GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 6, 1296, doi:10.1029/2002GL016610, 2003

Buttressing and fractional spreading of Tenerife, an experimental approach on the formation of rift zones

Thomas R. Walter[1]
Marine Geology and Geophysics, RSMAS, University of Miami, Miami, Florida, USA

Received 14 November 2002; revised 1 February 2003; accepted 12 February 2003; published 21 March 2003.

[1] The island of Tenerife is composed of three Miocene shields, which are centered by the Cañadas volcano since the Pliocene. Tenerife sits on more than 2 km thick oceanic sediments. Quaternary volcanism of the Cañadas series and giant landslides were principally confined to triaxial rift zones. The mechanism of triaxial rifting, however, has remained unclear. Physical analog models show that these rift zones may have formed by gravity-driven lateral escape of island segments, induced by loading of the deformable substratum. For experiments scaled to Tenerife, three adjacent sand cones were mounted onto viscous PDMS substratum. Gravitational spreading caused circumferential expansion of each cone, until a large edifice (Cañadas) was constructed in their center. The older cones now acted each as a buttress; radial fractures were overprinted by fractional spreading of the Cañadas edifice. This resulted in formation of three main extensional zones, resembling the triaxial rifting configuration of Tenerife. *INDEX TERMS:* 8122 Tectonophysics: Dynamics, gravity and tectonics; 8168 Tectonophysics: Evolution of the Earth: Stresses—general; 8434 Volcanology: Magma migration; 8499 Volcanology: General or miscellaneous. **Citation:** Walter, T. R., Buttressing and fractional spreading of Tenerife, an experimental approach on the formation of rift zones, *Geophys. Res. Lett.*, *30*(6), 1296, doi:10.1029/2002GL016610, 2003.

1. Introduction

[2] Large volcanic edifices are known to be subject to gravitational spreading and plastic flowage - an idea originally adapted from gravity tectonics and glaciology [cf. *Ramberg*, 1981]. Associated deformation is characterized by vertical shortening, and volume-preserving lengthening in the horizontal plane. *Fiske and Jackson* [1972] simulated the gravity field of morphologic ridges and suggested that rift zones generate a self-stabilizing gravitational stress field. *Nakamura* [1980] and *Dieterich* [1988] confirmed that weak substrata play a fundamental role in volcano dynamics, where basal slippage provides the necessary space for parallel dike intrusions along rift zones. In the past ten years, several studies demonstrated how a volcano situated on a viscous deformable layer spreads outward, deforming by a flexure beneath, thrust faulting in the periphery and internal faulting [see *Borgia et al.*, 2000, and references therein]. Depending on the thickness ratio of weak substratum and brittle cover, a volcano may slightly sag and form minor deformation, or may completely spread and develop radial fault systems [*Merle and Borgia*, 1996, *van Wyk de Vries and Matela*, 1998]. As demonstrated experimentally and theoretically, a volcano is spreading, if a) the ratio of the thickness of brittle substratum and the height of the volcano is less than 0.4, and b) the brittle - ductile ratio in the substratum is less than 3 [*Merle and Borgia*, 1996, cf. *Borgia et al.*, 2000, equation 27a]. As shown in the next section, the volcanic island of Tenerife (Figure 1) might have been prone to significant gravitational spreading - a mechanism previously not considered in structural studies on the Canary Islands.

2. Substratum and Architecture of Tenerife

[3] The Canary Islands are comprised of seven volcanic islands, formed on old (Jurassic) oceanic crust close to the passive continental margin of northwest Africa [*Schmincke et al.*, 1998]. Due to the proximity to the African continent, sedimentation rates were high around the Islands [*Collier and Watts*, 2001]. Quantitative ODP and DSDP data of the sediments exist only for the uppermost hundreds of meters [*Weaver et al.*, 1998]. Seismic reflection data show details of the thick sedimentary cover. The contact between the sediments and the loaded oceanic crust is inclined <0.5° towards the islands center [*Watts et al.*, 1997, *Ye et al.*, 1999]. *Watts et al.* [1997] identified more than 2–3 km thick Jurassic to early Neogene age sediments, below Tenerife's apron. *Collier and Watts* [2001] studied sediment accumulation in more detail, determining that beneath Tenerife, prevolcanic strata (Unit I and Unit II) are about 2 km thick. Overlying units III and IV are of slightly higher seismic velocity and approximately 1.5–2 km thick. Unit III is thought to have formed in the early stages of volcanism, while the following units (IV–V) are clearly synvolcanic. On such sediments, Tenerife is the third largest volcano on Earth after Mauna Kea and Mauna Loa, with a total volume of about 1.5×10^5 km^3 [*Watts et al.*, 1997]. This work focuses on how the lower oceanic sediments could have influenced the structural evolution of the island.

[4] Tenerife formed by coalescence of at least four individual volcanoes (Figure 1). Three Miocene basaltic shield volcanoes are partly preserved in the deeply eroded corners of the island. These are Teno in the northwest (6.7–4.5 Ma), Anaga in the northeast (6.5–3.5 Ma) and Roque del Conde in the south (12–6.4 Ma) [*Ancochea et al.*, 1990]. Around 3.5 Ma ago volcanic activity migrated to the midpoint of the three old edifices forming the Cañadas edifice, which progressively connected the subaerial portions of the once separated edifices. Since then, Quaternary volcanic activity was concentrated along extensional axes,

[1]Formerly at Department of Volcanology, GEOMAR, Kiel, Germany.

0094-8276/03/2002GL016610

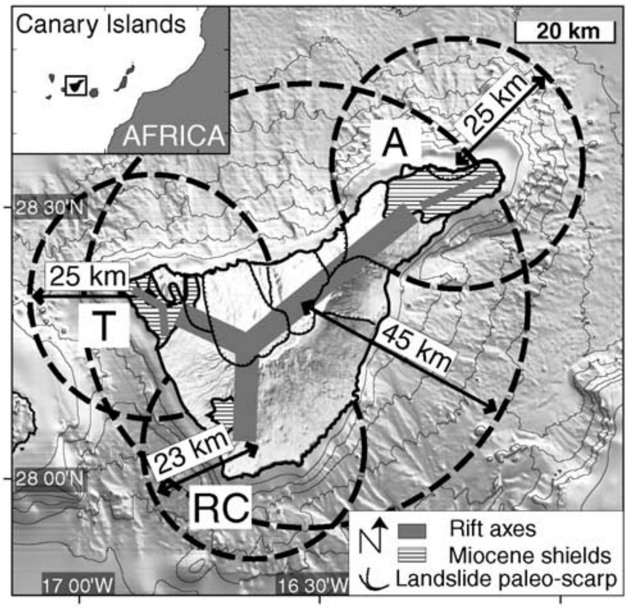

Figure 1. Location and triangular structure of Tenerife. Miocene shields Teno (T), Anaga (A), Roque del Conde (RC) are centered by Cañadas. The diameter of each edifice was obtained by measuring the mean maximal length of submarine canyons, denoting least radius of each cone. Note the relation of landslide scarps to the triaxial rift zone. Bathymetric data (contour interval .5 km) was provided by D. Masson and S. Krastel [cf. *Watts and Masson*, 2001; *Krastel et al.*, 2001].

oriented from the central peak of Cañadas towards Teno, Roque del Conde and Anaga [*Ancochea et al.*, 1990, *Carracedo*, 1996]. Dike intrusions along these three rift zones caused further volcano expansion. As a result, the Cañadas edifice has been subject to major sector collapses, with unstable flanks commonly located between two rift zones of the triaxial system [*Carracedo*, 1996; *Watts and Masson*, 2001].

[5] Since volcano destruction by giant landslides is often influenced or even a consequence of rifting [cf. *Elsworth and Voight*, 1996], the understanding of rift zone development is crucial. The structural design of Tenerifes triaxial rift zones is thought to have formed by endogenous forces, where rising mantle material domed the crust until its rupture threshold was reached [*Carracedo*, 1996]. According to the least-effort principle, a triaxial fracture zone will form with typical separation angles of 120° [*Luongo et al.*, 1991, *Carracedo*, 1996]. The rift zones are thus thought to have initiated early in Tenerife's history and root deeply beneath the volcano. As shown below, physical analog models however suggest that rift zone formation may result mostly from gravitational spreading.

3. Experiments Scaled to Tenerife

[6] Analog experiments were carried out to simulate volcanic edifice spreading of Tenerife. These experiments were designed to account for a) deformable prevolcanic sediments of a mean thickness of 2 km, b) an overlying more competent unit, composed of ~1 km thick synvolcanic sediments, and c) progressive loading by three distinct edifices, followed by loading of a fourth larger edifice in their center (Figure 2).

[7] The experimental setup consisted of a 1 m^2 PVC box, filled with a layer of viscous PDMS (Polydimethylsiloxane) and a sand-layer above. Piles of sand were placed on top to simulate the volcanoes. The experimental setup thus is basically similar to that of *Merle and Borgia* [1996].

[8] The models simulated Tenerife, where similarity to the prototype was achieved by geometric, kinematic and dynamic scaling. To investigate the architecture of Tenerife, I first modeled three separate spreading cones of the heights H and diameters D. After time t a fourth cone was placed in center of the former deformed cones. The similarity conditions were based on material properties, such as density ρ, the internal friction coefficient μ, and the weak substratum viscosity ν. The geometric and dynamic variables for the experiments and prototype Tenerife are given in Table 1.

[9] By using dry eolian sand of low cohesion (grain size 0.3 mm) that fits the Navier-Coulomb criterion, brittle deforming materials were imitated [*Schellart*, 2000]. Weak prevolcanic sediments were simulated by using Newtonian-behaving PDMS [cf. *ten Grotenhuis et al.*, 2002] with a viscosity $\nu = 3 \times 10^4$ Pa s. Scaling was achieved by utilizing the Buckingham-Π theorem, where five dimensionless numbers ought to maintain the same ratios for the prototype and experimental values [*Merle and Borgia*, 1996], while their ratio Π^* approach 1. As shown in Table 1, the Π values preserve scaling.

[10] Geometric scaling was 0.5×10^{-5}, meaning that 1 km in nature is scaled to approximately 0.5 cm in experiments. The stress ratio was $\sigma^* = 0.5 \times 10^{-5}$, where the models are σ^*-times weaker than the prototype. With an inclination of 25–30°, the initial flank steepness of the sand cones may have been exaggerated. After spreading, however, the measured mean flank inclination was 10 to 15°, comparable to those on Tenerife (Table 1). Based on the basal shear-stress equation, which is a function of the load and the slope angle of the surface, the topography determines the direction of motion, not so much the basal slope [*Ramberg*, 1981]. Thus the elastic lithospheric flexure (less than 0.5° reflector inclination, *Watts et al.* [1997]) was not considered in these

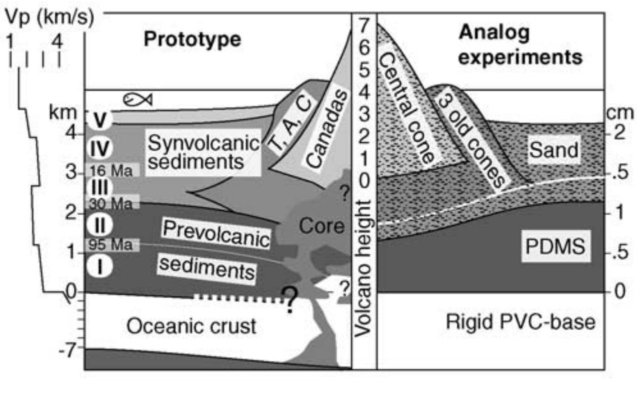

Figure 2. Sketch of dimensions in Tenerife (left) and experiments (right). Units I–V seismic stratigraphy [cf. *Collier and Watts*, 2001] was converted into scaled experimental proportions. Velocity profile after *Watts et al.* [1997] also shows a velocity decrease in the substratum.

Table 1.

A	Variable[a]	Definition	Prototype: Miocene	Prototype: Canadas	Experiments: Old	Experiments: Young	Unit
Geometric scaling	H	Height of volcanic cone	4000	7000	0,02	0,035	m
	D	Diameter of volcanic cone	50000	90000	0,23	0,38	m
	S2	Thickness of brittle substratum	1000	1000	0,005	0,005	m
	S1	Thickness of weak substratum	2000	2000	0,01	0,01	m
Kinematic and dynamic scaling	$\rho 1$	Density of volcanic cone	2700	2700	1400	1400	kg/m^3
	$\rho 2$	Density of substratum	2500	2500	1200	1200	kg/m^3
	ν	Viscosity of weak substratum	5E18	5E18	30000	30000	Pa s
	μ	Internal friction coefficient	0,6	0,6	0,6	0,6	
	g	Gravity acceleration	9,8	9,8	9,8	9,8	m/s
	t	Time span of deformation	9E13	3E13	1,7E5	5,8E4	s
B	**Dimensionless**	**Π-numbers[b]**	**Π***		**Π***		
Buckingham theorem	$\Pi 1 = H/D$	Potential instability	0.8		0.9		
	$\Pi 2 = S2/H$	Intrinsic strength of S	1.0		1.0		
	$\Pi 3 = S2/S1$	Intrinsic weakness of S	1.0		1.0		
	$\Pi 4 = \rho 1/\rho 2$	Volcano floating potential	0.9		0.9		
	$\Pi 5 = \rho g H t/\mu$	Process rate	1.2		1.2		

[a]Variables from prototype Tenerife and as used in scaled experiments (sizes measured after t).
[b]Dimensionless Π-numbers, which are in the same range, verify scaling of the experiments. The Buckingham ratios Π*, defined by $\Pi_{prototype}$ divided by $\Pi_{experiment}$, approach 1, therefore similarity is maintained.

experiments. Further simplifications made were to neglect the influence of pore pressure variances, to model mechanically isotropic volcanic cones, and to disregard intermittent magmatic loading and/or erosive processes.

4. Experimental Results

[11] Simple "endmember" models were performed to understand spreading of a) a single cone, and b) two neighboring cones. The dimensions and Π-values used are similar to those given in Table 1. In the single cone experiment, a small concentric bulge at the periphery developed into wrinkle ridge thrust faults (Figure 3A). Fracturing of the cone occurred mainly along radially oriented leaf graben structures, while the extensional stress culminated in subsidence of the cone apex. Thus the structures are comparable to the findings of *Merle and Borgia* [1996]. The least compressive stress was circumferential to the cone, implying that in nature intrusions could propagate radially. In contrast, spreading of two neighboring volcanoes whose aprons partly overlap, caused the formation of a main graben in-between both cones. In nature, this effect of buttressing is likely to result in a main rift zone connecting two volcanic edifices - an effect that became significant for the evolution of the "Tenerife-experiments".

[12] The first step of the Tenerife-experiments was to model three adjacent sand-cones (Figure 3B). After 32 hours of spreading, a fourth larger cone (the Cañadas) was constructed in the center, partly situated on the flanks of the older deformed edifices. Normal faults formed near the junction of the cones, propagating toward the older cones and inward to the Cañadas apex. Section F-F′ shows the geometry of these faults, which define zones of extension and thus potential rift zones. A triaxial rift system developed in the central edifice. Section G-G′ parallel to the rift zone shows steepening, thrusting and slight folding of the inner flank of the older cone, defining a local indentation of the central cone into the older edifice. In view of

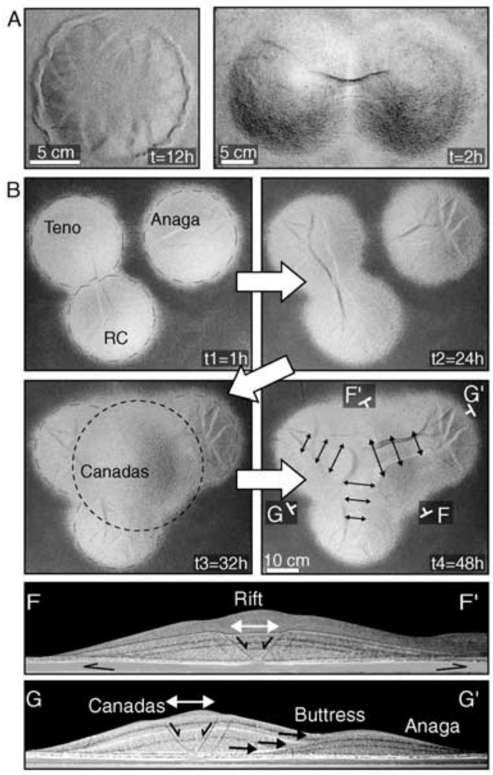

Figure 3. Experimental results. A. Endmember models of a single cone with radial leaf grabens (left photo), and two neighboring cones with a main rift in-between (right). B. Tenerife experiments. Three separate sand cones spread for 32 hours (equation 3 Ma). A rift is visible between "Teno" and "Roque del Conde". Then a fourth cone was constructed in the center, deforming the amalgamated edifice for 16 h (1 Ma). Three main extensional zones formed, the best pronounced rift is directed to the most distant cone (here: Anaga). Note small thickness change of the PDMS substratum in section photos.

this, the unbuttressed flanks appear structurally isolated and are free to spread outward. The transition of the free flank towards the buttressed flank is at the surface moreover bordered by small left-lateral and right-lateral fractures associated with strike-slip normal faults on either side.

5. Discussion and Implications

[13] Volcano flank deformation, landslide susceptibility and the flexural response of the crust are probably the best-known examples of gravity-induced structural modifications of large edifices. As described in this paper, the growth history and loci of older (buried) edifices largely influence the mechanism of spreading and thus the successive intrusive and eruptive behavior of a younger edifice. The intrusive triaxial skeleton of Tenerife is related mainly to volcano spreading, and not to hotspot-induced doming as previously believed. This implies that the development and expression of unstable flanks and sector collapses between the rift zones is not initiated in early doming stages of the region, but is caused and may change by edifice spreading conditions. Situated on deformable substratum, the three Miocene shield volcanoes Roque del Conde, Anaga and Teno buttressed the growing Cañadas volcano. In the experiments, initial structures of the deformed older cones were then overprinted by three main extensional zones that appear by spreading of the younger Cañadas cone.

[14] Gravitational spreading of overlapping edifices may promote and adjust rifting. Thus it should be considered that a major consequence of this gravity tectonics is to open pathways for further magma to rise, and/or to release a plumbed magmatic system. Moreover, zones of high fluid flow and alteration will most likely concentrate along the extensional zones in the edifice. This causality could have had an important role in destabilizing the Cañadas edifice of Tenerife, where e.g. solely to the north at least 6 giant landslides have occurred [*Watts and Masson*, 2001].

6. Conclusions

[15] Structural similarities of Tenerife and the analog experiments suggest that deformable sediments underlie this central Canary Island and had strong control on its structural formation. The architecture of Tenerife, its triaxial rift zone configuration and sites of sector instability, is controlled by gravitational spreading and partitioned lateral escape of edifice sectors. The gravity-controlled extension portrays an internal volcano-tectonic process, once more revealing that in previous volcanological studies the weight of deep endogenous forces may have been overrated.

[16] **Acknowledgments.** Helpful comments by A. Borgia, A. Klügel, and H. Schmincke improved this paper. Critical and thoughtful reviews by J. Stix and A. Briais are greatly appreciated. My thanks go to D. Masson and S. Krastel for providing bathymetric data. This work was funded by Post-Doctoral grant, of CSTARS Miami and the Deutsche Forschungsgemeinschaft (WA1642).

References

Ancochea, E., J. M. Fuster, E. Ibarrola, A. Cendrero, J. Coello, F. Hernan, J. M. Cantagrel, and C. Jamond, Volcanic evolution of the island of Tenerife (Canary Islands) in the light of new K-Ar data, *J. Volcanol. Geotherm. Res.*, *44*, 231–249, 1990.

Borgia, A., P. Delaney, and R. P. Denlinger, Spreading volcanoes, *Annu. Rev. Earth Planet. Sci.*, *28*, 539–570, 2000.

Carracedo, J. C., Morphological and structural evolution of the western Canary Islands: Hotspot induced three-armed rifts or regional tectonic trends?, *J. Volcanol. Geotherm. Res.*, *72*, 151–162, 1996.

Collier, J. S., and A. B. Watts, Lithospheric response to volcanic loading by the Canary Islands: Constraints from seismic reflection data in their flexural moat, *Geophys. J. Int.*, *147*, 660–676, 2001.

Dieterich, J. H., Growth and persistence of Hawaiian volcanic rift zones, *J. Geophys. Res.*, *93*, 4258–4270, 1988.

Elsworth, D., and B. Voight, Evaluation of volcano flank instability triggered by dyke intrusion, in *Volcano Instability on the Earth and Other Planets*, edited by W. J. McGuire, A. P. Jones, and J. Neuberg, *Geol. Soc. London*, *110*, 45–53, 1996.

Fiske, R. S., and E. D. Jackson, Orientation and growth of Hawaiian volcanic rifts, *Proc. R. Soc. London*, *329*, 299–320, 1972.

Krastel, S., H.-U. Schmincke, C. L. Jacobs, R. Rihm, T. P. La Bas, and B. Alibés, Submarine landslides around the Canary Islands, *J. Geophys. Res.*, *106*, 3977–3997, 2001.

Luongo, G., E. Cubellis, F. Obrizzo, and S. M. Petrazuoli, A physical model for the origin of volcanism of the Tyrrhenian margin, *J. Volcanol. Geotherm. Res.*, *48*, 173–185, 1991.

Merle, O., and A. Borgia, Scaled experiments of volcanic spreading, *J. Geophys. Res.*, *101*, 13,805–13,817, 1996.

Nakamura, K., Why do long rift zones develop in Hawaiian volcanoes?, *Bull. Geol. Soc. Jpn.*, *25*, 255–267, 1980.

Ramberg, H., *Gravity, Deformation and the Earth's Crust; in Theory, Experiments and Geological Application*, 452 pp., Academic, San Diego, Calif., 1981.

Schellart, W. P., Shear test results for cohesion and friction coefficients for different granular materials, *Tectonophysics*, *324*, 1–16, 2000.

Schmincke, H.-U., A. Klügel, T. Hansteen, K. Hoernle, and P. Bogaard, Samples from the Jurassic ocean crust beneath Gran Canaria, La Palma and Lanzarote (Canary Islands), *Earth Planet. Sci. Lett.*, *163*, 343–360, 1998.

ten Grotenhuis, S. M., S. Piazolo, T. Pakula, C. W. Passchier, and P. D. Bons, Are polymers suitable rock analogs?, *Tectonophysics*, *350*, 35–47, 2002.

van Wyk de Vries, B., and R. Matela, Styles of volcano-induced deformation, *J. Volcanol. Geotherm. Res*, *81*, 1–18, 1998.

Watts, A. B., and D. G. Masson, New sonar evidence for recent catastrophic collapses of the north flank of Tenerife, Canary Islands, *Bull. Volcanol.*, *63*, 8–19, 2001.

Watts, A. B., C. Peirce, J. Collier, R. Dalwood, J. P. Canales, and T. J. Henstock, A seismic study of lithospheric flexure in the vicinity of Tenerife, *Earth Planet. Sci. Lett.*, *146*, 431–447, 1997.

Weaver, P. P. E., H.-U. Schmincke, J. V. Firth, and W. Duffield, *Proceedings of the ODP: Scientific Results*, *157*, pp. 655, 1998.

Ye, S., R. Rihm, J. J. Dañobeitia, J. P. Canales, and J. Gallart, A crustal transect through the northern and northeastern part of the volcanic edifice of Gran Canaria, *J. Geodyn.*, *28*, 3–26, 1999.

T. R. Walter, Division of Marine Geology and Geophysics, RSMAS, University of Miami, 4600 Rickenbacker Cswy., FL 33149, USA. (twalter@rsmas.miami.edu)