Insight into subvolcanic magma plumbing systems

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The Island of Hawaii, which is among the best-studied volcanic islands on Earth, provides lush ground for debates in volcanology that focus on how magmatic systems evolve in space and time. Hawaiian volcanoes evolve through four eruptive stages that are characterized by distinct composition, magma supply rate, and degree of mantle melting (e.g., Clague, 1987a, 1987b, and references therein). The pre-shield stage, first identified on Loihi Seamount (Moore et al., 1982), erupts mostly alkalic basalt and basanite that reflect a small magma supply and derive from relatively small degrees of mantle melting. During the shield stage, tholeiitic basalt (like that currently erupted at Kilauea and Mauna Loa) dominates, and reflects comparatively high magma supply and the greatest degree of mantle melting; it is during the shield stage that >95% of the volume of the volcanic edifice is constructed. Transitional and alkalic basalt characterize the post-shield stage, which reflects a return to smaller magma supply and a smaller degree of mantle melting. More evolved compositions (e.g., hawaiite, mugearite, trachyte) are also typically associated with this stage. The final stage, the post-erosional or rejuvenated stage, erupts alkalic basalt, basanite, and nephelinite. These eruptions represent the smallest magma supply and smallest degree of mantle melting.

Magma supply rates of the four stages have been used to infer the location of the associated subvolcanic magma plumbing system (Fig. 1). Evidence from xenoliths erupted in lavas from each stage also delimits magma accumulation depths because magma entrains xenoliths only from the level of the magma reservoir or shallower (Clague, 1987a, 1987b). The relatively high magma supply that characterizes the shield stage provides the thermal impetus to maintain a shallow-level magma plumbing system (3–7 km below the surface), and only xenoliths of shallow origin have been identified (e.g., basaltic xenoliths interpreted to be pieces of dikes or sills [Clague, 1987a]). It is also likely that a deeper chamber is present during the shield stage (e.g., Wright, 1971; Bohrson and Clague, 1988). As magma supply decreases during the shield to post-shield transition, this shallow system likely crystallizes. The xenolith population for the post-shield stage includes crystalline inclusions such as cumulate dunite or websterite that form between 4.5 and 9 kbar, based on phase equilibria constraints and trapping pressures of CO_2 inclusions (Bohrson and Clague, 1988; Roedder, 1965). Rare gabbro from layer 3 of the oceanic crust has also been identified (Clague, 1987a). Thus, a likely location for the deeper chamber is at the base of the oceanic crust. The relatively low magma supply associated with the pre-shield and rejuvenated stages apparently precludes any persistent crustal magma plumbing system; spinel lherzolite and garnet pyroxenite xenoliths originate in the mantle based on geobarometry, compositional characteristics, and other constraints (e.g., Frey and Roden, 1987; Frey, 1982).

Although rare on Hawaiian volcanoes, the more evolved compositions also provide insight into plumbing system dynamics. Early post-shield stage lavas from Mauna Kea, erupted between 250 and 70–65 ka, include transitional and alkalic basalts of the Hamakua volcanics. Between 65 and 4 ka, magma supply diminished and likely led to the thermal death of the shallow-level magma reservoir. The principle site of magma accumulation apparently moved to near the base of the oceanic crust, where more silica-rich compositions (hawaiite and mugearite of the Laupahoehoe volcanics) formed (Wolfe et al., 1997). Support for deepening of the principle accumulation zone is found in leucocratic xenoliths, interpreted to be the plutonic equivalent of hawaiite and mugearite, that formed near the crust-mantle boundary (Fodor, 2001). At Hualalai volcano, trachytes, which are the most evolved volcanics, erupted between ca. 114 and 92 ka during the shield to post-shield transition (ca. 130 and 100 ka; Moore and Clague, 1991). Isotopic and petrologic data suggest that the trachytes formed in a shallow magma chamber by fractional crystallization of alkalic basalt parental magma (Cousens et al., 2003). Fine-grained leucocratic xenoliths (e.g., diorites, monzodiorites) erupted in summit deposits are the plutonic equivalent of mugearite, a composition that has not been identified among erupted products but is intermediate between alkalic or transitional basalt and trachyte. Parental magma to these xenoliths is most likely transitional to alkalic basalt that evolved near the crust-mantle boundary (Shamberger and Hammer, 2006).

An interesting study by J. Vazquez, P. Shamberger, and J. Hammer (Vazquez et al., 2007, this issue) uses dating of zircon by high-resolution ion microprobe to provide insight into the timing of formation of evolved magmas on Mauna Kea and Hualalai. ^{238}U-^{230}Th zircon ages from

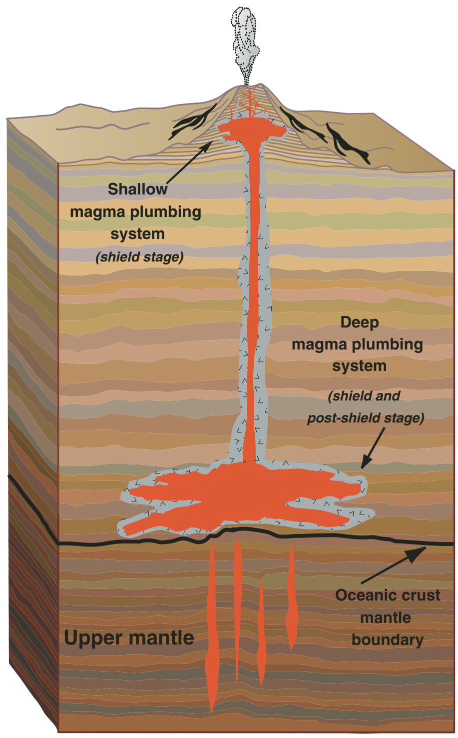

Figure 1. Schematic illustration of deep and shallow magma plumbing systems associated with shield and post-shield stages of Hawaiian magmatism. Relatively low magma supply associated with pre-shield and rejuvenated stages precludes persistent crustal plumbing systems. Figure modified after Spera and Bohrson (2004).

Mauna Kea diorite cluster at ca. 125 and 65 ka, and are interpreted to reflect a dynamic crystallization environment during the transition between Hamakua and Laupahoehoe volcanism. The ~60 k.y. difference in apparent ages of the zircon populations may reflect a long episode of crystallization of a single magma batch. Alternatively, the older population may provide evidence of zircon formation in an older but apparently related magma, followed by recycling of zircon into a younger magma batch. Zircons from Hualalai leucocratic xenoliths cluster at ca. 41 and 257 ka, times that are much earlier than (~120 k.y.) and much later than (~60 k.y.) the shield to post-shield transition. Despite a possible petrogenetic link between the xenoliths and trachyte (Shamberger and Hammer, 2006), these ages are also very different from the period of major trachytic volcanism. Multiple episodes of differentiation to intermediate and evolved compositions clearly occurred on Hualalai, although there appears to be no extrusive age equivalent for the dated xenoliths. If the older zircons reflect evolution from transitional or alkalic basalt, then the shield to post-shield transition on Hualalai may have been protracted, and deep and shallow magma chambers may have existed simultaneously. Alternatively, shield-stage tholeiitic parental magma that underwent fractionation in a deep chamber may have produced transitional basalt that differentiated to form the xenoliths. Regardless of the origin of the xenoliths, one of the intriguing outcomes of this work is recognition of the potentially complex geometry of the subvolcanic plumbing system.

Interpretation of zircon ^{238}U-^{230}Th ages and their relationships to associated magmatic processes has illuminated understanding of, among other issues, the efficacy and timing of crystal entrainment (e.g., antecryst, phenocryst, xenocryst) in magmatic systems, accumulation and residence times of magmas, and the structural complexity of subvolcanic plumbing systems (e.g., Reid et al., 1997; Bacon and Lowenstern, 2005; Charlier et al., 2005). As more age data become available and are integrated with other constraints such as thermal and chemical modeling of magmatic systems (e.g., Annen et al., 2006; Spera and Bohrson, 2001, 2002), there emerges the potential to develop snapshots in time of the physical, chemical, and thermal state of a magmatic system. Integration of these snapshots allows development of models for how magma plumbing systems respond to changes in time-integrated variations in magma supply, heat and mass transport, and other relevant variables. While this endeavor holds great potential and is a most exciting effort in volcanology, it is clearly not without challenges. Foremost among these, in the study of volcanic systems, is the incomplete record of magmatism. The nature of edifice development obscures a great deal of the eruptive history. Intrusive to extrusive ratios (e.g., White et. al., 2006) highlight the additional complication that much of the intruded volume does not erupt, and thus a great deal of the magmatic history is recorded only in the subsurface. Xenoliths can provide critical constraints about magmatism, but application of what is learned through the study of these small pieces of a subvolcanic system to broader spatial and temporal domains is limited. Deciphering the fingerprints of individual magmatic processes, such as magma recharge and crustal assimilation, and the chronology of these processes in a complex magmatic system, also remain a challenge, but exciting studies that integrate in situ major and trace element and isotopic studies of minerals and melt inclusions with whole-rock analyses and field campaigns are providing an unprecedented record of how magma bodies form and evolve. Finally, the focus of Vazquez et al. on the shield to post-shield transition also highlights an ongoing endeavor in the study of ocean islands. Changes in magma supply, composition, and other characteristics of the four stages of Hawaiian volcanism allow exploration of the composition of plume components, as well as the structure and melting dynamics of the plume (e.g., DePaolo et al., 2001). Better documentation of the transitions between stages should further illuminate how plume structure, composition, and behavior contribute to the observed volume and compositional variations among Hawaiian volcanoes.

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