and Oceanography; Fernandes et al., 2004), a dense GPS network was installed in Faial and Pico Islands (details in Item DR3). It consists of 31 stations, distributed mostly along the coastlines. One station (PRIB) is located near sea level in the central part of the collapse area, close to the town of Ribeiras. Four GPS campaigns were carried out on Faial and Pico Islands between 1999 and 2006. Measurements were made in survey mode, with a minimum of three sessions (24 h consecutive observation each) per station. The data set was complemented by synthetic aperture radar (SAR) data, aimed at producing interferograms and quantifying vertical displacements between 2006 and 2009 (for details, see the Data Repository and Catalão

[1]GSA Data Repository item 2012264, Item DR1 (detailed morphology of Pico southeastern slump), Item DR2 (thick lava flows overlying the talus deposits), and Item DR3 (methods and data processing; GPS and InSAR), is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

et al. [2011]). The GPS horizontal surface velocities of Pico were used to estimate the parameters of the rigid body motion model associated with regional plate tectonics. The residuals between the rigid body motion and the geodetic data are attributed to intra-island deformation and are a good measure of local variations of the strain field.

Residual velocities computed at PRIB (2σ uncertainties) show a slight southeast displacement, with an average value of 1.6 ± 1.3 mm/yr, and a significant average vertical subsidence of 7.1 ± 1.9 mm/yr. Such downward vertical motion is consistent with the values obtained from radar interferometry (Fig. 4), although those data were acquired between 2006 and 2009 and show slightly higher rates of subsidence. The InSAR (In—interferometric) data show that the sectors outside of the collapse area are rather stable, with no significant vertical movement or little subsidence (<5 mm/yr), whereas downward vertical movement in the collapse area reaches 12 mm/yr, i.e., a net subsidence of 7 to 12 mm/yr. The highest rates are observed in the central part of the collapse, whereas the sector bounded by the main fault scar shows values between 5 and 8 mm/yr.

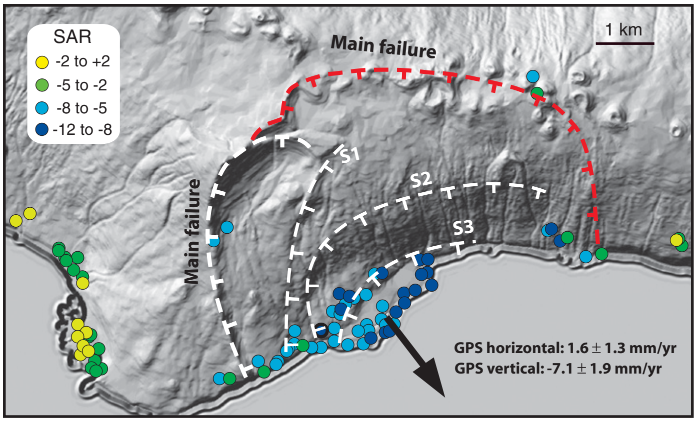

Figure 4. Horizontal and vertical displacement rates within collapse area derived from GPS and synthetic aperture radar (SAR) data acquired from 2001–2006 and 2006–2009, respectively. Distinct colors for various rates of average vertical displacements are in mm/yr. Negative values and positive values are for downward and upward movements, respectively.

SLUMP MECHANISMS AND PROPAGATION

Previous studies have considered that the present configuration of the southeastern flank of Pico could reflect vertical caldera collapse (Woodhall, 1974; Mitchell et al., 2011). This is inconsistent with observed geology and our data, because (1) the horseshoe shape of the failures supports lateral movement; (2) central caldera collapse should have cut the east and west flanks of the old volcano in a symmetrical way, but its eastern flank is not exposed on land; and (3) present-day vertical motion is inconsistent with caldera collapse of the oldest volcanic lavas of the island. Lateral collapse has been proposed, but is considered as currently inactive (Nunes, 1999; Nunes et al., 2006; Mitchell et al., 2011); this is inconsistent with our data. One may argue that the measured displacements could result from active movements along strike-slip faults coinciding with the main axis of the island (Madeira and Brum da Silveira, 2003), with possible development of a pull-apart structure between such faults. However, such right-lateral movement would imply compression along the north-south main collapse rim, which is inconsistent with the measured flank spreading.

The main scar extends to the eastern parts of the ridge main axis, where numerous young cones have developed. The localization of the main failure surface thus may have been influenced by dike intrusion and magma push along the main rift zone, a mechanism frequently advocated to explain the development of flank instability on volcanic islands (Moore et al., 1994; Elsworth and Day, 1999; Hildenbrand et al., 2006).

The initiation of the failure is not well constrained in time, because there are insufficient geochronological data. Extrapolating the measured rate of subsidence along the main rim (net value of 5 mm/yr on average) suggests gradual downward movement during the past 60 k.y., but displacement rates may not have been constant through time. Nevertheless, the several curved scars developed farther east show less vertical offset and affect younger lava flows erupted from vents that apparently migrated sequentially eastward. This suggests recent eastward propagation of the failure within the central outer parts of the moving mass. The development of volcanic cones along the trace of the several secondary curved scars thus probably reflects the opening of lateral cracks, which served as local pathways for recent magma ascent. Although our InSAR data do not record present differential movement along S3, the formation of this arcuate scarp is here interpreted as resulting from recent deformation close to the island shore, which yielded the recurrent detachment of coastal segments. This is consistent with the presence of a moderate-sized debris field on the southern submarine slope of the ridge, identified from marine geophysical surveys (Mitchell, 2003).

Our new geodetic data show that the present deformation affects a significant part of the southeastern flank of Pico Island, and not solely the central lava delta. Therefore, other causes of subsidence such as recent lava cooling or compaction of underlying sediments cannot adequately explain the recorded movement, especially as a similar recent lava delta developed west of the collapse area does not show any appreciable downward movement (Fig. 4). Differential deformation at the foot of the various scars identified here also suggests the discrete displacement of large blocks along several curved faults with typical normal kinematics, as recognized or suspected on the Hilina fault system in Hawaii (Smith et al., 1999), the Cumbre Vieja western sector collapse on La Palma in the Canary Islands (Hildenbrand et al., 2003; González et al., 2010), or on the east flank of the dormant Damavand volcano in northern Iran (Shirzaei et al., 2011). The rates of subsidence reported here are significantly higher than the rates measured on the western slope of La Palma, but they are one order of magnitude lower than the values recorded on the southern mobile flank of Kilauea volcano in Hawaii (Owen et al., 2000). With a subaerial volume estimated as ~10 km^3, the southeastern collapse of Pico also appears to be significantly smaller than typical Hawaiian giant landslides (Moore et al., 1994), but the structures on Pico may evidence only the proximal part of a much larger complex potentially affecting the deep base of the submarine flank.

FURTHER EVOLUTION?

The lack of volcanic eruptions or detectable inflation of the volcanic ridge over the period of geodetic monitoring implies that active downward displacement of the southeastern mobile flank of Pico Island is not a direct result of forceful magma intrusion along the rift zone. In addition, the lack of detected shallow earthquakes within the collapse area during this geodetic monitoring time interval suggests that creep is currently the main mode of deformation.

The higher rates of current vertical displacement measured near sea level possibly reflect cumulative displacements along the main rim of the collapse, and additional displacements along the more recent outer failures, especially S2 (Fig. 4). By this hypothesis, vertical displacements in the outer flank reach an average value of ~3–5 mm/yr, which is similar to or slightly higher than the maximum horizontal displacement rate derived from our GPS station (2.9 mm/yr), when uncertainties are accounted for. Such data support the fact that the distal part of the ridge is currently moving along a steep fault with a minimum dip of 45° toward the southeast. This is consistent with the exposed geometry of the outer arcuate structure S2, which therefore constitutes a priority target for further monitoring and hazard assessment, e.g., eventual block detachment and associated potential tsunami.

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REFERENCES CITED

Borges, J.F., Bezzeghoud, M., Buforn, E., Pro, C., and Fitas, A., 2007, The 1980, 1997 and 1998 Azores earthquakes and some seismo-tectonic implications: Tectonophysics, v. 435, p. 37–54, doi:10.1016/j.tecto.2007.01.008.

Boulesteix, T., Hildenbrand, A., Gillot, P.Y., and Soler, V., 2012, Eruptive response of oceanic islands to giant landslides: New insights from the geomorphologic evolution of the Teide–Pico Viejo volcanic complex (Tenerife, Canary): Geomorphology, v. 138, p. 61–73, doi:10.1016/j.geomorph.2011.08.025.

Calvert, A.T., Moore, R.B., McGeehin, J.P., and Rodrigues da Silva, A.M., 2006, Volcanic history and $^{40}Ar/^{39}Ar$ and ^{14}C geochronology of Terceira Island, Azores, Portugal: Journal of Volcanology and Geothermal Research, v. 156, p. 103–115, doi:10.1016/j.jvolgeores.2006.03.016.

Catalão, J., Nico, G., Hanssen, R., and Catita, C., 2011, Merging GPS and atmospherically corrected InSAR data to map 3D terrain displacement velocity: IEEE Transactions on Geoscience and Remote Sensing, v. 49, p. 2354–2360, doi:10.1109/TGRS.2010.2091963.

Catita, C., Feigl, K.L., Catalão, J., Miranda, J.M., and Victor, L.M., 2005, InSAR time series analysis of the 9 July 1998 Azores earthquake: International Journal of Remote Sensing, v. 26, p. 2715–2729, doi:10.1080/01431160512331337835.

Clouard, V., and Bonneville, A., 2004, Importance of submarine landslides in French Polynesia, *in* Hekinian, R., ed., Oceanic hotspots: Intraplate submarine magmatism and tectonism: Berlin, Springer, p. 209–238.

Duffield, W.A., Stieljes, L., and Varet, J., 1982, Huge landslide blocks in the growth of Piton de la Fournaise, La Réunion and Kilauea volcano, Hawaii: Journal of Volcanology and Geothermal Research, v. 12, p. 147–160, doi:10.1016/0377-0273(82)90009-9.

Elsworth, D., and Day, S.J., 1999, Flank collapse triggered by intrusion: The Canarian and Cape Verde archipelagoes: Journal of Volcanology and Geothermal Research, v. 94, p. 323–340, doi:10.1016/S0377-0273(99)00110-9.

Fernandes, R.M.S., Bastos, L., Ambrosius, B.A.C., Noomen, R., Matheussen, S., and Baptista, P., 2004, Recent geodetic results in the Azores Triple Junction region: Pure and Applied Geophysics, v. 161, p. 683–699, doi:10.1007/s00024-003-2469-y.

Gillot, P.Y., Lefèvre, J.C., and Nativel, P.E., 1994, Model for the structural evolution of the volcanoes of Réunion Island: Earth and Planetary Science Letters, v. 122, p. 291–302, doi:10.1016/0012-821X(94)90003-5.

González, P.J., Tiampo, K.F., Camacho, A.G., and Fernández, J., 2010, Shallow flank deformation at Cumbre Vieja volcano (Canary Islands): Implications on the stability of steep-sided volcano flanks at oceanic islands: Earth and Planetary Science Letters, v. 297, p. 545–557, doi:10.1016/j.epsl.2010.07.006.

Hildenbrand, A., Gillot, P.Y., Soler, V., and Lahitte, P., 2003, Evidence for a persistent uplifting of La Palma (Canary Islands), inferred from morphological and radiometric data: Earth and Planetary Science Letters, v. 210, p. 277–289, doi:10.1016/S0012-821X(03)00133-X.

Hildenbrand, A., Gillot, P.Y., and Bonneville, A., 2006, Off-shore evidence for a huge landslide of the northern flank of Tahiti-Nui (French Polynesia): Geochemistry Geophysics Geosystems, v. 7, p. 1–12, doi:10.1029/2005GC001003.

Hildenbrand, A., Madureira, P., Marques, F.O., Cruz, I., Henry, B., and Silva, P., 2008, Multi-stage evolution of a sub-aerial volcanic ridge over the last 1.3 Myr: S. Jorge Island, Azores Triple Junction: Earth and Planetary Science Letters, v. 273, p. 289–298, doi:10.1016/j.epsl.2008.06.041.

Keating, B.H., and McGuire, W.J., 2000, Island edifice failures and associated tsunami hazards: Pure and Applied Geophysics, v. 157, p. 899–955, doi:10.1007/s000240050011.

Klügel, A., Walter, T.R., Schwarz, S., and Geldmacher, J., 2005, Gravitational spreading causes en-echelon diking along a rift zone of Madeira Archipelago: An experimental approach and implications for magma transport: Bulletin of Volcanology, v. 68, p. 37–46, doi:10.1007/s00445-005-0418-6.

Krastel, S., Schmincke, H.U., Jacobs, C.L., Rihm, R., Le Bas, T.P., and Alibes, B., 2001, Submarine landslides around the Canary Islands: Journal of Geophysical Research, v. 106, p. 3977–3997, doi:10.1029/2000JB900413.

Le Friant, A., Boudon, G., Deplus, C., and Villemant, B., 2003, Large-scale flank collapse events during the activity of Montagne Pelee, Martinique, Lesser Antilles: Journal of Geophysical Research, v. 108, 2055, doi:10.1029/2001JB001624.

Lipman, P.W., Normak, W.R., Moore, J.G., Wilson, J.B., and Gutmacher, C.E., 1988, The giant submarine Alika debris slide, Mauna Loa, Hawaii: Journal of Geophysical Research, v. 93, p. 4279–4299, doi:10.1029/JB093iB05p04279.

Madeira, J., and Brum da Silveira, A., 2003, Active tectonics and first palaeoseismological results in Faial, Pico and Sao Jorge Islands (Azores, Portugal): Annals of Geophysics, v. 46, p. 733–761.

McGuire, W.J., 1996, Volcano instability: A review of contemporary themes, *in* McGuire, W.J., et al., eds., Volcano instability on Earth and other planets: Geological Society of London Special Publication 110, p. 1–23, doi:10.1144/GSL.SP.1996.110.01.01.

McMurtry, G.M., Herrero-Bervera, E., Cremer, M.D., Smith, J.R., Sherman, C., and Torresan, M.E., 1999, Stratigraphic constraints on the timing and emplacement of the Alika 2 giant Hawaiian submarine landslide: Journal of Volcanology and Geothermal Research, v. 94, p. 35–58, doi:10.1016/S0377-0273(99)00097-9.

McMurtry, G.M., Fryer, G.J., Tappin, D.R., Wilkinson, I.P., Williams, M., Fietzke, J., Garbe-Schoenberg, D., and Watts, P., 2004, Megatsunami deposits on Kohala volcano, Hawaii, from flank collapse of Mauna Loa: Geology, v. 32, p. 741–744, doi:10.1130/G20642.1.

Mitchell, N.C., 2003, Susceptibility of mid-ocean ridge volcanic islands and seamounts to large-scale landsliding: Journal of Geophysical Research, v. 108, 2397, doi:10.1029/2002JB001997.

Mitchell, N.C., Quartau, R., and Madeira, J., 2011, Assessing landslide movements in volcanic islands using near-shore marine geophysical data: South Pico Island, Azores: Bulletin of Volcanology, v. 74, p. 483–496, doi:10.1007/s00445-011-0541-5.

Moore, J.G., Normark, W.R., and Holcomb, R.T., 1994, Giant Hawaiian landslides: Annual Review of Earth and Planetary Sciences, v. 22, p. 119–144, doi:10.1146/annurev.ea.22.050194.001003.

Morgan, J.K., Moore, G.F., Hills, D.J., and Leslie, S., 2000, Overthrusting and sediment accretion along Kilauea's mobile south flank, Hawaii: Evidence for volcanic spreading from marine seismic reflection: Geology, v. 28, p. 667–670, doi:10.1130/0091-7613(2000)28<667:OASAAK>2.0.CO;2.

Nunes, J.C., 1999, A actividade vulcânica na ilha do Pico do Plistocénico Superior ao Holocénico: Mecanismo eruptivo e hazard vulcânico [Ph.D. thesis]: Ponta Delgada, Portugal, Universidade dos Açores, 356 p.

Nunes, J.C., Camacho, A., Franca, Z., Alves, M., Vieira, R., Velez, E., and Ortiz, E., 2006, Gravity anomalies and crustal signature of volcano-tectonic structures of Pico Island (Azores): Journal of Volcanology and Geothermal Research, v. 156, p. 55–70, doi:10.1016/j.jvolgeores.2006.03.023.

Owen, S., Segall, P., Lisowski, M., Miklius, A., Denlinger, R., and Sako, M., 2000, Rapid deformation of Kilauea volcano: Global positioning system measurements between 1990 and 1996: Journal of Geophysical Research, v. 105, p. 18,983–18,998, doi:10.1029/2000JB900109.

Quidelleur, X., Hildenbrand, A., and Samper, A., 2008, Causal link between Quaternary paleoclimatic changes and volcanic islands evolution: Geophysical Research Letters, v. 35, L02303, doi:10.1029/2007GL031849.

Samper, A., Quidelleur, X., Lahitte, P., and Mollex, D., 2007, Timing of effusive volcanism and collapse events within an oceanic arc island: Basse Terre, Guadeloupe archipelago (Lesser Antilles Arc): Earth and Planetary Science Letters, v. 258, p. 175–191, doi:10.1016/j.epsl.2007.03.030.

Shirzaei, M., Walter, T.R., Nankali, H.R., and Holohan, E., 2011, Gravity-driven deformation of Damavand volcano, Iran, detected through InSAR time series: Geology, v. 39, p. 251–254, doi:10.1130/G31779.1.

Silva, P.F., Henry, B., Marques, F.O., Hildenbrand, A., Madureira, P., Mériaux, C.A., and Kratinová, Z., 2012, Palaeomagnetic study of a sub-aerial volcanic ridge (São Jorge Island, Azores) for the past 1.3 Myr: Evidence for the Cobb Mountain Subchron, volcano flank instability and tectono-magmatic implications: Geophysical Journal International, v. 188, p. 959–978, doi:10.1111/j.1365-246X.2011.05320.x.

Smith, J.R., Malahoff, A., and Shor, A.N., 1999, Submarine geology of the Hilina slump and morpho-structural evolution of Kilauea volcano, Hawaii: Journal of Volcanology and Geothermal Research, v. 94, p. 59–88, doi:10.1016/S0377-0273(99)00098-0.

Tilling, R.I., Koyanagi, R.Y., Lipman, P.W., Lockwood, J.P., Moore, J.G., and Swanson, D.A., 1976, Earthquake and related catastrophic events, island of Hawaii, November 29, 1975: A preliminary report: U.S. Geological Survey Circular 740, 33 p.

Walter, T.R., and Schmincke, H.U., 2002, Rifting, recurrent landsliding and Miocene structural reorganization on NW-Tenerife (Canary Islands): International Journal of Earth Sciences, v. 91, p. 615–628, doi:10.1007/s00531-001-0245-8.

Woodhall, D., 1974, Geology and volcanic history of Pico Island Volcano, Azores: Nature, v. 248, p. 663–665, doi:10.1038/248663a0.

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