InSAR observations of the 1995 Fogo, Cape Verde, eruption: Implications for the effects of collapse events upon island volcanoes

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[1] Fogo volcano, Cape Verde Islands, erupted in April 1995 after 43 years of dormancy. About 46 10^6 m^3 of lava erupted during 7.5 weeks from vents on the SW flank of Pico do Fogo into Cha das Caldeiras. Interferograms obtained from 1993–1998 ERS SAR data show ground deformation due to the feeder dike but lack evidence for any volcano-wide deformation related to volume changes of a shallow magma reservoir. This suggests that Fogo is fed from a relatively deep, mantle-lithospheric source (>16.5 km depth), consistent with petrological data. This supports the concept that Cha das Caldeiras is the fill of a collapse scar created by a giant landslide, and not a collapse caldera overlying a central, shallow magma chamber. The disturbance of the magmatic system by giant landslides may explain why some oceanic island volcanoes with high magma supply rates currently lack well-developed shallow reservoirs. *INDEX TERMS:* 8414 Volcanology: Eruption mechanisms; 8419 Volcanology: Eruption monitoring (7280); 8494 Volcanology: Instruments and techniques; 1206 Geodesy and Gravity: Crustal movements—interplate (8155)

1. Introduction

[2] Fogo volcano is the active expression of the ~50Ma old Cape Verde mantle hot spot, located ~700 km off West Africa (Figure 1). The Cape Verde Islands ride atop the African plate SWS with a velocity of ~0.9 cm/yr but do not form a linear island chain. Fogo volcano (the island has the same name) is the 4th largest of the Cape Verde Islands. The submarine part of Fogo overlaps the adjacent edifice of Brava. No historic eruptions have been reported on Brava although it is seismically more active [*Heleno da Silva and Fonseca*, 1999].

[3] The most prominent structure of Fogo is a 9 km NS-elongated plain at ~1700 m elevation (Figure 1). We refer to this plain by its local geographic name "Cha das Caldeiras" (we do not abbreviate it to "caldera" because this is generally associated with a vertical collapse structure). It is bounded to the N, W and S by the up to 1000 m-high Monte Amarelo escarpment. Pico do Fogo, the active cone and highest elevation of the island (2829 m above sea level, ~7000 m above the ocean floor) is located in the E.

[4] Fogo erupted between 1500 (the arrival of the first settlers) and 1750 many times from the summit of Pico do Fogo. Since then, eruptions occurred from fissures on its lower flanks and within Cha das Caldeiras. Historic eruptions occurred in 1769, 1785, 1799, 1816 (questionable), 1847, 1853, 1857, and 1951.

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2. The 1995 Eruption

[5] On 2 April 1995 a basaltic eruption started on the SW flank of Pico do Fogo ~300 m above Cha das Caldeiras. Several vents formed along a ~1.7 km WSW radial fissure and along a secondary fissure further west (Figure 1). After 2 days, activity was restricted to one vent on the WSW fissure. The eruptive style evolved from Hawaiian to Strombolian with lava fountains feeding voluminous aa flows. By April 22 the character of lava changed to pahoehoe until the eruptive activity ceased by May 26. The eruption produced a 4.7 km^2 lava flow in Cha das Caldeiras destroying one of the most fertile agricultural grounds in Cape Verde and displacing 2000 inhabitants.

3. Observational Data

[6] We have used Synthetic Aperture Radar (SAR) images of the ERS satellites acquired at different times to form interferograms. The interferogram represents ground displacements in radar line-of-sight direction (LOS displacement) that may have occurred during the time between the acquisitions. One cycle of phase (1 fringe) represents 2.8 cm LOS displacement (e.g., *Massonnet and Feigl* [1998]; *Zebker et al.* [2000]; *Amelung et al.* [2000a, 2000b]). The radar is more sensible to vertical than to horizontal displacements (incidence angle 23° from vertical). Because of Fogo's steep slopes (20°–28°) the E flank can only be observed from ascending orbits (radar looking E) and the W flank only from descending orbits (radar looking W).

[7] An interferogram obtained from 23 June 1993 and 3 Nov 1995 SAR images shows the ground deformation associated with the 1995 eruption (Figure 2a). Interferometric coherence is maintained on recent lava flows in Cha das Caldeiras and on the E flank of Fogo. A 3–4 Nov 1995 interferogram was used for the topographic correction. We selected this combination of interferograms out of all possible three- and four-pass combinations because it showed minimum atmospheric disturbances (Bperp: 66 m; for the topography pair: 135 m).

[8] In the area SW of the main vent several fringes start from two different locations consistent with a two-segment dike (Figure 2a). The maximum observed LOS displacements are 7 cm (2.5 fringes) NW of, and 10 cm (3.5 fringes) SW of the eruptive fissures. No measurements are available in the immediate vicinity of the fissure because of loss of coherence due to new lava. A phase signature on Fogo's lower E flank is probably an atmospheric artifact (N of the Espigao escarpment, Figure 2a), but a unique identification as such using the pair-wise image logic [*Massonnet and Feigl*, 1998] is not possible with the available images. At Pico do Fogo's upper E-flank 2–3 fringes arriving from the south terminate abruptly, perhaps because of local ground cracking (Figure 2a). We also obtained interferograms for a 3-year post-eruptive period starting 5 June 1995. They do not

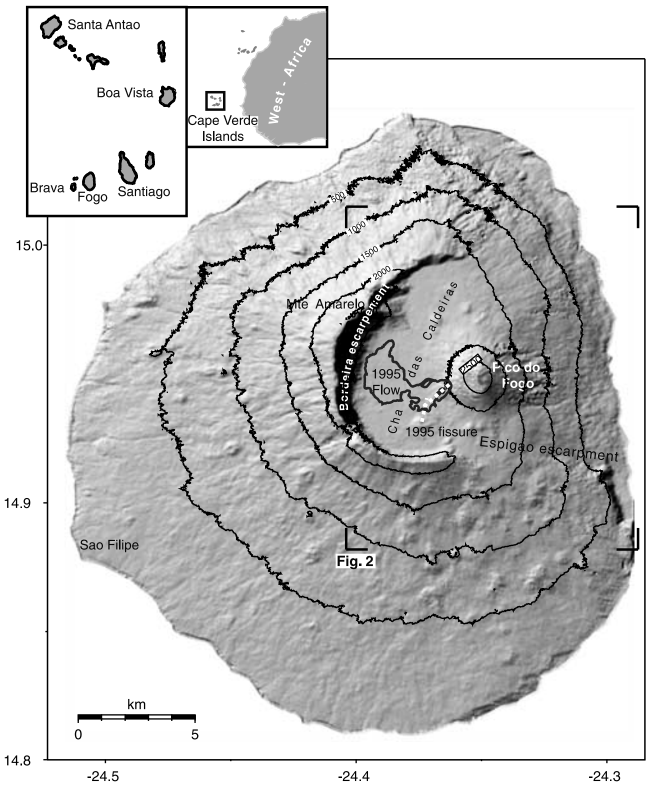

Figure 1. Shaded relief map of Fogo volcano. The 1995 eruption occurred from a two-segment fissure on the lower flank of Pico do Fogo and inside Cha das Caldeiras. Insets show the locations of the islands off the coast of Africa. The area of Figure 2a is indicated.

show any ground deformation except subsidence of the newly emplaced lava flow.

4. Modeling the Data

[9] To model the observed LOS displacements, we assume that ground deformation was caused by the intrusion of a two-segment dike, described by uniform elastic dislocations. The data consist of 828 LOS displacements obtained by sampling the unwrapped interferogram on a uniform grid. We use a non-linear simulated annealing inversion algorithm to find the model that minimizes the summed difference between model prediction and data [*Cervelli et al.*, 2001]. In the inversion we constrain the geometry of the two dislocations such that their upper edges coincide with the surface traces of the eruptive fissures and invert for their geometry, opening, and location. In the best-fitting model the (length, down-dip width, dip, opening) are (3.2 km, 2 km, 65° NW, 0.25 m) for the primary, and (1.8 km, 1.4 km, 55°S, 0.36 m) for the secondary dislocation (Figures 2b–2d). The primary dislocation accounts for 65% of the total dike volume of 2.5 10^6 m^3.

[10] A problem of this model is that the lower edges of the dislocations are not connected. This can be fixed by constraining the dislocations to be vertical in the inversion. In this case the best-fitting model is geologically more plausible (the dislocation openings are 0.5 m and 0.25 m, respectively), but the fit to the data is poorer than in the first case (RMS error of 12.1 mm versus 10.6 mm). A stable result of the inversions is the down-dip width of the dislocation of 2 km.

[11] We conclude that the InSAR observations are well explained by a two-segment feeder dike emplaced at ~2 km depth. We are unable to infer details about the geometry because of the relatively small signal and because of model simplifications (elastic effects of the topography are neglected). The data do not show evidence for the co-eruptive, seaward displacement of Fogo's eastern flank proposed by *Day et al.* [1999]. Note that a NW-dipping secondary dike is consistent with the seismicity [*Heleno da Silva et al.*, 1999].

5. Depth of the Magma Reservoir

[12] The InSAR data show no ground deformation other than that due to the dike and we now discuss the significance of this observation. Volcanoes with shallow magma reservoirs within the volcanic edifice generally show gradual inflation prior to eruptions, significant deflation during, and rapid inflation immediately after eruptions. Pre-eruptive inflation is caused by the intrusion of magma into the reservoir, co-eruptive deflation by the transfer of the erupting magma out of the reservoir, and post-eruptive inflation by replenishment of the reservoir from below. This cycle has been observed at Krafla, Iceland, at Mauna Loa and Kilauea, Hawaii [e.g., *Dvorak and Dzurisin*, 1997], and at Cerro Azul, Galapagos [*Amelung*, in preparation]. At Fogo, the lack of both, co-eruptive deflation and of post-eruptive inflation (in interferograms starting as early as 6 days after the end of the eruption) suggests that no shallow magma chamber was involved in the 1995 eruption.

[13] We now derive a minimum depth of the magma reservoir assuming that the associated ground deformation can be modeled by a point source of dilation in an elastic halfspace (Mogi's model). The surface displacement, u_z, depends on the volume change of the magma chamber, ΔV_{ch}, and on the source depth, d: $u_z = (1 - \nu)\Delta V_{ch}/\pi/d^2$ (above the source). ν is Poisson's ratio (we assume $\nu = 0.25$). With an estimate of ΔV_{ch} and an upper limit for u_z we thus can derive a minimum d. By differencing pre- and post-eruptive digital elevation models (derived from 6 Oct–10 Nov 1993 and 3–4 Nov 1995 interferograms) we obtain an eruptive volume of 46 10^6 m^3, roughly consistent with field estimates [*Torres et al.*, 1997]. Assuming that ΔV_{ch} is 70% of the eruptive volume (because of lava vesicularity, ash, and because some of the voided reservoir space may be filled by bulk expansion of the residing magma and exsolved gases *Johnson et al.* [2000]), plus the intrusive volume (2.5 10^6 m^3), we find ΔV_{ch} = 35 10^6 m^3. Less than 3 cm of volcano-wide subsidence may have gone undetected by the interferogram, $u_z < 3$ cm. The reservoir depth thus is $d > 16.5$ km, consistent with 32 ± 10 km depth inferred from petrology [*Munha et al.*, 1997].

6. Implications for Volcano Structure

[14] Summit calderas of basaltic shield volcanoes form by collapse of the caldera floor into previously evacuated magma

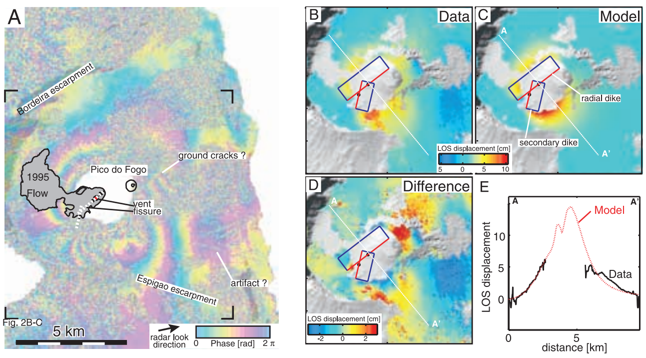

Figure 2. (a) June 1993–Nov. 1995 interferogram of Fogo volcano. (b) unwrapped phase, (c) best-fitting model, (d) difference between data and model predictions. (e) profile. Surface projection of best-fitting dislocation model is also shown (red lines denote dislocation upper edges).

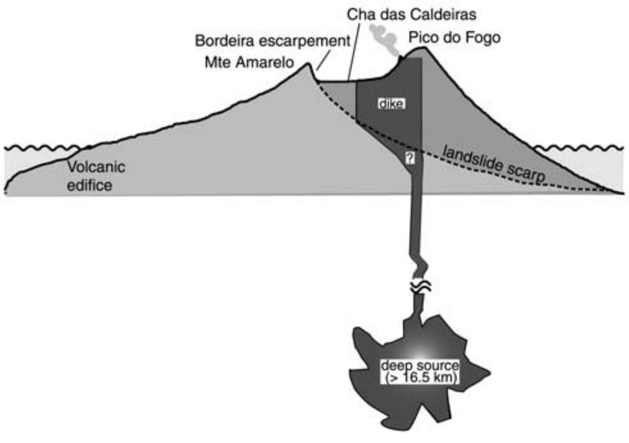

Figure 3. Structural cartoon of Fogo volcano. The Bordeira escarpement (up to 1000 m high) was created by a giant landslide and a new volcano was build on the landslide scarp.

chambers. Modern examples are found at volcanoes in the Galapagos Islands. Cha das Caldeiras was previously interpreted to be a collapse caldera and the Bordeira escarpment as a caldera-bounding fault [*Machado*, 1965]. In an alternative hypothesis, the Bordeira escarpement was formed by a lateral, large-scale gravitational collapse of the ancient volcano [*Day et al.*, 1999] and Cha das Caldeiras and Pico do Fogo are new eruptive features build since the collapse.

[15] The lack of a shallow magma chamber inferred from the interferograms argues against Cha das Caldeira being a central collapse caldera and favors the giant landslide hypothesis. A cartoon of Fogo volcano and the processes during the 1995 eruption is shown in Figure 3. Magma rose from a deep source (>16.5 km) to ~2 km depth where the feeder dike was emplaced; perhaps at the subsurface landslide scar which may act as a gravity and stress trap for buoyant magma. Note that the horseshoe-shaped seaward-oriented structure encompassed by the Bordeira escarpment in the W and the Espigao escarpment in the S (Figure 1) resembles the landslide-created Enclos-Grand Pentes structure of Piton de la Fournaise on Reunion Island [*Labazuy*, 1996].

7. Effects of Lateral Collapses of Oceanic Island Volcanoes on the Depth of Magma Reservoirs

[16] Our interpretation of the interferograms leads to the conclusion that Fogo currently lacks a shallow magma reservoir. This is in contrast to other oceanic island volcanoes and we now consider why this difference may arise. We use "shallow" to describe magma reservoirs within the volcanic edifice or upper crust in contrast to "deep" reservoirs within the lower crust or lithospheric mantle.

[17] Shallow magma reservoirs exist at Kilauea and Mauna Loa in Hawaii [*Dvorak and Dzurisin*, 1997] and at the western Galapagos volcanoes [*Amelung et al.*, 2000a]. Piton de la Fournaise lacks a well-developed shallow reservoir [*Sigmundsson et al.*, 1999], but probably has small magma pockets 1–2 km beneath the summit [*Lénat and Bàchelery*, 1990]. An intrusive complex is evidence for an ancient shallow reservoir [*Lénat et al.*, 2001]. For the Canary Islands petrological data indicate that the Las Canadas volcano on Tenerife had large, shallow reservoirs prior to, and between collapses [*Marti et al.*, 1994]. The successor Teide volcano has at most a small shallow reservoir [*Ablay and Marti*, 2000]. La Palma and El Hierro volcanoes presently lack shallow reservoirs [*Kluegel et al.*, 1997]; El Hierro had a shallow reservoir prior to the El Golfo I collapse [*Carracedo et al.*, 1999].

[18] Shallow magma chambers can only develop and persist if magma is supplied at rates sufficient to inhibit reservoir freezing [*Clague and Dixon*, 2000]. Magma supply rates of Fogo, Piton de la Fournaise, La Palma and El Hierro, which lack shallow reservoirs, are of the same order or greater than for the Galapagos volcanoes which have shallow reservoirs (but substantially less than for Kilauea and Mauna Loa, Table 1). This suggests that other parameters than the magma supply rate also control the presence of shallow reservoirs.

[19] We propose that giant, lateral collapses are responsible for the present-day lack of shallow reservoirs at high-magma-supply oceanic island volcanoes. These catastrophic mass-wasting events may remove shallow reservoirs and completely disturb the thermal and mechanical equilibrium of the volcano. Decompression-triggered eruptions and the absence of isolating rock mass lead to evacuation and freezing of the reservoir. After the collapse event shallow reservoirs will be reestablished with a time delay depending on the magma supply rate (Figure 4). They will persist until the next lateral collapse occurs. The absence of shallow reservoirs at Fogo, Piton de la Fournaise and at the W Canary volcanoes may therefore simply reflect the fact that the time elapsed since the last collapse has been insufficient for shallow reservoirs to establish themself. The shallow magma pockets at Piton de la Fournaise would eventually develop into a larger reservoir. At Kilauea and Mauna Loa (with high magma supply rates) reestablishment of shallow reservoirs would be much more rapid. The presence of shallow reservoirs at the W Galapagos volcanoes is consistent with the lack of giant landslides. Only Cerro Azul volcano had a recent giant landslide [*Naumann and Geist*, 2000]. This volcano has also the deepest reservoir [at ~5 km depth, *Amelung et al.*, 2000b],

Table 1. Magma Supply Rates of Oceanic Island Volcanoes

Volcano	Magma supply rate [10^6 m^3yr^{-1}]	Time period covered	Reference	Shallow magma reservoir
Mauna Loa	28	4000 yr	*Lipman* [1995]	yes
Kilauea	90–115	4000 yr	*Lipman* [1995]	yes
Piton de la Fournaise	10	80 yr	*Lénat and Bàchelery* [1990]	no
Cerro Azul, Sierra Negra, Alcedo	0.5–1	growth rate	*Naumann and Geist* [2000] and references therein	yes
El Hierro	0.12–0.36	growth rate	*Carracedo* [1999]	no
Fogo	>1.7[a,b]	337 yr[a,b]	this study[a,b]	no
La Palma	>0.52[c,d]	521 yr[c,d]	this study[c,d]	no

[a] Assuming that since 1664 50 km^2 of subareal edifice [see map of *Torres et al.*, 1997] was covered by 9 m thick lava flows, dike volume 2.5 10^6 m^3yr^{-1} for each of the 11 eruptions (as in 1995).

[b] Minimum estimate because 6 flows entered the ocean, because of repeated coverage of same ground, and because eruptions with widely spaced vents had greater dike volumes.

[c] Assuming that since 1480 25 km^2 of subareal edifice was covered by 9 m thick lava [*Carracedo et al.*, 1999]; dike volumes for each of the 7 eruptions as for Fogo.

[d] Minimum estimate because 6 flows entered ocean, and because of significant volumes of scoria cones and 1585 cryptodome.

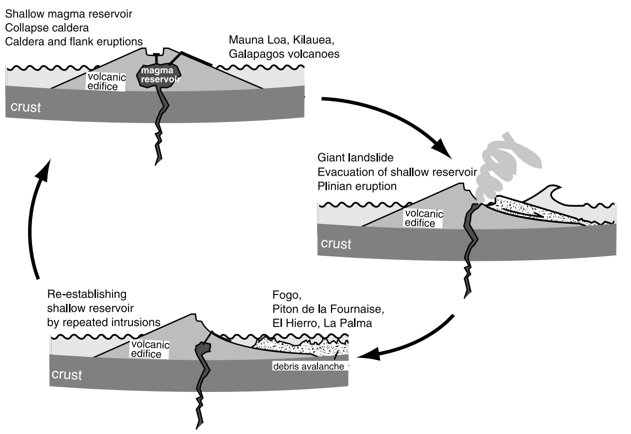

Figure 4. Cycle of an oceanic island volcano with high magma supply rate.

suggesting that it is in the process of migrating upwards. The lack of shallow reservoirs at Hualalai volcano, Hawaii and at the E Canary volcanoes, however, may be related to unsufficient magma supply rate. A similar cycle may be a general feature of basaltic volcanoes. The lack of a shallow reservoir at Etna (with relatively high magma supply rate) may be related to the collapse event that produced the Valle del Bove.

8. Conclusions

[20] The observed surface displacements associated with the 1995 eruption are consistent with the intrusion of a WSW oriented feeder dike system with the primary dike extending from $\sim$2 km depth to the surface. The deeper parts of the magmatic feeder system did not cause any ground deformation, suggesting that they were already in place prior to acquisition of the first SAR image in June 1993.

[21] The lack of volcano-wide deflation during, and of volcano-wide inflation after the eruption indicates that Fogo does not have a shallow magma storage. Fogo volcano appears to be fed from a deep (>16.5 km) source, consistent with petrologic data. This supports the concept of *Day et al.* [1999] that Cha das Caldeiras is not a central collapse caldera overlying a shallow magma chamber but the fill of a collapse scar created by a giant landslide of Monte Amarelo volcano.

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