# Years to weeks of seismic unrest and magmatic intrusions precede monogenetic eruptions

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## ABSTRACT

**Seismic, deformation, and gas activity (unrest) typically precedes volcanic eruptions. Tracking the changes of this activity with monitoring data makes it increasingly possible to successfully forecast eruptions from stratovolcanoes. However, this is not the case for monogenetic volcanoes. Eruptions from these volcanoes tend to be small but are particularly difficult to anticipate since they occur at unexpected locations and there is very limited instrumental monitoring data. Many monogenetic volcanic fields occur in high-density, populated areas and/or tourist destinations, and thus even a small eruption can have a major economic and societal impact. We have gathered the available instrumental data for unrest and combined it with new historical accounts of seismicity. Our occurrences are mainly from high magmatic flux oceanic islands (Canary Islands, Iceland, Papua New Guinea, Mexico, and Japan). We find that seismic activity may start one or two years before eruption, but it intensifies at approximately two or three months, and one or two weeks. The petrological and geochemical characteristics of the deposits show that multiple magma batches interacted in a subvolcanic reservoir, and multiple intrusions occurred on a similar time scales to the seismicity. We propose a general model for these eruptions where early dike intrusions in the crust do not erupt (e.g., stalled intrusions) and make small plumbing systems, but they probably are key in creating a thermal and rheological pathway for later dikes to be able to reach the surface. These observations provide a conceptual framework for better anticipating monogenetic eruptions in similar settings and magmatic fluxes and should lead to improved strategies for mitigation of their associated hazards and risks.**

## INTRODUCTION

One of the main problems in quantifying the probability of an eruption in a monogenetic volcanic field is the lack of monitoring data. Monogenetic fields can be intermittently active for millions of years, but the magmatic processes and unrest associated with eruptive episodes that form the individual volcanoes are very short compared with the quiescence periods (e.g., Koulakov et al., 2015). Many of the historical monogenetic eruptions have occurred before there was any instrumental monitoring data, and our current knowledge is based on a few accounts of historical eruptions (e.g., Baker, 1946; De la Cruz-Reyna and Yokoyama 2011; Sánchez, 2014). We have done an exhaustive revision and compilation of the unrest activity (mainly seismicity) of all the historical monogenetic eruptions for which we have had access (12 eruptions in total; Table 1). We have combined this information with the available data of the zoning patterns of crystals to derive a conceptual model that integrates the time scales from the crystals with the unrest seismic data, as has been done in stratovolcanoes such as Mount Etna (Kahl et al., 2011), Vesuvius (Morgan et al., 2006), or Mount St. Helens (Saunders et al., 2012).

TABLE 1. UNREST ACTIVITY AND TIMING OF MAGMATIC PROCESSES

| Eruption | Location | Date (A.D.) | Magma mixing or assimilation, and ascent times | Seismic unrest activity |
|---|---|---|---|---|
| SF, F, A* | Tenerife (Canaries) | 1704–1705 | 1 year<br>2 months<br>2 weeks | 1 week–1 month[†] |
| CH[§] | Tenerife (Canaries) | 1909 | Yes | 2 years[†]<br>2–3 months[†] |
| SJ[#] | La Palma (Canaries) | 1949 | Years<br>Few months<br>Days | 2.5 years[†]<br>90 days[†]<br>3 days[†] |
| T** | La Palma (Canaries) | 1971 | Yes | Weeks–months[†]<br>6 days[†] |
| EH[††] | El Hierro (Canaries) | 2011 | 1 month/25–150 days<br>3 weeks/2–90days | 4–5 years[§§]<br>3 months[§§]<br>1 month[§§] |
| J[##] | Michoacan (Mexico) | 1759 | 10–200 days | 5 months[†]<br>3 months[†] |
| P*** | Michoacan (Mexico) | 1943 | Yes | 2 months[§§]<br>Weeks[§§] |
| G[†††] | Goropu Mountains (Papua) | 1943 | Unknown | 2 years[†]<br>2–3 months[†] (?) |
| E[§§§] | Heimaey (Iceland) | 1973 | Yes | 2 days[§§]<br>1 day[§§] |
| IO[###] | Higashi-Izu (Izu Peninsula, Japan) | 1989 | Unknown | 2 weeks[§§]<br>9 days[§§] |

*SF—Siete Fuentes, F—Fasnia, A—Arafo. Petrological data from Albert et al. (2015). Unrest data from Sánchez (2014).

[†] —Seismic historical accounts.

[§] CH—Chinyero. Petrological data in this study (see the Data Repository [see text footnote 1]). Unrest data from Sánchez (2014).

[#] SJ—San Juan. Petrological data from Klügel et al. (2000). Unrest data from Sánchez (2014).

**T—Teneguía. Petrological data from Araña and Ibarrola (1973). Unrest data from Klügel et al. (1997) and Sánchez (2014).

[††] EH—El Hierro. Petrological data from Martí et al. (2013) and Longpré et al. (2014). Unrest data from Instituto Geográfico Nacional (www.ign.es).

[§§] —Monitored seismicity.

[##] J—Jorullo. Petrological data from Johnson et al. (2008). Unrest data from Yokoyama and De la Cruz-Reyna (1990), Carreón Nieto (2002) and De la Cruz-Reyna and Yokoyama (2011).

***P—Paricutín. Petrological data from Rowe et al. (2011). Unrest data from Yokoyama and De la Cruz-Reyna (1990).

[†††] G—Goropu. Unrest data from Baker (1946).

[§§§] E—Eldfell. Petrological data from Mattsson and Oskarsson (2005) and Higgins and Roberge (2007). Unrest data from Thorarinsson et al. (1973).

[###] IO—Ito-oki. Unrest data from Ukawa (1993).

## STUDIED ERUPTIONS AND PREVIOUS WORK ON MAGMATIC PROCESSES

The eruptions we have studied (Table 1) include seven in the Canary Islands (Spain), two in the Michoacan-Guanajuato region of Mexico, and one each for the Higashi-Izu area of Japan, the Goropu Mountains (Owen Stanley Range, Papua New Guinea), and Heimaey island (Iceland) (Table 1). Geochemical and petrological studies of these eruptions show that they were affected by open-system processes involving multiple magmas (Klügel et al., 2000; Johnson et al., 2008; Valentine and Hirano, 2010; Rowe et al., 2011; Martí et al., 2013; Longpré et al., 2014; Albert et al., 2015). Mixing between mafic magmas has been reported in seven of the ten cases (Table 1). For the Jorullo and Paricutin (Mexico) eruptions, in addition to mixing between similar magmas, upper-crustal assimilation has also been proposed, and implies stalling magma batches at various crustal levels (Johnson et al., 2008; Rowe et al., 2011). Thus, these petrological studies suggest that these monogenetic eruptions are not driven simply

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by dikes that travel from the mantle to the surface, but support a more complex scenario of magma interactions and assimilation in subvolcanic reservoirs, and has been proposed also for other systems (e.g., Németh et al., 2003; Johnson et al., 2008; Rowe et al., 2011; Brenna et al., 2012; Martí et al., 2013; Longpré et al., 2014; Albert et al., 2015; Cortés et al., 2015).

In addition, modeling of the zoning patterns of olivine crystals of the Siete Fuentes, Fasnia and Arafo eruptions in the Canary Islands (Albert et al., 2015) shows that there were several storage regions and magma mixing events that occurred approximately one year, two months, and two weeks before the eruption. Similar time frames from crystals have been found in the other studied eruptions of San Juan (Klügel et al., 2000), Jorullo (Johnson et al., 2008) and El Hierro (Martí et al., 2013; Longpré et al., 2014). Below we show that the time scales from the crystals and those of seismic unrest in these monogenetic eruptions can be correlated, and thus allow us to propose a new conceptual model of magma storage and migration before eruption.

## METHODS

Instrumental monitoring data are available for four eruptions, but only for El Hierro 2011 (Canary Islands) the data are of high quality by modern standards (López et al., 2012). For the rest of the eruptions, we recorded the time series of accounts of felt earthquakes in historical documents (see Table 1, and the GSA Data Repository[1]). Some documents give the number of seismic events, the effects on people, and buildings, and sometimes an intensity value (e.g., Mercalli scale). Other reports are not detailed enough to discern between intensities or to establish a detailed time series of the number of seismic events. The lack of data in some periods for some eruptions could be due to the lack of historical reports, not to the lack of earthquakes. We compared the time frames and intensity of seismic activity between different events using a normalization of times with respect to each eruption and number of events (Fig. 1).

We validated the use of historical earthquake accounts as a proxy for the level of seismicity before an eruption by using the recent data set from the El Hierro 2011 eruption (www.ign.es). We compared the number of felt earthquakes before and after the El Hierro 2011 eruption with the total number of monitored seismic events and geodetic data (Fig. DR1 in the Data Repository). We found that, in general, the evolution of felt seismicity and measured seismicity agree quite well (despite changes in the instrumentation in the seismic network), and hence validates our approach of using felt seismicity to compare between different eruptions.

## RESULTS

The seismic and felt earthquake data that we have compiled (Fig. 1) show that there are some common features between the eruptions. Some seismic events occur between one or two years before eruption, and they are followed by calm periods. Comparison of felt and instrumental seismicity, with deformation, during the El Hierro eruption (Supp. Fig. 1) suggests that seismicity earlier than a few months before an eruption could be, in fact, taken as background levels. However, for other cases (e.g., San Juan 1949 eruption, Canary Islands), there are seismic and petrological data (see above) that suggest that magmatic processes and associated unrest started earlier than a few months before the eruption. The amount of seismicity strongly increases two or three months before the eruption in almost all cases. These seismic crises might reflect the repetitive intrusions of magma in the crust, and thus probably correspond to mid-crustal stalled intrusions (Moran et al., 2011). These intrusions would stall and start to crystallize due to cooling or degassing, and create a small plumbing system. The depth at which these intrusions stall is difficult to constrain but some seismic and petrological data suggest 5–15 km below the volcano (Klügel et al., 1997; Johnson et al., 2008; Browne

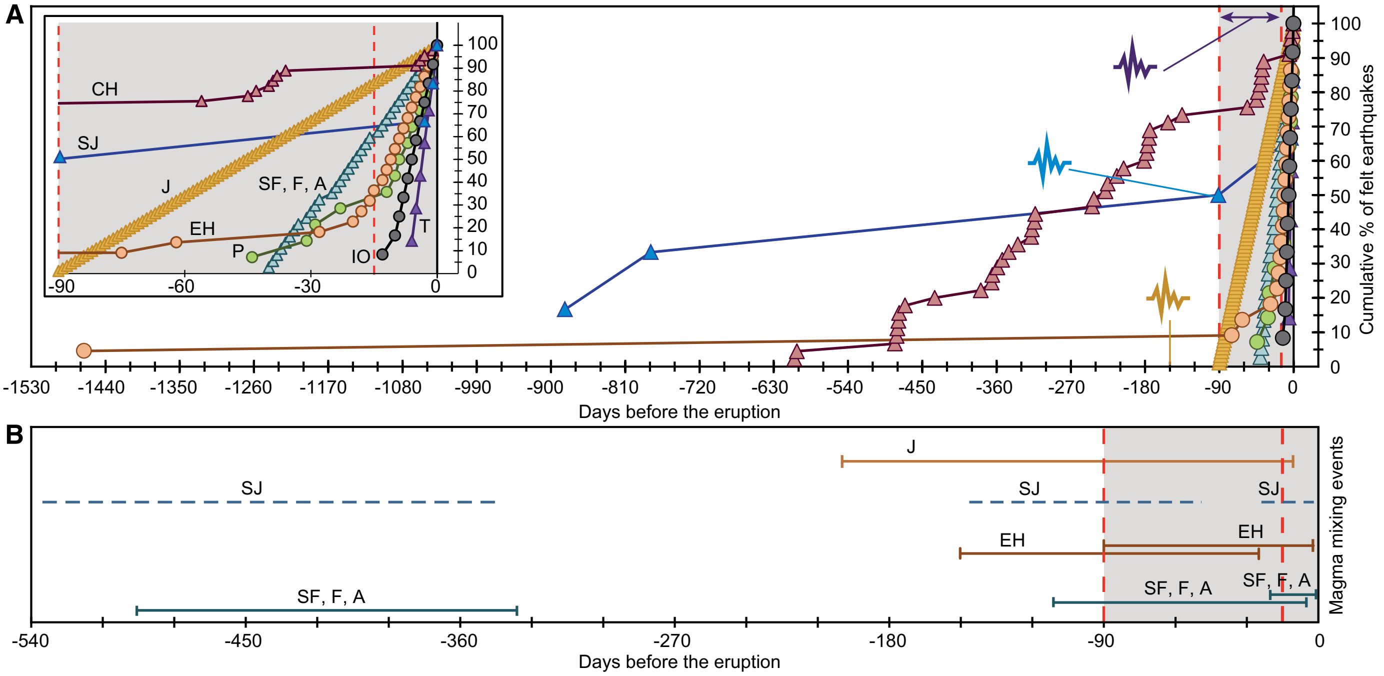

**Figure 1. Pre-eruptive seismic unrest of historical monogenetic eruptions and calculated mixing/intrusion times. The eruption is shown as a black line at time = 0. Red dashed lines indicate 90 and 15 days prior to the eruption. Gray areas correspond to 90 days before the eruption. A: Historical accounts are shown as triangles, and instrumentally monitored data as dots. Generally, the seismicity trend changes approximately two or three months, and one or two weeks, before the eruption. Inset shows a zoom view of the gray area of the main figure. Siete Fuentes, Fasnia and Arafo (SF,F,A: light blue triangles); Chinyero (CH: dark pink triangles); San Juan (SJ: dark blue triangles); Teneguía (T: purple triangles); El Hierro (EH: orange dots); Jorullo (J: yellow triangles); Paricutín (P: green dots); Ito-oki (IO: gray dots). Details of the seismicity are given in the Data Repository (see footnote 1). B: Calculated mixing times for the available eruptions. Times from San Juan eruption are only approximated (dashed lines). The data sources for this figure are reported in Table 1 and Data Repository.**

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[1] GSA Data Repository item 2016063, details of the seismicity and a brief petrological review, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

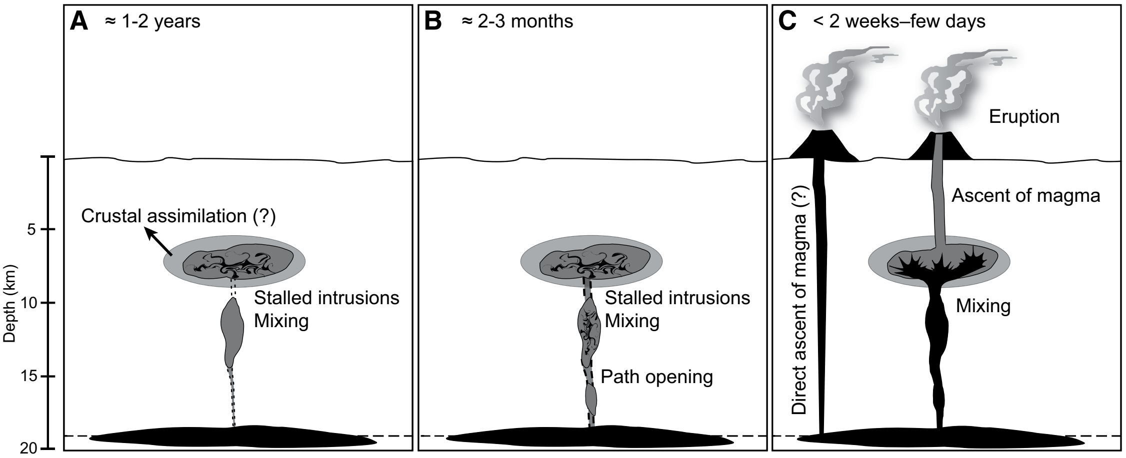

**Figure 2. Possible plumbing system configuration and evolution of events that may occur below monogenetic volcanoes (schematic and not to scale). The depth of the subvolcanic system may vary from 5 to 15 km. The depth of the magma source is also variable but is at least 20 km. A: Intrusion of magma approximately one or two years prior to the eruption, stalling of magma at 5–15 km due to the loss of buoyancy or freezing of dikes, and mixing processes registered by the crystals. Crustal assimilation occurs in some cases. Seismic activity is felt by the population in some cases. B: Renewal of magma intrusion, progressive opening of the path between deep and shallow reservoirs, and mixing processes registered by the crystals. Crustal assimilation occurs in some cases. The seismic activity is commonly felt by the population. C: Continued intrusion of mafic magma leads to easier transfer from deep to shallow reservoirs, and this allows the magma to finally erupt. Magma mixing (and crustal assimilation in some cases) are recorded by the crystals. Seismicity is felt by the population. Also shown the possibility that magma is directly transfer from the mantle to the surface.**

et al., 2010; Cerdeña et al., 2014; Cortés et al., 2015). Finally, virtually all the eruptions show a sharp increase in seismic activity approximately two weeks to two days before eruption, and might be related to magma migration toward the surface (Johnson et al., 2008). The time frames from the seismicity we have found match with those derived for the magma mixing and transport episodes derived from the crystal zoning studies (Fig. 1).

## DISCUSSION AND CONCLUSIONS

An intriguing aspect of the petrological and geochemical data for the eruptions we studied is that open systems and mixing are prevalent, and imply that magmas coming from depth are commonly intercepted by a shallower reservoir. This can be expected in areas with high volcanic fluxes such as Iceland, but not in, for example, the Canary Islands were eruptive fluxes are not high. The commonality of open-system processes for many of these events may rather indicate that the early seismicity corresponds to stalled intrusions. In other words, for the studied cases, magmas coming from depth in dikes were not able to go straight to the surface, but stalled at some intermediate depth (Figs. 2A and 2B). There are many parameters that control whether mafic dikes from the mantle will be able to reach the surface, including magma buoyancy, thermal survival, tectonic stress, or preexisting crustal discontinuities (Rubin 1995; Valentine and Gregg, 2008; Rivalta et al., 2015). Our data set does not allow us to identify a precise control on each of the eruptions, but the existence of a shallow plumbing system at mid-crustal levels (5–15 km) may suggest that dikes separated from their sources and traveled as small batches. Once at shallow depths (5–15 km), magmas can cool, probably degas and crystallize, and evolve toward more differentiated compositions. Repetitive intrusions of small magma batches at the same location are probably able to modify the thermal and rheological state of the crust through which they pass and reside, and thus, when renewed dike intrusions from depth occur, they require progressively lower energy to reach the surface and erupt (Fig. 2) (Strong and Wolff, 2003).

Our conceptual model stems from the available compilation of seismic unrest and petrology of the erupted magmas from a limited number of mainly high-flux systems from oceanic islands, and it might not be universal for all monogenetic eruptions. Some geochemical studies of deposits from monogenetic eruptions and their mantle xenoliths (e.g., Spera, 1984; Valentine and Perry 2007) have proposed direct magma transfer from the mantle to the surface. It seems plausible that monogenic eruptions from low-flux continental interiors that are controlled by tectonic processes might work differently, and may allow direct magma transfer from the mantle to the crust (e.g., Valentine and Perry, 2007). This would lead to shorter seismic unrest and thus less time to anticipate or prepare for the eruption (Fig. 2C). However, detailed petrological studies of the crystal cargo for such eruptions are lacking, and using bulk-rock geochemistry is difficult to identify open-system processes and mixing of magmas from the same liquid line of descent. Moreover, some studies of mantle xenoliths suggest magmas stalling at multiple depths (Klügel et al., 1997; Klügel, 2001; Jankovics et al., 2015). Detailed petrological studies (e.g., crystal zoning; Albert et al., 2015) of monogenetic eruptions coupled with experiments and numerical models of dike migration should be able to test the importance of repetitive intrusions in allowing mafic magmas from monogenetic eruption to reach the surface.

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