Learning to recognize volcanic non-eruptions

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An important goal of volcanology is to answer the questions of when, where, and how a volcano will erupt—in other words, eruption prediction. Generally, eruption predictions are based on insights from monitoring data combined with the history of the volcano. An outstanding example is the A.D. 1980–1986 lava dome growth at Mount St. Helens, Washington (United States). Recognition of a consistent pattern of precursors revealed by geophysical, geological, and geochemical monitoring enabled successful predictions of more than 12 dome-building episodes (Swanson et al., 1983). At volcanic systems that are more complex or poorly understood, probabilistic forecasts can be useful (e.g., Newhall and Hoblitt, 2002; Marzocchi and Woo, 2009). In such cases, the probabilities of different types of volcanic events are quantified, using historical accounts and geological studies of a volcano's past activity, supplemented by information from similar volcanoes elsewhere, combined with contemporary monitoring information.

During a volcanic crisis that involves magmatic activity (as distinct from, for example, a purely hydrothermal or tectonic process), a critical question is: Will magma reach the surface? This issue is at the root of any societally useful assessment of eruption potential and effects (e.g., Newhall and Hoblitt, 2002) and, therefore, should control the level of the response. History is replete with examples of volcanic crises that did not culminate in magmatic eruptions: Mount Baker, Washington, in 1975 (Frank et al., 1977); Akutan and Iliamna, Alaska, in 1996 (Lu et al., 2000; Roman et al., 2004); Iwate, Japan, in 1998 (Aizawa et al., 2009); and Fourpeaked, Alaska, in 2006 (Neal et al., 2009). Some crises have involved closing areas to the public or, in extreme cases, mandatory evacuations. For example, 73,000 people were removed from the island of Guadeloupe for several months in response to the 1976 unrest at Grande Découverte–La Soufrière (Boudon et al., 2008). These measures caused economic loss and undermined the credibility of scientists and officials, but probably would have saved lives had magma erupted at the surface (Marzocchi and Woo, 2009).

With such high stakes, how do we answer the question of whether magma will reach the surface during unrest? One requirement is monitoring the geophysical, geochemical, and geological manifestations of magmatic activity. Precursory unrest may follow a recognizable pattern that is indicative of likely future activity (Sandri et al., 2004), as at Mount St. Helens during the 1980s (Swanson et al., 1983). More often, historical activity and monitoring resources at a volcano are insufficient to identify such patterns. It is therefore important for the international community to build a comprehensive catalog of volcanic unrest that can be used in comparative investigations to better forecast of the outcome of a volcanic crisis. One such catalog (Newhall and Dzurisin, 1988) suggests that just 1–5 of 10 episodes of unrest at calderas result in any kind of eruption, with the value lowest in silicic centers and highest at mafic volcanoes, but that statistic does not distinguish between magmatic and phreatic activity (both, of course, can cause fatalities and economic loss), and it is skewed by a lack of reporting of non-eruptive unrest. A more comprehensive catalog being compiled by the World Organization of Volcano Observatories (www.wovodat.org) is benefitting from renewed interest in non-eruptive volcanic crises (e.g., the session *'Failed' Magmatic Eruptions: When Unrest Leads to Quiescence*, at the Fall meeting of the American Geophysical Union, San Francisco, California, 15–19 December 2008).

In addition to eruptive history and monitoring data, eruptive potential estimates can be informed by an understanding of the physical process of magma ascent through theoretical, laboratory, and field studies. Such research usually focuses on dike emplacement (which is common at mafic volcanoes) rather than intrusion into a preexisting conduit or cryptodome, because tabular intrusions are easily modeled using the principles of linear elastic fracture mechanics (e.g., Pollard, 1987; Rubin, 1995). Studies of the conditions of dike propagation versus arrest suggest that many factors can cause a dike to stall at depth; for instance, barriers created by stress conditions or mechanical anisotropy in host rock (Gudmundsson, 2002), insufficient volume or driving pressure for crack propagation (Taisne and Tait, 2009), inelastic processes at the dike tip (Rubin,1993), and insufficient dike width to overcome cooling and viscosity effects (Wilson and Head, 1981).

From field observations of dikes exposed at less than a few hundred meters depth, it is apparent that most dikes stalled before reaching the surface (e.g., Gudmundsson et al., 1999; Marinoni and Gudmundsson, 2000). Historical volcanic activity supports this finding. For example, only 9 of the 20 episodes of dike intrusion during 1975–1984 rifting at Krafla, Iceland, resulted in eruption (Sturkell et al., 2006), and non-eruptive intrusions have dominated magmatic activity at Kīlauea volcano, Hawai'i, for years at a time (Klein, 1982). Dikes that reached the surface are, however, often common beneath small-volume basaltic eruptive centers (e.g., Keating et al., 2008).

One of the most spectacular exposures of shallowly emplaced dikes is at Miyakejima volcano, Japan. The summit of Miyakejima collapsed in A.D. 2000 when magma withdrew from beneath the volcano to feed a large flank intrusion and submarine eruption (Nakada et al., 2005). The resulting outcrop exposed more than 165 dikes in a several-hundred-meter-high vertical scarp. Geishi et al. (2010, p. 195 in this issue of *Geology*) report that only ~7% of the dikes were connected to surface eruptive vents. Some of these dikes may have fed eruptions on the flanks of the volcano, but fewer than 30 eruptive fissures are exposed on the flanks of Miyakejima (although additional fissures could be covered by young lava flows or may have been destroyed during the collapse). The observations of Geishi et al. clearly demonstrate that most dikes at Miyakejima did not erupt, even if they ascended to within tens of meters of the surface.

Geishi et al. also examine thickness variations in the best dike exposures and find that arrested dikes ("non-feeders") tend to thicken steadily with shallowing depths. This observation is consistent with theory (Pollard and Holzhausen, 1979), analogue experiments (Rivalta and Dahm, 2006), and field studies (Poland et al., 2008) and suggests increased overpressure within an ascending dike due to a combination of volatile expansion within the magma and decreasing host rock stiffness (volcanic deposits tend to be poorly consolidated at shallow depths). In contrast, dikes that fed surface eruptions ("feeders") at Miyakejima have a relatively constant thickness with depth, and flare within a few tens of meters of the surface, similar to the thickness distributions observed by Keating et al. (2008) in dikes that fed small-volume cinder cone eruptions. Thickness differences probably reflect that feeder dikes record the integrated effects of both emplacement and inelastic processes associated with eruption (e.g., wall rock erosion, multiple magma pulses, etc.; Keating et al., 2008), whereas non-feeder thickness is controlled by elastic deformation of the host rock in response to magma overpressure.

The results of Geishi et al. are an important step toward quantifying the probability that an intrusion will erupt at mafic volcanoes similar to Miyakejima, as well as identifying the differences between eruptive and non-eruptive intrusions. Rarely are so many feeder- and non-feeder dikes observed in such close proximity; thus, the Miyakejima exposure offers an excellent opportunity for assessing models of dike emplacement, arrest, and eruption. Future research at Miyakejima should focus on why some dikes reached the surface and others did not. For instance, analysis of feeder and non-feeder dike compositions can test for systematic differences in magma viscosity, volatile content, and other parameters. During a volcanic crisis, it is, of course, difficult to determine the physical and chemical properties of ascending magma, and volcanologists must rely on monitoring proxies like ground deformation, seismicity, and gas emissions to infer dike characteristics (e.g., Nishimura, 2006). Combining insights from spectacular exposures like that at Miyakejima with laboratory and theoretical work will ultimately establish better connections between monitoring data and magma ascent, bringing us closer to the goal of distinguishing between volcanic crises that will result in eruption and those that will not.

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