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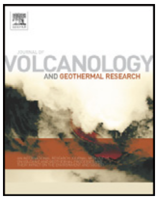

Review

Calderas and magma reservoirs

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A R T I C L E I N F O

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A B S T R A C T

Large caldera-forming eruptions have long been a focus of both petrological and volcanological studies; petrologists have used the eruptive products to probe conditions of magma storage (and thus processes that drive magma evolution), while volcanologists have used them to study the conditions under which large volumes of magma are transported to, and emplaced on, the Earth's surface. Traditionally, both groups have worked on the assumption that eruptible magma is stored within a single long-lived melt body. Over the past decade, however, advances in analytical techniques have provided new views of magma storage regions, many of which provide evidence of multiple melt lenses feeding a single eruption, and/or rapid pre-eruptive assembly of large volumes of melt. These new petrological views of magmatic systems have not yet been fully integrated into volcanological perspectives of caldera-forming eruptions. Here we explore the implications of complex magma reservoir configurations for eruption dynamics and caldera formation. We first examine mafic systems, where stacked-sill models have long been invoked but which rarely produce explosive eruptions. An exception is the 2010 eruption of Eyjafjallajökull volcano, Iceland, where seismic and petrologic data show that multiple sills at different depths fed a multi-phase (explosive and effusive) eruption. Extension of this concept to larger mafic caldera-forming systems suggests a mechanism to explain many of their unusual features, including their protracted explosivity, spatially variable compositions and pronounced intra-eruptive pauses. We then review studies of more common intermediate and silicic caldera-forming systems to examine inferred conditions of magma storage, time scales of melt accumulation, eruption triggers, eruption dynamics and caldera collapse. By compiling data from large and small, and crystal-rich and crystal-poor, events, we compare eruptions that are well explained by simple evacuation of a zoned magma chamber (termed the Standard Model by Gualda and Ghiorso, 2013) to eruptions that are better explained by tapping multiple, rather than single, melt lenses stored within a largely crystalline mush (which we term complex magma reservoirs). We then discuss the implications of magma storage within complex, rather than simple, reservoirs for identifying magmatic systems with the potential to produce large eruptions, and for monitoring eruption progress under conditions where successive melt lenses may be tapped. We conclude that emerging views of complex magma reservoir configurations provide exciting opportunities for re-examining volcanological concepts of caldera-forming systems.

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> *"However, there is a pleasure in recognizing old things from a new point of view." Richard Feynman, 1948*

1. Introduction — why review calderas?

The importance of studying caldera-forming eruptions cannot be under-estimated. Caldera-forming eruptions include some of the largest volcanic events ever to affect the Earth. Many of these have produced large volumes (>100 km^3) of highly evolved crystal-poor melt. As a result, an enduring paradigm of both igneous petrology and volcanology has been one of melt accumulation, evolution and eruption from a single melt-dominated magma chamber. This conceptual metaphor has provided a framework for petrological models of magma evolution and differentiation, and for volcanological models of eruption initiation, magma withdrawal and caldera collapse (Fig. 1). Key features include: (1) development of stably zoned magma chambers by crystal fractionation, where crystal-liquid separation is driven by settling of individual crystals or crystal plumes within a large batch of liquid that cools from the margins inward; (2) eruption initiation by injection of a vertical and pressurized dyke, located either in an axisymmetric position or at the chamber margin; (3) magma withdrawal starting from the top of the melt lens and propagating downward, as evidenced by deposits that are reversely zoned in composition and/or pre-eruptive temperature and pressure; and (4) caldera formation by collapse of an underpressured magma chamber after some fraction of magma has been withdrawn, with the timing of collapse determined by the strength and thickness of the overlying country rock relative to width of the magma chamber.

Over the past few decades, however, detailed volcanological, petrological and geophysical studies of individual (intermediate–silicic) magmatic systems have shown that (1) magma storage regions are composed primarily of crystalline mush (crystals plus interstitial liquid; Fig. 2; e.g., Hildreth, 2004; Hildreth and Wilson, 2007; Lipman, 2007; Bachmann and Bergantz, 2008; Reid, 2008; Bachmann, 2010; Deering et al., 2011; Walker et al., 2013; Simon et al., 2014), (2) large melt volumes may be assembled rapidly (Charlier et al., 2005; Wilson and Charlier, 2009; Druitt et al., 2012; Allan et al., 2013; Gebauer et al., 2014; Simon et al., 2014; Wotzlaw et al., 2014), (3) caldera-forming

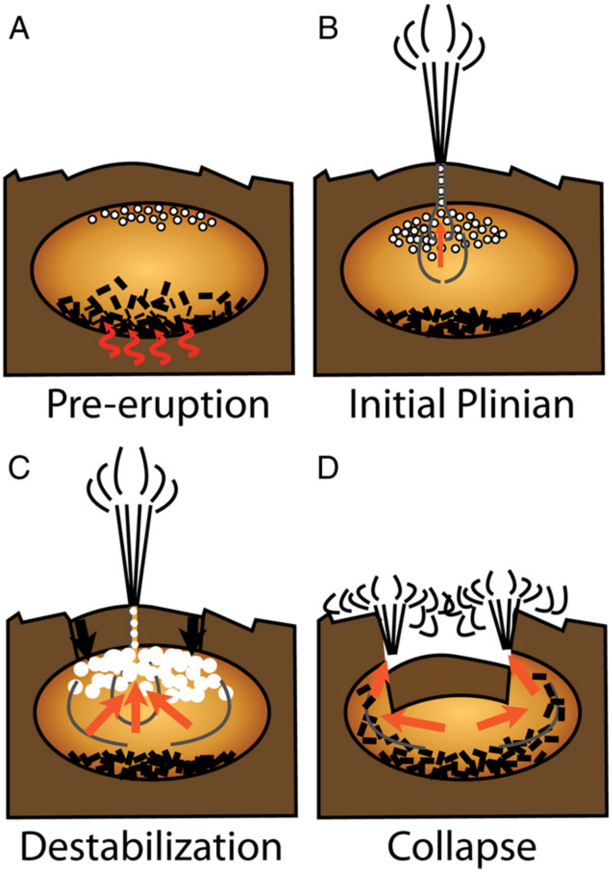

Fig. 1. The Standard Model of caldera formation. (A) Stably stratified magma chamber forms over thousands of years by crystal settling and upward migration of volatiles. (B) Eruption starts with Plinian activity through a single vent, driven primarily by volatile exsolution. (C) Evacuation of magma causes under-pressurization and destabilization of the reservoir. (D) Caldera forms by roof collapse.

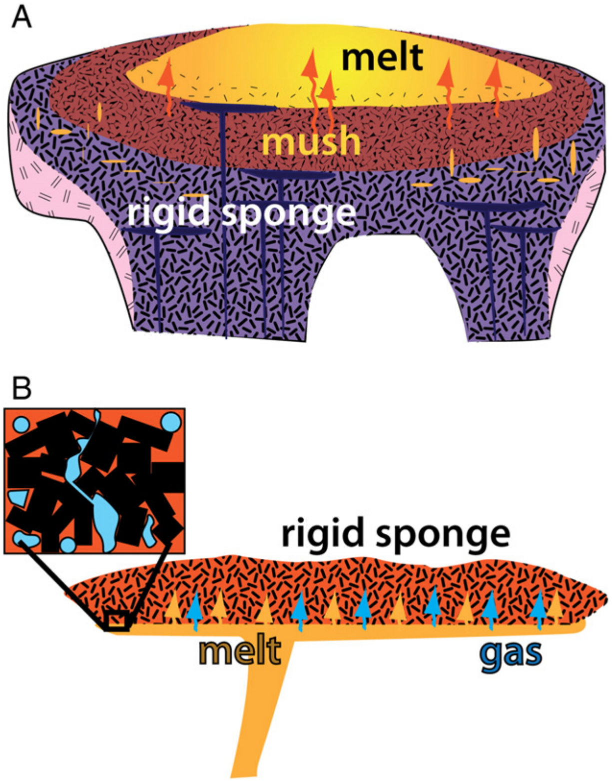

Fig. 2. End member models of caldera-producing magmatic systems. (A) Crystal-poor (CR), and often zoned, eruptions are fed from a single melt body contained within a much larger and more crystalline system comprising a crystal mush (~50% crystals) and surrounding rigid sponge (>65% crystals); modified from Hildreth (2004). (B) Crystal-rich (CR) eruptions occur by rejuvenation of a near-rigid crystal mush (by input of melt and/or gas); modified from Bachmann and Bergantz (2006); Huber et al. (2011).