Structural Control of Flank Volcanism in Continental Rifts

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Many volcanoes emerge from the flank (footwall) of normal faults in continental rift zones. Because such locations are commonly topographically high and exhibit minor compressional structures, the association is enigmatic. A simple flexing plate model shows that deformation of a flexurally supported upper crust during normal faulting generates a dilational strain field in the footwall at the base of the crust. This strain field allows cracking and tapping of preexisting melt.

A COMMON OBSERVATION IN REGIONS of continental extension is the occurrence of flank volcanism, in which volcanism and associated shallow level intrusions are found in the footwalls of normal faults. The association is temporal as well as spatial. Volcanism is generally active as long as the fault is active, and, as fault activity migrates, so too does volcanism. These observations suggest that there is a coupling between processes of brittle deformation in the upper crust and those involving magma injection in the lower crust.

We explain this association with the use of a numerical model (*1*) in which the upper crust is modeled as an elastic beam with a reduced effective elastic thickness, and the lower crust behaves as a fluid. Deformation is driven entirely by gravity and includes the modifying effects of erosion and sedimentation.

The temporal and spatial association between normal faulting and volcanism is most evident in regions where crustal extension is active and in its early stages. For example, in the Taupo rift of North Island,. New Zealand, two volcanoes, Mount Tarawera and Mount Edgecumbe, are on the footwall side of the major Edgecumbe-Onepu fault and outside the zone of active rifting (Fig. 1A). The fault last moved in the 1987 Edgecumbe magnitude $M_s \approx 6.3$ earthquake, and it offsets basement by ~1 km (*2*). In the 1987 fault scarp, Holocene soils are interlayered with volcanic ash derived from Mount Tarawera. Moreover, the Taupo eruptive event of ~A.D. 150, considered to be the largest volcanic eruption of the last 7000 years (*3*), appears to have occurred immediately to the southeast (in the footwall) of the main rift-bounding faults.

In the Rungwe volcanic field (Fig. 1B), part of the western arm of the East African rift system (*4*), the oldest source of volcanism associated with the rifting is late Miocene [~7 million years old (Ma)] and is sited on the flank of the rift-bounding Livingstone faults (*4*). Active rifting has migrated toward the axial zone, where a series of Pliocene and Quaternary volcanoes sit in the footwall of the active Mbaka fault system, the most prominent fault system in the axial zone. Extensive volcanism also occurred on the flanks of the Gregory rift [for example, the Kapiti volcanic rocks along the tilted Aberdare Range and basalts along the Nguruman escarpment (*5*)]. Farther north, in the Ethiopian rift, the Gorfu, Entotto, and Gara Mariam centers are further examples of flank volcanism (*6*). In general, volcanic activity throughout the eastern rift follows that of faulting (*5, 6*).

Another example comes from the active Long Valley magmatic complex (Fig. 1C). Present seismic activity under Mammoth Mountain (Figs. 1C and 2D) is confined to a well-defined dike-like shape below about 6 km; above this level, events spread laterally (*7*). Seismic swarms are typical in this region and are generally attributed to the development of a dike (*8*). Mammoth Mountain lies in the footwall of the active Sierra Nevada range-bounding normal fault (*9*), although this relation is partly obscured by the 700,000-year-old caldera rim.

In 1980, a series of moderate earthquakes occurred in the footwall of the active Hilton Creek fault (Figs. 1C and 3) that were characterized by significant non-double-couple focal mechanisms (*10*). Julian (*11*) suggested that these earthquakes were associated with active magmatic intrusion. During the early part of 1990, the resurgent dome within the caldera was extending at a rate five times that of normal (*12*), presumably from the motion and intrusion of magmatic material at depth. Both the resurgent dome and the initial vent for the Plinian deposit of the 700,000-year-old Bishop tuff are in the footwall of the Hilton Creek fault (*13*) (Fig. 1C). We suggest that the volcanic processes and associated seismicity within the Long Valley caldera complex are connected to the evolution of the main Sierra Nevada (Hilton Creek) range-front fault system.

There are many other examples from virtually every rift system in the world. These systems include the Latir volcanic field and the Spanish Peaks complex, which represent the early stage of extension in the Rio Grande rift, United States (*14*); early volcanism along the flanks of the Baikal rift, Soviet Union (*15*); early volcanism along the eastern margin of the Red Sea (*16*); basaltic magmatism along the eastern edge of the Basin and Range province, particularly the St. George field in southwest Utah, which lies in the footwall of the active Hurricane normal fault (*17*); middle Miocene and Pliocene volcanism in the Death Valley region, California (*1, 18*); Mount Etna, Sicily, which has an unusual location on the nonvolcanic side of an island arc (*19*) that may be explained by its position in the footwall of the active Messina normal fault; the Quaternary volcanic Chaine des Puys, which is related to Quaternary normal faulting near Clermont Ferrand that has reactivated structures associated with the Oligocene Limagne graben (*20*); and the large volcanic complexes of Mount Kilimanjaro, Mount Kenya, and Mount Elgon along the Gregory rift, East Africa (*5*).

The approach to modeling these structures follows from that used by King and Ellis (*1*). In the model the x_1 axis is vertical and positive downwards, and the x_3 axis is horizontal. Two horizontal gravitating interfaces are defined. One represents the earth's surface, and the second represents the base of the brittle layer. At $x_3 = -60$ km, the horizontal displacement along a vertical

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