Arc magmatism, calderas, and supervolcanoes

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In the spectrum of volcanological phenomena, caldera-forming explosive volcanism enjoys significant interest from a broad swath of the geological community. Reasons for this interest include the facts that caldera-forming eruptions (CFEs) are associated with extreme hazard and environmental impact at all scales, they are the windows through which we may view batholith formation, and their magmatic systems are vital to the evolution of the continental crust. Recently, attention has focused on CFEs and their relation to supervolcanoes and the volcano-plutonic connection. Over the past six decades, significant progress has been made in understanding the processes of caldera formation, the geometry of subsidence, and the development of associated magmatic systems (see Williams, 1941; McBirney, 1990; Smith, 1979; Hildreth, 1981; Walker, 1984; Lipman, 1997; Cole et al., 2006; and Bachmann et al., 2007, for reviews). However, although fundamental, the broader systemic context of caldera formation has received minimal attention. For instance, beyond the association of intermediate and silicic calderas with active continental margins, little further attention is paid to this fundamental association. This is symptomatic of our efforts to understand calderas; we recognize that the plate tectonic environment is a primary factor in their development, but we rarely attempt to investigate this further, preferring to focus on the eruptive processes, deposits, mechanics, and magmatism of CFEs. To date, the relationship between caldera-forming volcanism and its plate tectonic controls remains largely intuitive, with little hard supporting science. In this issue of Geology (p. 627–630), Hughes and Mahood attempt to redress this balance by investigating the relationship between caldera occurrence and several simple tectonic parameters. Examining calderas from 19 largely circum-Pacific arcs, they found that caldera occurrence positively correlates with convergence rate, crustal composition, and local extension. No relationship is found with subduction obliquity or duration of present arc activity.

No doubt that such a synoptic effort is likely to have some errors of omission and admission. Some might be understandable; the requirement of a caldera results in the omission of large explosive eruptions that did not form calderas at the site of eruption, such as the A.D. 1600 eruption of Huaynaputina (Peru), the 1902 Santa Maria eruption (Guatemala), and the 1932 Quizapu eruption, among others (see Lavallee et al., 2006, and references therein). Others, like the exclusion of the New Zealand arc, will elicit stronger reaction. The Taupo volcanic zone, which is one of the most prolific modern CFE provinces on Earth, exemplifies the situation where magma is erupted as a function of the extension rate in highly extended, young, thin continental crust.

The most intuitive of the correlations offered by Hughes and Mahood (that with convergence rates), if taken simply to equate to subduction-related mantle magma production, ratifies a canon of our science that the flux of basaltic magma is the primary control on the production of the silicic magmatic systems that feed CFEs (e.g., Smith, 1979; Hildreth, 1981). Importantly, Hughes and Mahood restrict the correlation to "normal" arc systems, and draw a distinction with "flare-ups" during which supervolcanic CFEs typically develop.

This is an important distinction because the super-sized nature of supervolcanic systems (Volcanic Explosivity Indices[1] of 8 and above) is thought to require an elevated basaltic flux from the mantle that provides a thermal and mechanical environment supportive of large-scale silicic magma production and storage (Hildreth, 1981; Best and Christiansen, 1991; de Silva and Gosnold, 2007). The largest CFEs, those of supervolcanic proportions, occur during major caldera-forming events that sample the tops off these magma systems. The eruptions may occur at individual centers with protracted histories like Toba (Indonesia) (Chesner et al., 1991), Cerro Galan (Argentina) (Sparks et al., 1985), and Valles (New Mexico) (Self et al., 1986)). Alternatively eruptions may be part of regional episodes of supervolcanism known as ignimbrite flare-ups, where multiple eruptions from spatially and temporally related centers map out the development of an upper-crustal batholith beneath. Such volcanic flare-ups have been described from western North America (Coney, 1972), the Sierra Madre Occidental, Mexico (Ferrari et al. 2002), and the Altiplano Puna volcanic complex of the Andes (de Silva, 1989; de Silva et al., 2006). A plutonic connection to these surface flare-ups may be found in the Sierra Nevada of California (Ducea, 2001) and other cordilleran batholiths (Lipman, 2007). Thermal and mechanical maturation of the crustal column as a result of protracted magmatism has been connoted to be an essential factor in the development of these supervolcanic systems (de Silva and Gosnold, 2007; Lipman, 2007).

This view of supervolcanic systems brings into question the inclusion of the Toba supervolcano by Hughes and Mahood in their analysis. It is also paradoxical to the anti-correlation between the duration of present arc activity and the development of CFEs in the arc systems found by Hughes and Mahood—protracted magmatism should intuitively result in progressively more favorable conditions for silicic magma generation and storage. Resolution of the paradox appears to lie with the realization that it is not simply duration, but the magnitude of the mantle flux that is important, and de Silva and Gosnold (2007) have drawn a distinction between a steady-state arc ("normal" of Hughes and Mahood) and an arc in flare-up mode (Fig. 1); originally articulated by Hildreth (1981) as low-flux and high-flux systems. Under steady-state arc conditions, basaltic magma flux may focus locally to produce CFEs as large as VEI 6 and rarely 7 (10–100 km^3 of magma), but CFEs of supervolcanic proportion are not known. Conversely, under flare-up conditions, triggered by some major change in the mantle magma productivity, such eruptions are the culmination of extraordinary silicic magma productivity that results from the elevated power input from the mantle. Magma production rates in the two modes of arc operation are quite different. The most rapidly developing steady-state arc systems like the Aleutians are estimated to have magma production rates of 1.8×10^{-4} km^3 km^{-1} yr^{-1} (Jicha et al., 2006), while magma production rates during the flare-up of the Altiplano Puna volcanic complex were as high as 6×10^{-3} km^3 km^{-1} yr^{-1} (de Silva and Gosnold, 2007), an order of magnitude higher. One of the consequences of this elevated flux during flare-up mode is that the crust undergoes a thermomechanical evolution that promotes supervolcanic CFEs through the positive feedback between mantle power, magma production, and advection of heat through the crust and the impact on the mechanical strength of the crust

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[1] The Volcanic Explosivity Index (VEI; Newhall and Self, 1982) provides a measure of the magnitude of an eruption based on a combination of erupted tephra volume and eruption plume height. The index uses a semi-quantitative logarithmic scale where each successive value of the index represents 10× greater volume of material erupted. Supervolcanic eruptions are defined as those where at least 1000 km^3 of tephra were produced during the eruption, and these classify as VEI 8 or greater. The largest arc caldera-forming eruption in historic times was the A.D. 1815 eruption of Tambora (Indonesia). Approximately 100 km^3 of tephra was produced, resulting in a VEI 7 classification—an order of magnitude smaller than a supervolcanic eruption. For reference, the A.D. 1980 eruption of Mount St. Helens (Washington, United States) was a VEI ~5 eruption, with only 1 km^3 of tephra.

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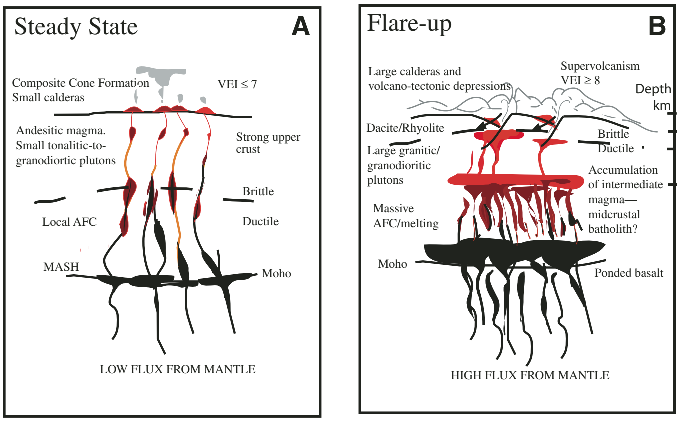

Figure 1. Contrasting behavior of steady-state and flare-up arc magmatic systems and the resulting caldera-forming eruptions. Arcs may switch between these modes due to changes in plate tectonic fundamentals. A: Steady-state refers to the magmatic flux that characterizes the long-term evolution of the volcanic setting. In this case, the low flux from the mantle drives andesite production and the development of composite cones. Rarely, these systems ramp up to produce explosive eruptions of VEI ≤ 7 and small calderas. Small tonalite-to-granodiorite plutons develop beneath these. There is a strong upper crust with midcrustal brittle-ductile transition. B: Flare-ups are transient events of high magmatic flux that punctuate the much lower background steady-state flux. Here the development of supervolcanoes is driven by an elevated power input from the mantle, resulting in progressive thermal and mechanical maturation of the crust. There is a weak upper crust with brittle-ductile transition in the uppermost crust. Large granodioritic and granitic plutons accumulate in the mid and upper crust to feed eruptions of VEI 8 or greater. Depth is scaled to an ~40-km-thick crust. Modified from de Silva et al., 2006. AFC—assimilation and fractional crystallization.

(de Silva et al., 2006; de Silva and Gosnold, 2007). Under a normal arc flux, the lack of correlation between CFEs and the duration of arc activity found by Hughes and Mahood suggests that the feedbacks are muted, and thermal maturation is at a level where the CFE magnitude is buffered at a lower level. This assertion is supported by work at the Aucanquilcha volcanic complex, a normal arc volcanic center neighboring the flare-up of the Altiplano Puna volcanic complex. Here, Klemmetti and Grunder (2008) show that despite 10 Ma of protracted magmatism, peak magmatic rates (assuming a 5-to-1 plutonic:volcanic ratio) of only 8×10^{-5} km^3 km^{-1} yr^{-1} were obtained at Aucanquilcha. No major CFEs have occurred despite a largely dacitic composition akin to the magmas that erupted from the supervolcanoes of the Altiplano Puna volcanic complex.

The work by Hughes and Mahood provides a valuable baseline for discussion of the plate tectonic context of CFEs, and their work will require us to examine our understanding of arc geometry, magmatism, stress state, and their relation to explosive eruptions. These authors should be given kudos for taking this on, and their work should reawaken dormant prejudices. I hope their work will spur more efforts to establish a more systemic understanding of CFEs. The implications of their work for supervolcanic CFEs, like Toba, will no doubt generate considerable discussion.

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