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Volcano–tectonic interactions as triggers of volcanic eruptions

Andrea Gabrieli [a,b,c,*], Lionel Wilson [a,b], Stephen Lane [a]

[a] Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK
[b] Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Mānoa, 1680 East-West Road, Honolulu, HI 96922, USA
[c] Department of Geology and Geophysics, University of Hawai'i at Mānoa, 1680 East-West Road, Honolulu, HI 96922, USA

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ABSTRACT

Surface displacements and edifice deformations at active volcanoes can occur when magma reservoirs begin to inflate as new magma enters them. Volcanoes are also subjected to a variety of external lithospheric stresses that are thought to be responsible for triggering volcanic unrest or modifying ongoing activity. However, despite many observations, it is uncertain whether these phenomena can actually interfere with magma chamber dynamics since it is not clear why some volcanoes are more subjected to these interactions than others. In order to determine whether external stresses interfere with volcanic activity, a viscoelastic 3D Finite Element Mogi-based model of Kīlauea volcano's magma chamber was implemented. First, the model was used to replicate an inflation cycle without external stresses. Its results were then compared with the ones obtained if the same model was subjected to tidal stress modulation and a strong (M_w = 7.7) tectonic earthquake. The model showed that tidally-induced pressurization is not sufficiently large to modify the pressure in a 5 km deep volcanic magma chamber, but it suggested how the magma chamber pressure build-up rate can be influenced by tidal pressurization and thus why some volcanoes seem to experience tidal interferences more than others. Furthermore, the model's results suggested why magma chambers are about the same size as calderas both on the Earth and on other Solar System silicate planets. System. Finally, it was used to propose an explanation of why a short-lived eruption at Kīlauea volcano, Hawai'i, began 30 min after the 1975 magnitude 7.7 (M_w) Kalapana earthquake.

1. Introduction

Volcano–tectonic interactions have only relatively recently started to be extensively investigated by geoscientists (Watt et al., 2008). There is evidence that earthquake activity is significantly correlated with volcanic eruptions both in time (Linde and Sacks, 1998) and space for the far-field (200–800 km) (Lemarchand and Grasso, 2007; Manga and Brodsky, 2006) and the near-field (Alam and Kimura, 2004). Also there is a positive correlation between the size of earthquakes and both the V.E.I. index (Marzocchi et al., 2002) and the volume of erupted material (Walter and Amelung, 2006; Walter, 2007) in volcanic eruptions. In particular, regional earthquakes may trigger volcanoes to erupt. Pinatubo's (Philippines) 1991 (Bautista et al., 1996) and Puyehue-Cordon Caulle's (Chile) 1960 (Lara et al., 2004) eruptions have all been related to some extent to strong regional earthquakes. In addition, it has been inferred that ongoing volcanic activity could be enhanced by tectonic earthquakes. For example, it was observed that two volcanoes on Java increased their activity after a Magnitude 6.4 offshore earthquake (Harris and Riepepe, 2007) and that volcanic tremor signals at Stromboli, Italy, were modified after tectonic earthquakes (Fattori Speranza and Carniel, 2007).

Nevertheless, such volcano–tectonic interactions are still not entirely understood. In fact, there is much disagreement on the way tectonic earthquakes are linked to volcanoes. One of the most accepted reasons for dynamic triggering is an increased nucleation of bubbles (Manga and Brodsky, 2006). Moreover, some geoscientists stress that volcanic eruptions are mainly triggered by compressive stresses that act on the magma chamber (Nakamura, 1975; Nostro et al., 1998) and others emphasize that decompressive stresses are more important because they enable more magma to enter the chamber, inflating it (Bursik et al., 2003; Walter and Amelung, 2006). Finally, Hill et al. (1994) cast doubt on the two previous hypotheses and suggest that compression-decompression cycles of seismic waves determine the formation of micro factures that facilitate the intrusion of dykes in the shallow crust.

* Corresponding author at: Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Mānoa, 1680 East-West Road, Honolulu, HI 96922, USA
E-mail address: edu">gabrieli@higp.hawaii.?edu (A. Gabrieli).

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However, earthquakes are not the only external lithospheric phenomena that have been considered as triggers of volcanic eruptions. The unloading of volcanic edifices because of volcanic landslides and deglaciation, lunisolar Earth and ocean tides, and deep atmospheric high-low pressure variations such as those related to typhoons, cyclones and hurricanes have been thought to play a role in triggering or modifying volcanic activity (Stein, 1999; Hill et al., 2002), providing that the volcano is "*in a nearly critical state*" (Schimozuru, 1987).

There are many examples showing that the displacement of a huge amount of rocks during a landslide can lead to an explosive decompression if the slide fault is deep enough to intersect the magma beneath the surface (Parfitt and Wilson, 2008). Furthermore, although it is accepted that deglaciation causes unloading of both volcanic edifices (Maclennan et al., 2002) and the mantle, which in turn increases the melting rate of the rocks (Schimdt et al., 2013) and modifies eruption rates and magma compositions (Pagli and Sigmundsson, 2008), whether lithospheric stresses related to ocean and Earth tides and atmospheric pressure changes are sufficiently large to affect volcanic states is still widely debated. The static stress drop of a strong tectonic earthquake may vary between 10^6 and 10^7 Pa, whereas the tidal load stress is estimated to be 5 orders of magnitude smaller (Varga and Grafarend, 1996). Nevertheless, statistical analysis of the times of eruptive and seismic events conducted at Mount Saint Helens, U.S.A. (McNutt and Beavan, 1984), Stromboli and Etna, Italy (Johnston and Maulk, 1972; Sottili et al., 2007), Kīlauea, Hawai'i (Rydelek et al., 1988), Mayon, Philippines (Jentzsch et al., 2001) and on Jupiter's moon Io (Peale et al., 1979) suggested that a correlation with the tidal stress modulation might exist. There is also other evidence of rock rheology being affected by tides due to pore pressures (Kümpel, 1997). Furthermore, a significant correlation between all of the 52 historic Kīlauea volcano eruptions and the fortnightly Earth tide has been found (Dzurisin, 1980) and daily fluctuations of the level of the Halema'uma'u lava lake have been observed and linked to Earth tides (Schimozuru, 1987). Nonetheless, although a correlation was found, there is no evidence that tidal stresses may be responsible for triggering an eruption. Furthermore, the same correlation was not found at Mauna Loa volcano, Hawai'i, despite its proximity to Kīlauea (Schimozuru, 1987). However, if lunisolar Earth and ocean tides influenced the inner dynamics of the magma in the Hawaiian volcanoes or in any other terrestrial volcano, they would be significantly related to whether the magma chamber was highly pressurized (Schimozuru, 1987) and to the latitude of the volcano, because tidal stress is a function of latitude (Varga and Grafarend, 1996).

All these phenomena have been studied in the last decade and many of the effects that they cause on volcanic systems have been described. Nevertheless, the physical mechanisms that rule such interactions are still uncertain. The main problem is that all these external pressure sources might play a role in triggering volcanic activity, providing that the volcano is "in a nearly critical state" (Schimozuru, 1987) and what "critical state" means quantitatively is not known. Therefore, a Finite Element Mogi-based model of Kīlauea volcano's magma chamber was developed for this project to determine whether lithospheric stresses disturb the activity state of volcanoes by firstly determining the eruption-triggering "critical state" and secondly by analyzing how external stresses might affect this value.

2. Methods

One of the most commonly monitored geophysical phenomena is deformation because modifications of the shape of the volcanic edifice are easily measured and generally indicate underground magma movements and pressure variations in the magma reservoir (Scandone and Giacomelli, 2004). If ground deformation due to a new magmatic intrusion is considered, the most common scenario is that the displacement measured at the surface starts as new magma begins to enter the plumbing system of the volcano and to fill the magma chamber. As soon as the pressure within the magma chamber is sufficiently high to cause a rupture in the surrounding country rock, a failure may occur and a new dyke may start to propagate causing a decrease of the pressure within the magma chamber and eventually a deflation of the whole volcanic edifice.

The rate and the extent of these ground deformations depend on many elements such as the geometry of the volcano, the rate of intrusion, and the depth of the magma reservoir. At Kīlauea volcano the average horizontal deformation rate measured with two GPS stations 8 km apart on opposite sides of the caldera (USGS, 2014) is 0.1 m/year (Poland et al., 2012).

Based on the work of Yamakawa (1955), who applied elasticity theory to a spherical magma body, Mogi (1958) showed that the vertical and horizontal displacements of the ground surface could be related to the change in internal pressure of the chamber, ΔP and to the change in volume, ΔV. Volume and pressure changes of the magma reservoir are linked together by the Mogi equations and in turn are linked to the crustal strength of the country rock (Newman et al., 2006). Consequently, this means that adopting a reasonable country rock rheology is extremely important for the current study. It was initially assumed that the total pressure of the magma that is responsible for inflating the magma chamber and causing surface displacement was comparable to the overall lithostatic pressure, otherwise rock failure leading to an eruption might occur.

In this project, the Mogi-Yamakawa model was used to develop a three dimensional viscoelastic deformation model for Kīlauea volcano (Poland et al., 2012). Kīlauea volcano is the youngest of five subaerial volcanoes that form the Big Island of Hawai'i. Its elliptical summit caldera measures 4.5×3 km (Decker et al., 1987a,b). Kīlauea displays two rift zones: the South-West and the East, which diverge from the summit caldera and extend subaerially for 35 and 125 km, respectively. The East rift zone hosts the current eruption that started on January 3rd, 1983 (Decker et al., 1987a,b). These two Rift Zones are zones of weaknesses that cause the southern flank of Kīlauea to move toward the ocean at a rate of several centimeters per year (Tilling et al., 2014). Strong tectonic earthquakes, like the magnitude 7.7 (M_w) Kalapana earthquake of November 29th, 1975, are often associated with this movement (Hawaiian Volcano Observatory, 1995; Nettles and Ekström, 2004).

Following the magma chamber modeling carried out by Newman et al. (2006) and Chen et al. (2009), in order to create a model of Kīlauea's magma chamber, the free Finite Element software Lisa v8.00 was chosen. The deep magma chamber dynamics analysis was conducted with a 1064 elements and 1225 nodes Mogi-derived 3D Finite Element Model. The volcanic area that was considered was a 80 km long, 10 km high and 70 km wide rectangular parallelepiped volume, which was set in a x, y, z tridimensional Cartesian Coordinate System. Based on Cayol and Cornet (1998) and Bonaccorso and Davis (1999), the Young's modulus was set to 100 GPa and the Poisson's ratio to 0.25. In the center of the region, there was an ellipsoidal magma chamber. A total chamber volume of 25 km^3 was chosen to be consistent with most geophysical estimates of various parts of the Kīlauea magmatic system (Delaney et al., 1990; Johnson, 1995). The depth of the center of the model magma chamber was chosen as 5 km, implying that magma vesiculation processes are minimal (Decker et al., 1987a,b). Around the position of the magma chamber, the grid of the Finite Element Model was denser (Fig. 1) to better calculate the final stress and shear stress maps. The grid is made of three types of cells: the cells are respectively 0.8, 0.2 and 0.025 km