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Bayesian estimation of magma supply, storage, and eruption rates using a multiphysical volcano model: Kīlauea Volcano, 2000–2012

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A B S T R A C T

Estimating rates of magma supply to the world's volcanoes remains one of the most fundamental aims of volcanology. Yet, supply rates can be difficult to estimate even at well-monitored volcanoes, in part because observations are noisy and are usually considered independently rather than as part of a holistic system. In this work we demonstrate a technique for probabilistically estimating time-variable rates of magma supply to a volcano through probabilistic constraint on storage and eruption rates. This approach utilizes Bayesian joint inversion of diverse datasets using predictions from a multiphysical volcano model, and independent prior information derived from previous geophysical, geochemical, and geological studies. The solution to the inverse problem takes the form of a probability density function which takes into account uncertainties in observations and prior information, and which we sample using a Markov chain Monte Carlo algorithm. Applying the technique to Kīlauea Volcano, we develop a model which relates magma flow rates with deformation of the volcano's surface, sulfur dioxide emission rates, lava flow field volumes, and composition of the volcano's basaltic magma. This model accounts for effects and processes mostly neglected in previous supply rate estimates at Kīlauea, including magma compressibility, loss of sulfur to the hydrothermal system, and potential magma storage in the volcano's deep rift zones. We jointly invert data and prior information to estimate rates of supply, storage, and eruption during three recent quasi-steady-state periods at the volcano. Results shed new light on the time-variability of magma supply to Kīlauea, which we find to have increased by 35–100% between 2001 and 2006 (from 0.11–0.17 to 0.18–0.28 km^3/yr), before subsequently decreasing to 0.08–0.12 km^3/yr by 2012. Changes in supply rate directly impact hazard at the volcano, and were largely responsible for an increase in eruption rate of 60–150% between 2001 and 2006, and subsequent decline by as much as 60% by 2012. We also demonstrate the occurrence of temporal changes in the proportion of Kīlauea's magma supply that is stored versus erupted, with the supply "surge" in 2006 associated with increased accumulation of magma at the summit. Finally, we are able to place some constraints on sulfur concentrations in Kīlauea magma and the scrubbing of sulfur by the volcano's hydrothermal system. Multiphysical, Bayesian constraint on magma flow rates may be used to monitor evolving volcanic hazard not just at Kīlauea but at other volcanoes around the world.

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1. Introduction

The rate at which magma is supplied to a volcano plays a direct and fundamental role in controlling eruptive style, duration, and volume (Dvorak and Dzurisin, 1993). Yet, magma supply rate (MSR) – and changes in MSR which drive evolving eruption hazard – must be inferred indirectly and as a result may be known only approximately.

Multiphysical, physics-based forward models can be used to relate the physics of magma ascent and eruption with a wide range of observations (Anderson and Segall, 2011). Most simply, conservation of mass dictates that MSR be balanced by rates of magma storage and eruption. By estimating storage and eruption rates, it is therefore possible to constrain MSR (Swanson, 1972; Dvorak and Dzurisin, 1993). At reasonably well-monitored volcanoes, magma storage rates may be obtained from observations of ground deformation, and eruption rates obtained from the volumes of erupted

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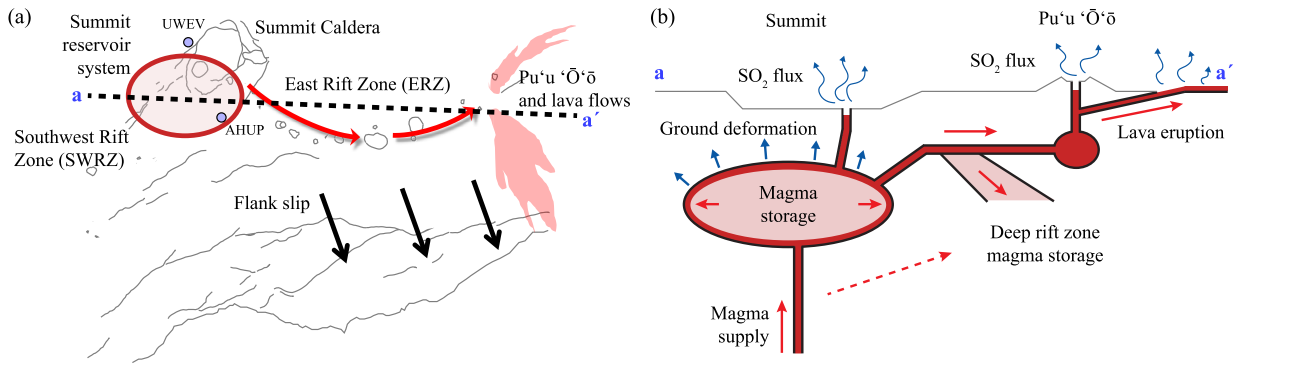

Fig. 1. Map of Kīlauea's summit (a) and schematic cross section (b) showing conceptual model geometry. Magma transport and storage regions and lava flows are schematic only. Dashed line in (b) indicates possible alternate path of magma into the deep rift (both are consistent with the mathematical model design). The lava lake shown in (b) did not exist prior to 2008.

products or through a proxy, such as gas or thermal emission rates. These calculations additionally require independent knowledge of various properties of the volcanic system, such as the magma's volatile content (needed to relate gas emissions with eruption rate). A probabilistic framework makes it possible to include uncertainties associated with both data and independent information in estimates of MSR, and to quantitatively separate the effects of uncertainties from actual changes in supply rate, enhancing our ability to understand and forecast changing volcanic hazard.

Bayes' Theorem allows us to combine a model of the volcanic system – capable of predicting observed data – with independent *a priori* (prior) information in order to formulate posterior probability density functions (PDFs) that characterize our knowledge of model parameters, such as magma supply rate, and their associated uncertainty. In the Bayesian approach, uncertainties in data and prior information are described probabilistically. In contrast with the common approach of fixing "nuisance" model parameters to assumed values, prior distributions for all parameters take the form of PDFs. In this work we construct prior PDFs directly from the results of previous quantitative studies; as such, these priors are not subjective, except to the extent that they must usually be constructed from discrete and sometimes conflicting published values. Posterior PDFs describe our ability to resolve model parameters given the ability of the model to fit observed data, and the independent constraint offered by the prior PDFs. Multiphysical volcano models are well-suited for Bayesian analysis, as they are capable of relating magma physics with a wide range of observations using a relatively simple model parameterization (Anderson and Segall, 2011, 2013).

Kīlauea Volcano, believed to be fed by an upwelling plume originating within the mantle (Wolfe et al., 2009), is the youngest sub-aerial volcano in the Hawaiian–Emperor chain. Kīlauea (Fig. 1) has been in semi-continuous eruption from East Rift Zone (ERZ) vents since 1983 and is one of the world's most comprehensively-monitored volcanoes, offering an outstanding opportunity to estimate time-variable rates of magma supply, storage, and eruption at an extraordinarily active volcano. Observations suggest that the volcano's MSR has waxed and waned during 2000–2012. Following long-term subsidence of the broader summit region and Southwest Rift Zone (SWRZ) during the 1990s at up to ∼5 cm/yr (Fig. 2), rapid inflation and high rates of CO_2 and SO_2 emissions were believed to be associated with a surge in magma supply beginning in ∼2003 (Poland et al., 2012); summit deflation associated with eruptive activity followed the supply surge, and although inflation resumed in ∼2010 it was associated with low rates of ERZ effusion (Poland, 2014) possibly caused by low rates of magma supply. Existing constraints on MSR are largely empirical, however, since the data sets on which these inferences are based are treated independently rather than as a part of a coherent model. Coupling

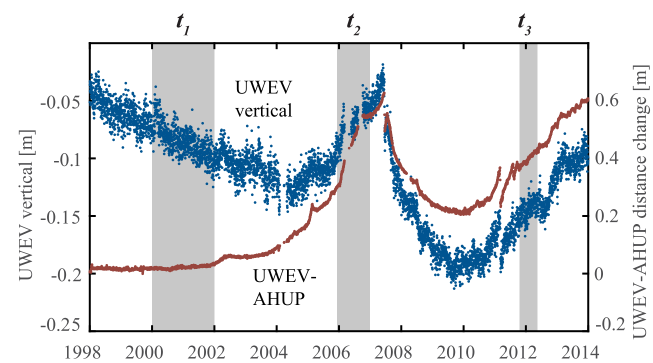

Fig. 2. Summit deformation and relationship to time periods examined in this study (shaded gray bars). GPS station locations are shown in Fig. 1.

a multiphysical model of the system with diverse observations in a Bayesian inverse procedure – and incorporating recent advances in our conceptual understanding of Kīlauea along with new techniques for measuring the volcano's storage and eruption rates – should yield improved quantitative understanding of the volcano's time-variable magma flow rates.

2. Model and observations of Kīlauea Volcano

The basic conceptual model of Kīlauea Volcano was introduced by Eaton and Murata (1960). Magma supplied to Kīlauea from a source in the mantle rises into summit storage reservoirs, in which it accumulates and from which it may erupt at the surface or move laterally along rift zones, resulting in intrusions and eruptions tens of km from the summit. Although punctuated by dike intrusions and other transient behavior, during eruptions the system often enters a state of quasi-steady magma flux (Swanson, 1972; Tilling et al., 1987). Since the 1983 onset of Kīlauea's currently ongoing ERZ eruption, magma has, for the most part, passed from depth through the summit reservoir and migrated subhorizontally along the ERZ for ∼20 km before erupting as lava flows near the Pu'u 'Ō'ō eruptive vent. A second eruptive vent opened in 2008 at Kīlauea's summit; this vent exhibits a clear magmatic connection with the summit reservoir and ERZ vent (Rowe et al., 2015; Thornber et al., 2015; Patrick et al., 2015) and currently hosts an active lava lake which emits a persistent plume of gas and minor amounts of tephra (Orr et al., 2012).

Decades of ground deformation, seismic, gravity, and petrologic data at Kīlauea have revealed that magma storage at the volcano occurs principally in the summit reservoir system, the shallow rift zones, and possibly within the deeper rifts. Summit storage occurs in a complex of reservoirs at different depths (Baker and Amelung, 2012; Poland et al., 2014). In the shallow rift zones, magma stor-