Recognising incipient instability and lateral collapse precursors in steep - sided oceanic island volcanoes.

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Although Kilauea volcano, Hawaii is commonly regarded as the type example of an unstable oceanic island volcano, it is in many respects atypical of such volcanoes. The Hawaiian volcanoes are both larger and substantially less steep than many oceanic island volcanoes, with heights of up to 10 km above the ocean floor and slopes averaging 5 - 8°. In contrast, volcanoes such as the Cumbre Vieja, La Palma; Teide, Tenerife; and Pico do Fogo, Fogo rise 7 to 8 km above the surrounding ocean floor but have average slopes between 15° and more than 20°. The maximum average subaerial slope of Pico do Fogo is no less than 28°! The greater slope angles make these islands intrinsically less stable.

The south flank of Kilauea is also atypical in that it shows semi - continuous, partly incremental (co - seismic) seaward movement which continues through inter - eruptive periods (Swanson et al. 1976). This probably reflects the persistence of magma and ductile, high - temperature cumulates in the deeper parts of the Kilauean rift zones (Clague & Denlinger 1994). In contrast, studies of the Cumbre Vieja and Pico do Fogo volcanoes (see also McGuire and Moss, this volume) indicate that these volcanoes do not deform during inter - eruptive periods but show clear signs of instability before, during and after near - surface intrusion emplacement and volcanic eruptions. There is however no evidence for major deformation of these volcanoes, accumulated over numerous eruptions. Furthermore, examination of the San Andres fault system on the island of El Hierro indicates that there was at most a few tens of metres of slip on this fault system before sudden slip of about 300 metres in an aborted lateral collapse event (Day et al., 1997). These observations imply, therefore, that steep oceanic island volcanoes can become prone to catastrophic flank failure after only a little precursory deformation; but that such failure is only likely to occur during the course of eruptions or intrusion events. It is therefore important to recognise features that indicate that an oceanic island volcano is evolving towards, or already in, a state of potential catastrophic instability.

1. <u>Development of seaward - facing normal fault or non - magmatic dilational fissure systems, and associated oblique - or strike - slip accommodation faults, in surface outcrop</u>. The best evidence for the onset of flank instability on oceanic island volcanoes is provided by surface ruptures associated with fault systems within the flanks. Examples include the fault system formed along the crest of the Cumbre Vieja volcano during the 1949 eruption, with a maximum surface offset in excess of 4 m; and major "dry" fissures developed over a distance of several kilometres in the 1951 eruption of Pico do Fogo. These fault systems ruptured the surface during eruptions: a critical problem is therefore distinguishing them from faulting around the upper tips of dykes. Useful criteria include: (i) geometry: the normal fault system is asymmetric and seaward - facing (graben above dykes are more symmetrical) while the fissure system shows no axial subsidence; (ii) timing of formation: both the 1949 faults and the 1951 fissures developed well after the start of the eruptions, in periods not directly associated with emplacement or drain-back of magma; (iii) evidence for the absence of magma in the immediate subsurface, such as a lack of fumarolic activity.

2. <u>Seismological indicators of the development of seaward - facing fault systems in the sub - surface</u>. Whether flank fault systems associated with incipient lateral collapse have surface expressions or are "blind" (see below), their activity during eruptive episodes produces distinctive patterns of seismicity. During the 1949 eruption on La Palma, seismicity appears to have been most intense in a north - south elongated region at shallow depth (1 -2 km ?) beneath the western flank of the volcano, downslope from the eruptive vents (Fig. 1). This is interpreted as indicating the presence of a seaward - dipping detachment fault beneath this western flank which, together with the

surface - rupturing normal faults that define the fi~ture headwall, forms an incipient collapse structure. The seismicity on Fogo during the 1 95 1 eruption is not well - enough known to show whether a similar structure existed there but shallow seismicity during and after the 1995 eruption on Fogo (Heleno da Silva et al., this volume) may define part of a developing incipient collapse structure. A distinctive feature of seismicity associated with these incipient lateral collapse structures appears to be that it is at its most intense weeks to months after the start of the destabilising eruptions. This delay has important implications for the likely mechanism of destabilisation (Elsworth et al., this volume).

3. Volcanic rift reorganisation; corresponding re - arran~ements of subsurface dyke swarms in old, incised collapsed volcanoes. The majority of oceanic island volcanoes are characterised by the presence of discrete linear zones in which vents are concentrated ("volcanic rift zones"): these correspond to discrete feeder dyke swarms in the subsurface. The rift zones are defined both by the distribution of vents and by elongation directions of individual vents or groups of vents, which are controlled by the orientation ofthe underlying dykes (Tibaldi 1995). In many volcanic islands these rift zones radiate out from the summit of the volcano and define a triple - rift ("Mercedes Star") geometry, or more - or - less linear two - rift geometries governed by the buttressing effect of older volcanoes (as at Kilauea) or by regional tectonic stresses (as in the Azores and on Karthala). A distinctive precursor of lateral collapse appears to be reorganisation of these rift zones as the edifice becomes weakened and the magmatically- or regionally- controlled stress regime at depth becomes decoupled from the topographically - controlled near - surface stress regime. As dykes pass upwards from the one stress regime to the other they rotate into a new preferred orientation by progressive segmentation, producing en echelon groups of elongate vents. In old volcanoes which have been affected by lateral collapses and subsequently deeply incised these changes are manifested in late dyke and intrusion swarms with distinctive orientations and en echelon geometries: examples are provided by the Presa de los Hornos complex in the Roque Nublo volcano of Gran Canaria; dyke swarms in the Guimar edifice on Tenerife; and dyke swarms in the Monte Amarelo edifice on Fogo. Reorganisation of volcanic riflc zones into new geometries related to developing fault systems has occurred in the Cumbre Vieja volcano, La Palma over the past 7000 years or so (Fig. 2); and in the Pico do Fogo volcano within historic time. Surface rupture by the flank fault systems has occurred much more recently on both of these volcanoes and so it appears that incipient lateral collapses develop first as blind fault systems in the subsurface, and only breach the surface at a later stage.

Other changes, such as the abandonment of shallow magma bodies and an increase in the abundance of xenoliths from the deep crust and mantle lithosphere, as the magma feeding system is destabilised by the increasing instability of the volcano above, may also occur. Incipient, potentially catastrophic instability at steep oceanic island volcanoes can only be reliably identified by a combination of detailed geological mapping, highly precise geochronological work, and geophysical monitoring.

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Fig. 1. Mercalli intensity contours of seismicity associated with the 1949 eruption of the Cumbre Vieja, La Palma, showing displacement of isoseisms to the west of the surface fault break and eruptive vents. After Bonelli (1950)

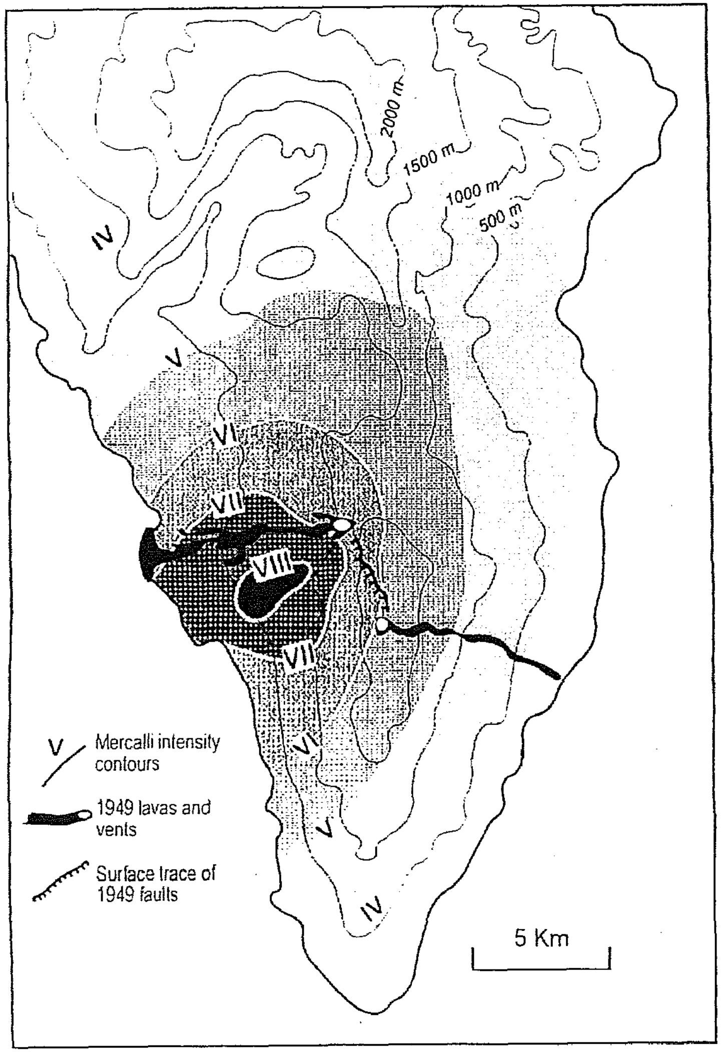

Fig. 2. Change in distribution and orientation of elongate volcanic vents in the central part of the Cumbre Vieja, La Palma, after about 7000 a B.P. Note en echelon groups of vents (all historic) on the western flank of the volcano.