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The correlation between run-up and repose times of volcanic eruptions

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SUMMARY

Volcanoes usually show signs of unrest before an eruption. Establishing physical controls on the duration of precursory activity, that is run-up time, could improve understanding of the dynamics of magma ascent from a shallow magma reservoir to the surface. Another observable indicative of eruption dynamics is the interevent repose time, that is, the time between magmatic eruptions. The repose time could be associated with the mechanism that recharges the magmatic system. Both of these quantities depend on magma viscosity and hence magma composition in addition to other factors. In this work we investigate the interrelationship between run-up time, repose time and silica content by compiling a database of 73 magmatic eruptions from 34 different volcanoes around the world. Run-up and repose time are correlated with ~40 per cent of the variance in the data well explained by a linear correlation. Both of these quantities are significantly correlated with silica content, but although repose times and silica content are highly correlated, run-up times show a weaker correlation with silica content. The data range from basaltic to dacitic with a preponderance of low silica eruptions, so we can investigate the gross influence of viscosity in controlling both run-up and repose time. We also investigate the role of volume erupted finding repose times correlated with the erupted volumes. The trends are clearest when comparing a large range of silica on the global data set and appear to be obscured by other processes for subsets that cover only a small range of silica contents. High silica, and thus by inference high viscosity, systems have longer repose and run-up times and tend to erupt larger quantities of material. The observed interrelationships can provide new insights for constraining physical and probabilistic models for volcanic hazard mitigation.

Key words: Time-series analysis; Volcano monitoring; Volcanic hazards and risks.

INTRODUCTION

Volcanic eruptions commonly have geophysically observable precursors. Before an eruption, seismicity, ground deformation and gas emission may increase (e.g. Lipman & Mullineaux 1981; Tokarev 1985; Yokoyama 1988; Yokoyama *et al*. 1992; Cornelius & Voight 1994; ; Newhall & Punongbayan 1996; Yokoyama & Seino 2000; Druitt & Kokelaar 2002; Cervelli *et al*. 2006; De la Cruz-Reyna *et al.* 2008**)**. The intensity of those precursory phenomena varies substantially in size and temporal duration for different volcanoes, yet most eruptions have at least some sign of the impending eruption. Identifying the systematics of these precursory (run-up) sequences is a long-term goal of volcanology (Klein 1984; Rymer & Brown 1989; Scarpa 2001; McNutt 2005; Aiuppa *et al.* 2007).

There is a huge and thriving literature about the physical origin of the eruption precursory signals and their link with magma movements in the crust. Brittle failure earthquakes can be generated by magma pressure on the country rock (Tokarev 1971; Kilburn 2003), pressure from degassing processes (Menand & Tait 2001) or even fracture of the magma (LaVallee *et al*. 2008). Similarly, long-period seismicity can be associated with fluid movement (Aki & Ferrazini 2000; Burlini *et al*. 2007; Benson *et al*. 2008). In all of these cases, the duration of the seismic unrest in some way records the magmatic motion and its cascading effects through the hosting crust.

Therefore, it is natural to expect that the duration of the precursory activity is related to magma mobility. Higher viscosity magmas should have longer precursory times, that is magma run-up time, because the velocity of magma propagation is inversely proportional to the viscosity (Rubin 1995). Although such a correlation between composition and precursory time has been suggested (e.g. McNutt 1996), it has not been systematically investigated in the literature. Discerning such a relationship on a single volcano is relatively difficult, in large part because of the lack of detailed constraints on the viscosity and state of the magma at depth.

One strategy for overcoming the large uncertainties is to use a large data set which encompasses extreme variations in composition so that the data captures end-member behaviour. In this study, we take this approach by assembling data from eruptions worldwide over the last 70 yr with well-documented precursory activity. The inferred viscosity in this data set varies by eight orders of magnitude and thus becomes the most dominant parameter in the system allowing us to systematically study its correlation with precursory time for the first time.

Recent work has also suggested that precursory time is related to repose time between eruptions (Sigmundsson *et al*. 2010). The time between eruptions as well as the magma run-up time is controlled by the recharge of the magma chamber and the accumulation of pressure. Both of these processes are also sensitive to magma viscosity and thus might be expected to vary from volcano to volcano. However, magma within the crust undergoes regional and local stress distribution, volatile exsolution, friction and freezing effects that might have control on both repose and run-up time. A systematic study on repose and run-up times could give empirical justification to all these hypotheses. Again, a study at a single edifice would be difficult, but capitalizing on the large viscosity variations from edifice to edifice might be instructive.

In this paper we investigate the interrelationships among run-up time, recurrence interval and silica content by using 73 eruptions that were selected because of their well-documented chemistry, repose and run-up times. We carefully define and discuss the operational definitions of repose and run-up time. Next we observe a significant correlation between recurrence and repose time along with a dependency on petrology and proceed to perform a number of tests to evaluate both random and epistemic uncertainty. We examine outliers from the correlations in detail. In an aside, we also investigate the relationships between the parameters and eruptive volume. We then discuss if the range of the observed run-up times is compatible with run-up times inferred using a very simple dyke velocity model and independent estimation of viscosities for a comparable range of magmatic composition. Finally, we interpret the observed correlations as possible manifestations of the control of viscosity on the precursory and recharge processes.

DEFINITIONS

We define the run-up time $t_{\mathrm{run-up}}$ as the time elapsed from the initiation of observed magmatic unrest to the onset of a magmatic eruption. The run-up time defined in this way should be related to the time taken by the magma to move from a magma chamber to the surface. Although this definition of run-up seems a very straightforward one, it leads us to very complicated questions: (1) How do you define a starting point for a magmatic eruption? and (2) How do you define the starting point of a magmatic unrest?

To answer question (1), we define the start of an eruption as when juvenile magma material is detected at the surface. Despite this simple definition, sometimes this information is not easily available for explosive eruptions because phreatic- and phreato-magmatic activity can obscure when juvenile material is first ejected. We tackle this problem using information available in literature about petrography and petrology of the eruptive products. Table 1 indicates references for the magmatic composition and petrography of each eruption.

Answering question (2) is a difficult matter. The defined starting point for volcanic unrest depends on the ability to detect precursory volcanic signals above variable background levels, and it is unavoidably related to a particular type of volcano and quality of the monitoring system. Signs of pre-eruptive unrest vary and eruptions in this study include both examples of elevated seismicity and increased ground deformation. In addition, the data for precursory activity usually are not easily available, are often strongly heterogeneous and in some cases are only qualitative (see Newhall & Dzurisin 1988; Simkin & Siebert 1994; Benoit & McNutt 1996). This makes very difficult to set a comprehensive scheme for defining the onset date of magmatic unrest and the relative run-up time for volcanic eruptions.

Given the great variability among eruptions and scarcity of detailed pre-eruptive data available for direct interpretation, we have deferred to the authors of each study and used the local definition of run-up time for this work. This strategy is inherently dangerous both because it does not use a quantitative or precise definition of background and because it uses *a posteriori* interpretation given by authors about volcanic signs. For instance, it does not account for the highly variable ability to detect precursory activity depending on the frequency of visual observation and the proximity of geophysical monitoring instruments. Another major limitation of this approach is for very active and noisy volcanoes, for example, Stromboli in Italy, Yasur in Vanuatu Islands or Llaima and Villarica in South America. All of those volcanoes have quasi-continuous explosive activity that makes almost impossible to measure the duration of pre-eruptive signals except for a very few cases when effusive activity is well isolated from the normal paroxysmal activity. However, this strategy is the only easily accessible method because there is no worldwide volcanic geophysical database available.

In many studies made after an eruption, authors describe the characteristics and duration of precursory activity well. For example in Aki & Ferrazini (2000; table 3), the authors give clear information about the precursory activity for eruptions from 1985 to 1996 at Piton de la Fournaise, a well-monitored volcano. This single data set allows comparison of multiple eruptions in a consistent way. De la Cruz-Reyna *et al*. (2008) made very useful observations of the Popocatepetl volcano 1994 eruption and its very long precursory activity. In this case, the documentation is sufficient to make reasonable statements about the precursory activity for even a single event. Similar quantitative studies we found elsewhere in the literature identify the starting point for a magmatic unrest. The precise sources of documentation for each eruption in this study are listed in Table 1.

In most of these studies the time for the precursory activity is indicated by precursory seismicity (e.g. Tokarev 1985; Yokoyama 1988; Yokoyama *et al*. 1992; Gil Cruz & Chouet 1997; Yokoyama & Seino 2000; Soosalu *et al*. 2005; table 1); a few cases have ground deformation and seismicity (e.g. Lockwood *et al*. 1987; Cervelli *et al*. 2006). We neglected in this study other precursory signals such as thermal anomaly and gas fluxes only because that information is not available for all eruptions we use here. We confirm the information taken from the literature with the monthly and weekly report of Smithsonian Institution, Global Volcanism Program (GVP; www.volcano.si.edu) as a source of information. For example, in the case of the 1999 eruption of Tungurahua volcano there is no literature regarding the precursory activity, so we integrate the information from monthly report from the Smithsonian Institute, Bulletin of the Global Volcanism Network (BGVN) 24:11 from GVP website (http://www.volcano.si.edu). For events where we found some discrepancy between seismicity and deformation as precursory signals, we always refer to the seismicity for the run-up time value, because seismicity is a more homogeneous datum all over the eruptions we investigate.

We also collected data on the relative repose or interevent time t_{repose} defined as the time elapsed between the onset of two subsequent eruptions. As stated before, we consider the onset of an eruption as the time when first juvenile material is present in volcanic ejecta. We use the onset time rather than cessation time to define the interval between eruptions (Klein 1982; Mulargia *et al.*

Table 1. Data set of run-up times, repose times, silica content and volume erupted. For some eruptions the run-up time duration is also bracketed together with the onset date. In those cases we only found the specification of the duration of the precursory activity and not the precise start time. The start date for those eruptions is a convention that allows us to use a homogeneous notation for all event and easily convert into Julian days. In nearly all cases the eruption start point is assumed to be at 00:00:00. The exceptions are Usu 2000 eruption and Okmok 2008 eruption where the real onset time for both precursory activity and eruption start are known.

	Volcano	Magma (SiO_2 wt per cent)	Run-up time (yyyy-mm-dd hh mm ss)	Repose time (yyyy-mm-dd hh mm ss)	Volume (bulk) 10^6 m^3	References
1	Augustine (Au) 2006	Andesite 60.00 per cent[a]	2005-11-17 00:00:00 2006-01-11 00:00:00	1986-03-27 00:00:00 2006-01-11 00:00:00	VEI 3	Cervelli *et al*. (2006) Roman *et al*. (2006) BGVN (30:12 and 31:01)
2	Bezymianny (Bz) 1956	Andesite/dacite 59.90 per cent	1955-09-29 00:00:00 1956-03-30 00:00:00	950-07-02 00:00:00[b] 1956-03-30 00:00:00	Tephra: 2800 VEI 5	Bogoyavlenskaya *et al*. (1985) Tokarev (1985)
3	Chaiten 2008 (Ch)	Rhyolite 75.6 per cent[c]	2008-04-30 20:56:00 2008-05-02 23:58:00	<9870 ± 90 BP[d,b] 2008-05-02 23:58:00	 VEI 5	Basualto *et al*. (2008) Carn *et al*. (2009) Castro & Dingwell (2009) Naranjo & Stern (2004) OVDAS-SERNAGEOMIN (2008a,b)
4	Eyjafjallajökull (Ey) 2010	Basalt 48 per cent Andesite 58 per cent	2009-12-15[e,f] 00:00:00 2010-03-20 00:00:00	1821-12-19 00:00:00 2010-03-20 00:00:00		BGVN (35:03) Icelandic Met Office (2011) Institute of Earth Sciences (2011)
5	El Chichon (EC) 1982	Andesite 55.88 per cent	1981-01-15 00:00:00[g,f] 1982-03-28 00:00:00	1376-07-02 00:00:00[b] 1982-03-28 00:00:00 (∼550 ± 60 yr)	Tephra: 2300 VEI 5	De la Cruz-Reyna & Martin Del Pozzo (2009) Havskov *et al*. (1983) Jiménez *et al*. (1999) Luhr *et al*. (1984) Macias *et al*. (2003) Tilling (2009) Yokoyama (1988) Yokoyama *et al*. (1992)
6	Galeras (Ga) 1992	Andesite/dacite 59.40 per cent	1988-06-15 00:00:00[f] 1991-10-09 00:00:00	1936-08-27 00:00:00 1991-10-09 00:00:00	Lava: 0.4 Tephra: 2.8 VEI 2	Calvache & Williams (1997) Calvache *et al*. (1997) Cortes et al., 1997 Gil Cruz & Chouet (1997)
7	Grimsvotn (Gr) 2004	Basaltic andesite 50.00 per cent[h]	2004-10-31 21:00:00 2004-11-01 00:00:00 (3 hr)[i]	1998-12-18 00:00:00 2004-11-01 00:00:00	VEI 3	BGVN (29:10) Hjaltadottir *et al*. (2005) Sigmarsson *et al*. (2000). Sturkell *et al*. (2006)
8	Guagua pichincha 1999 (GP)	Dacite 64.50 per cent	1998-09-15[j,f] 00:00:00 1999-09-26 00:00:00	1660-11-27 00:00:00 1999-09-26 00:00:00	Lava: >6 VEI 3	BGVN (23:08 to 24:10) Garcia-Aristizabal *et al*. (2007) Wright *et al*. (2007)
9	Hekla (Hk1) 1980	Basaltic andesite 54.90 per cent	1980-08-16 23:35:00 1980-08-17 00:00:00 (25 min)	1970-05-05 00:00:00 1980-08-17 00:00:00	Lava: 200 Tephra: 70 VEI 3	Moune *et al*. (2006) Soosalu *et al*. (2005) Sverrisdottir (2007)
10	Hekla (Hk2) 1981	Basaltic andesite 55.40 per cent	1981-04-16 23:37:00 1981-04-17 00:00:00 (23 min)	1980-08-17 00:00:00 1981-04-09 00:00:00	Lava: 120 Tephra: 60 VEI 2	Idem
11	Hekla (Hk3) 1991	Basaltic andesite 54.70 per cent	1991-01-16 23:30:00 1991-01-17 00:00:00 (30 min)	1981-04-09 00:00:00 1991-01-17 00:00:00	Lava: 150 Tephra: 20 VEI 3	Idem

Table 1. (*Continued.*)

	Volcano	Magma (SiO_2 wt per cent)	Run-up time (yyyy-mm-dd hh mm ss)	Repose time (yyyy-mm-dd hh mm ss)	Volume (bulk) 10^6 m^3	References
12	Hekla (Hk4) 2000	Basaltic andesite 55.00 per cent	2000-02-25 22:41:00 2000-02-26 00:00:00 (79 min)	1991-01-17 00:00:00 2000-02-26 00:00:00	Lava: 286 Tephra: 10 VEI 3	Idem
13	Kilauea (Kil1)	Basalt 47.89 per cent	1968-08-21 21:00:00 1968-08-22 00:00:00 (3 hr)	1967-09-05 00:00:00 1968-08-22 00:00:00	Lava: 0.13 VEI 0	Casadevall & Dzurisin (1987) HVO (2005) Klein *et al*. (1987) Marske (2010) Garcia *et al.* (1992)
14	Kilauea (Kil2)	Basalt 50.29 per cent	1968-10-06 21:00:00 1968-10-07 00:00:00 (3 hr)	1968-08-22 00:00:00 1968-10-07 00:00:00	Lava: 6.6 VEI 0	Idem
15	Kilauea (Kil3)	Basalt 49.55 per cent	1969-02-16 00:00:00 1969-02-22 00:00:00 (6 d)	1969-10-07 00:00:00 1969-02-22 00:00:00	Lava: 16.1 VEI 0	Idem
16	Kilauea (Kil4)	Basalt 49.55 per cent	1969-05-21 00:00:00 1969-05-24 00:00:00 (3 d)	1969-02-22 00:00:00 1969-05-24 00:00:00	Lava: 185 VEI 0	Idem
17	Kilauea (Kil5)	Basalt 50.09 per cent	1971-09-17 00:00:00 1971-09-24 00:00:00 (7 d)	1971-08-14 00:00:00 1971-09-24 00:00:00	Lava: 7.7 VEI 0	Idem
18	Kilauea (Kil6)	Basalt 49.36 per cent	1973-05-04 00:00:00 1973-05-05 00:00:00 (24 hr)	1972-02-03 00:00:00 1973-05-05 00:00:00	Lava: 1.2 VEI 0	Idem
19	Kilauea (Kil7)	Basalt 50.40 per cent	1974-07-18 15:00:00 1974-07-19 00:00:00 (9 hr)	1973-11-10 00:00:00 1974-07-19 00:00:00	Lava: 6.6 VEI 0	Idem
20	Kilauea (Kil8)	Basalt 48.08 per cent	1974-09-16 00:00:00 1974-09-19 00:00:00 (3 d)	1974-07-19 00:00:00 1974-09-19 00:00:00	Lava: 10.2 VEI 0	Idem
21	Kilauea (Kil9)	Basalt 48.40 per cent	1974-12-24 00:00:00 1974-12-31 00:00:00 (7 d)	1974-09-19 00:00:00 1974-12-31 00:00:00	Lava: 14.3 VEI 0	Idem
22	Kilauea (Kil10)	Basalt 50.82 per cent	1977-09-12 00:00:00 1977-09-13 00:00:00 (24 hr)	1975-09-29 00:00:00 1977-09-13 00:00:00	Lava: 32.9 VEI 0	Idem
23	Kilauea (Kil11)	Basalt 49.63 per cent	1979-11-15 00:00:00 1979-11-16 00:00:00 (24 hr)	1977-09-13 00:00:00 1979-11-16 00:00:00	Lava: 0.58 VEI 0	Idem

Table 1. (*Continued.*)

	Volcano	Magma (SiO_2 wt per cent)	Run-up time (yyyy-mm-dd hh mm ss)	Repose time (yyyy-mm-dd hh mm ss)	Volume (bulk) 10^6 m^3	References
24	Kilauea (Kil12)	Basalt 49.92 per cent	1982-04-29 20:00:00 1982-04-30 00:00:00 (4 hr)	1979-11-16 00:00:00 1982-04-30 00:00:00	Lava: 0.5 VEI 0	Idem
25	Kilauea (Kil13)	Basalt 50.44 per cent	1983-01-01 00:00:00 1983-01-03 00:00:00 (3 d)	1982-09-25 00:00:00 1983-01-03 00:00:00	Lava: >3000 VEI 1	Idem
26	Mauna Loa (ML1) 1975	Basalt 52.04 per cent	1974-08-15 00:00:00[f] 1975-07-06 00:00:00	1950-06-01 00:00:00 1975-07-06 00:00:00	Lava: 3 VEI 0	Lockwood *et al*. (1987)
27	Mauna Loa (ML2) 1985	Basalt 51.37 per cent	1984-03-24 21:30:00 1984-03-25 00:00:00 (∼2 hr 30 min)	1975-07-06 00:00:00 1984-03-25 00:00:00	Lava: 220 VEI 0	Lockwood *et al*. (1987)
28	Miyakejima (My) 2000	Basaltic andesite 54.00 per cent	2000-06-26 00:00:00 2000-06-27 00:00:00	1983-10-03 00:00:00 2000-06-27 00:00:00	Tephra: 9.3 VEI 3	Nakada *et al*. (2005) Uhira *et al*. (2005) Saito *et al*. (2005)
29	Mt Etna (Etn1) 2001	Basalt 48.05–47.06 per cent	2001-07-12 00:00:00 2001-07-17 00:00:00	1995-07-30 00:00:00[k] 2001-07-17 00:00:00	Tephra: 5 Lava: 25 VEI 2	Allard *et al*. (2006) Falsaperla *et al.* (2005) Ferlito *et al*. (2009)
30	Mt ETNA (Etn2) 2002	Basalt 47.20–47.70 per cent	2002-10-26 20:12:00 2002-10-26 22:55:00[l] (2 hr)	2001-06-21[m] 00:00:00 2002-10-26 00:00:00	Tephra: 30 ± 2 Lava: 20 ± 5 VEI 3	Allard *et al*. (2006) Andronico *et al*. (2005)
31	Mt. S. Helens (MSH1) 1980	Dacite 62.00 per cent	1980-03-20 00:00:00 1980-05-18 00:00:00	1857-04-15 00:00:00[n,f] 1980-05-18 00:00:00	Lava: 74 Tephra: 1200 VEI 5	Christiansen & Peterson (1981) Endo *et al*. (1981) Lipman *et al*. (1981)
32	Mt. S.Helens (MSH2) 2004	Dacite 64.85 per cent	2004-09-23 00:00:00 2004-10-01 00:00:00	1980-05-18 00:00:00 2004-10-01 00:00:00	Lava: 93 VEI 2	Moran *et al*. (2008) Pallister *et al*. (2008)
33	Mt. Spurr (MSp) 1992	Andesite 56.00 per cent	1991-08-15 00:00:00[f] 1992-06-27 00:00:00	1953-07-09 00:00:00 1992-06-27 00:00:00	Tephra: 150 VEI 4	Power *et al*. (2002) Gardner *et al*. (1998)
34	Okmok (Ok) 2008	Basaltic andesite[o] 56.00 per cent	2008-07-12 14:00:00 2008-07-12 19:43:00[p] (∼5 hr)	1997-02-11 00:00:00 2008-07-12 19:43:00	VEI 4	BGVN (33:06) Johnson *et al*. (2010)
35	Pavlof (Pv1) 1996	Basaltic andesite 53.00 per cent[q]	1996-09-13 00:00:00 1996-09-16 00:00:00	1986-04-16 00:00:00 1996-09-16 00:00:00	VEI 2	Roach *et al*. (2001)
36	Pavlof (Pv1) 2007	Basaltic andesite 53.00 per cent	2007-08-14 00:00:00 2007-08-15 00:00:00	1996-09-16 00:00:00 2007-08-15 00:00:00	VEI 2	BGVN (32:08) AVO (2008) Waythomas *et al*. (2008)

Table 1. (*Continued.*)

	Volcano	Magma (SiO_2 wt per cent)	Run-up time (yyyy-mm-dd hh mm ss)	Repose time (yyyy-mm-dd hh mm ss)	Volume (bulk) 10^6 m^3	References
37	Pinatubo (Pi) 1991	Andesite 59.2 per cent Dacite 64.00 per cent	1991-03-15 00:00:00[f] 1991-06-07 00:00:00	1450-07-02 00:00:00[r,b] 1991-06-07 00:00:00 (∼500 ± 50 yr)	Tephra: $(1.1 \pm 0.5) \times 10^4$ Lava: 4 VEI 6	Wolfe & Hoblitt, 1996 Newhall *et al*. (1996) Hoblitt *et al*. (1996) Pallister *et al*. (1996) Luhr & Melson (1996)
38	Piton de la Fournaise (PF1)	Basalt 48.30 per cent	1983-12-03 21:40:00 1983-12-04 00:00:00 (∼3 hr)	1981-02-03 00:00:00 1983-12-04 00:00:00	Lava: 8 VEI 2	Aki & Ferrazini (2000) BGVN (8:11 to 23:03) Boivin & Bachelery (2009) Peltier *et al*. (2009) Villeneuve *et al*. (2008)
39	Piton de la Fournaise (PF2)	Basalt 49.20 per cent	1985-06-13 23:00:00 1985-06-14 00:00:00 (∼1 hr)	1984-01-18 00:00:00 1985-06-14 00:00:00	Lava: 1 VEI 1	Idem
40	Piton de la Fournaise (PF3)	Basalt 47.90 per cent	1985-08-04 21:23:00 1985-08-05 00:00:00 (2 hr 37 min)	1985-06-14 00:00:00 1985-08-05 00:00:00	Lava: 7 VEI 1	Idem
41	Piton de la Fournaise (PF4)	Basalt 48.85 per cent	1985-09-05 22:48:00 1985-09-06 00:00:00 (1 hr 12 min)	1985-08-05 00:00:00 1985-09-06 00:00:00	Lava: 14 VEI 1	Idem
42	Piton de la Fournaise (PF5)	Basalt 48.90 per cent	1985-12-01 23:43:00 1985-12-02 00:00:00 (17 min)	1985-09-06 00:00:00 1985-12-01 00:00:00	Lava: 0.7 VEI 1	Idem
43	Piton de la Fournaise (PF6)	Basalt 48.80 per cent	1985-12-27 23:46:00 1985-12-28 00:00:00 (14 min)	1985-12-01 00:00:00 1985-12-28 00:00:00	Lava: 7 VEI 1	Idem
44	Piton de la Fournaise (PF7)	Basalt 47.80 per cent	1986-03-17 14:36:00 1986-03-18 00:00:00 (9 hr 24 min)	1985-12-28 00:00:00 1986-03-18 00:00:00	Lava: 14 VEI 1	Idem
45	Piton de la Fournaise (PF8)	Basalt 49.00 per cent	1987-07-18 21:47:00 1987-07-19 00:00:00 (2 hr 13 min)	1987-06-10 00:00:00 1987-07-19 00:00:00	Lava: 0.8 VEI 1	Idem
46	Piton de la Fournaise (PF9)	Basalt 49.75 per cent	1987-11-29 22:30:00 1987-11-30 00:00:00 (1 hr 30 min)	1987-11-06 00:00:00 1987-11-30 00:00:00	Lava: 10 VEI 1	Idem
47	Piton de la Fournaise (PF10)	Basalt 48.56 per cent	1988-02-06 21:55:00 1988-02-07 00:00:00 (2 hr 05 min)	1987-11-30 00:00:00 1988-02-07 00:00:00	Lava: 8 VEI 1	Idem
48	Piton de la Fournaise (PF11)	Basalt 48.69 per cent	1988-05-17 23:29:00 1988-05-18 00:00:00 (31 min)	1988-02-07 00:00:00 1988-05-18 00:00:00	Lava: 15 VEI 1	Idem

Table 1. (*Continued.*)

	Volcano	Magma (SiO_2 wt per cent)	Run-up time (yyyy-mm-dd hh mm ss)	Repose time (yyyy-mm-dd hh mm ss)	Volume (bulk) 10^6 m^3	References
49	Piton de la Fournaise (PF12)	Basalt 48.85 per cent	1988-08-30 21:35:00 1988-08-31 00:00:00 (2 hr 25 min)	1988-05-18 00:00:00 1988-08-31 00:00:00	Lava: 7 VEI 1	Idem
50	Piton de la Fournaise (PF13)	Basalt 48.41 per cent	1988-12-13 19:29:00 1988-12-14 00:00:00 (4 hr 31 min)	1988-08-31 00:00:00 1988-12-14 00:00:00	Lava: 8 VEI 1	Idem
51	Piton de la Fournaise (PF14)	Basalt 49.42 per cent	1990-01-17 23:13:00 1990-01-18 00:00:00 (47 min)	1988-12-14 00:00:00 1990-01-18 00:00:00	Lava: 0.5 VEI 0	Idem
52	Piton de la Fournaise (PF15)	Basalt 50.00 per cent	1990-04-17 17:15:00 1990-04-18 00:00:00 (6 hr 45 min)	1990-01-18 00:00:00 1990-04-18 00:00:00	Lava: 8 VEI 0	Idem
53	Piton de la Fournaise (PF16)	Basalt 48.98 per cent	1991-07-17 23:08:00 1991-07-18 00:00:00 (52 min)	1990-04-18 00:00:00 1991-07-18 00:00:00	Lava: 2.8 VEI 0	Idem
54	Piton de la Fournaise (PF17)	Basalt 49.90 per cent	1992-08-26 23:03:00 1992-08-27 00:00:00 (57 min)	1991-06-18 00:00:00 1992-08-27 00:00:00	Lava: 5.5 VEI 1	Idem
55	Piton de la Fournaise (PF18)	Basalt 49.60 per cent	1998-03-07 12:00:00 1998-03-09 00:00:00 (∼36 hr)	1992-08-27 00:00:00 1998-03-09 00:00:00	Lava: 60 VEI 1	Idem
56	Popocatepetl (Pp) 1996	Andesite/dacite 62.41 per cent	1990-06-03 00:00:00 1996-03-01 00:00:00	1919-02-19 00:00:00 1996-03-01 00:00:00[s]	Lava: >28 VEI 3	De la Cruz-Reyna *et al*. (2008) De la Cruz-Reyna & Siebe (1997) Witter *et al.* (1997)
57	Rabaul (Rb1) 1994	Andesite/dacite 61.66 per cent	1994-09-17 21:00:00 1994-09-19 00:00:00 (27 hr)	1943-12-23 00:00:00 1994-09-19 00:00:00	Lava: 0.4 VEI 4	Williams (1995) Roggensack *et al*. (1996) Cunningham *et al*. (2009) BGVN (19:09 & 20:11/12)
58	Rabaul (Rb2) 1995	Andesite/dacite 61.40 per cent	1995-11-27 00:00:00 1995-11-28 00:00:00 (24 hr)	1994-09-19 00:00:00 1995-11-28 00:00:00	Lava: 4.5 ± 0.5 VEI 2	Williams (1995) Roggensack *et al*. (1996) Cunningham *et al*. (2009) BGVN (19:09 & 20:11/12)
59	Redoubt (Rd) 1989	Andesite 58.00 per cent Dacite 64.00 per cent	1989-12-13 01:00:00 1989-12-14 00:00:00 (∼23 hr)	1967-12-06 00:00:00 1989-12-14 00:00:00	Lava: 88 Tephra: 210 VEI 3	Chouet *et al*. (1994) Wolf & Eichelberger (1997)
60	Reventador (REV) 2002	Andesite 53.5–62.1 per cent	2002-11-02 06:00:00 2002-11-03 06:00:00 (∼24 hr[t])	1976-01-04 00:00:00 2002-11-03 06:00:00	Lava: 3.6×10^1 Tephra: 3.6×10^2 VEI 4	Hall *et al*. (2004) Lees *et al*. (2008) Samaniego *et al*. (2008)

Table 1. (*Continued.*)

	Volcano	Magma (SiO_2 wt per cent)	Run-up time (yyyy-mm-dd hh mm ss)	Repose time (yyyy-mm-dd hh mm ss)	Volume (bulk) 10^6 m^3	References
61	Ruapehu (Rh1) 1995	Andesite 58.50 per cent	1995-04-15 00:00:00[u,f] 1995-09-17 00:00:00	1977-07-16 00:00:00[v] 1995-09-17 00:00:00	Tephra: 30 ± 20 VEI 3	BGVN (20:05) Bryan & Sherburn (1999) Christenson (2000) Nakagawa *et al*. (2003) Sherburn *et al*. (1999)
62	Ruapehu (Rh2) 1996	Andesite 57.47 per cent	1996-06-14 08:00:00 1996-06-16 00:00:00 (40 hr)	1995-09-17 00:00:00 1996-06-16 00:00:00	Tephra: 4 VEI 3	Idem
63	Shishaldin (Shis) 1999	Basalt 51.94 per cent	1998-06-15 00:00:00[f] 1999-04-17 00:00:00	1995-12-23 00:00:00 1999-04-17 00:00:00	Lava: 43 VEI 3	Moran *et al*. (2002) Nye *et al*. (2002) Stelling *et al*. (2002)
64	Shiveluch (Shiv) 1964	Andesite/dacite 60.00 per cent	1964-02-24 00:00:00 1964-11-11 00:00:00	1944-11-05 00:00:00 1964-11-11 00:00:00	Tephra: 750 ± 50 VEI 4	Bogoyavlenskaya *et al*. (1985) Tokarev (1985)
65	Soufriere Hills 1995 (SHV)	Andesite 60.02 per cent	1994-06-15 00:00:00[w,f] 1995-09-25 00:00:00	1630-07-02 00:00:00[x,b] 1995-09-25 00:00:00 (365 ± 50 yr)	Lava: 1.2 x 10^2 VEI 3	Lipman *et al*. (1981) Devine *et al.* (1998) Gardner & White (2002) Kokelaar (2002) Watts *et al*. (2002)
65	Stromboli (Str) 2007	Basalt 52.39 per cent[y]	2007-02-14 00:00:00 2007-02-27 12:00:00	2002-12-28 18:30:00 2007-02-27 12:00:00[z]	Lava: ∼1	Barberi *et al*. (2009) Bonaccorso *et al*. (2003) Landi *et al*. (2009) Marchetti *et al*. (2009) Ripepe *et al*., (2009)
67	Tokachi (Tk2) 1962	Andesite 52.78 per cent	1962-05-01 00:00:00[aa] 1962-06-30 00:00:00	1924-05-24 00:00:00 1962-06-30 00:00:00	Tephra: 72 VEI 3	Murai (1963) Yokoyama (1964) Yokoyama (1988)
68	Tokachi (Tk1) 1988	Andesite 53.15 per cent	1988-07-15 00:00:00[bb,f] 1988-12-19 00:00:00	1962-06-30 00:00:00 1988-12-19 01:00:00	Tephra: 0.75 VEI 1	BGVN (13:11 to 14:06) Goto *et al*. (1997) Ikeda *et al*. (1990) Katsui *et al*. (1990) Okada *et al*. (1990)
69	Tungurahua (Tg) 1999	Andesite 58.58 per cent	1998-12-15 00:00:00[f] 1999-10-13 00:00:00[cc]	1916-03-03 00:00:00 1999-10-15 00:00:00	 VEI 3	BGVN (24:09 to 24:11) Hall *et al*. (1999) Arellano *et al*. (2008)
70	Unzen (Uz) 1991	Dacite 65.31 per cent	1989-11-15[f] 00:00:00 1991-02-12 00:00:00	1792-02-10 00:00:00 1991-02-12 00:00:00	Lava: 150 Tephra: >4.7 VEI 1	BGVN (15:07 to 16:05) Nakada & Motomura (1999) Nakada *et al*. (1999) Watanabe *et al*. (1999)
71	USU 1943 (Us1)	Dacite/rhyolite 70.24 per cent	1943-12-28 00:00:00 1944-08-15 00:00:00	1853-03-06 00:00:00 1944-08-17[dd] 00:00:00	Lava: 70? Tephra: 4 VEI 2	Mimatsu (1995) Matsubara *et al*. (2004) Tomiya & Takahashi (1995) Tomiya & Takahashi (2005) Yokoyama & Seino (2000) Yoshida & Nishimura (2004)
72	USU 1977 (Us2)	Dacite 69.65 per cent	1977-08-05 16:00:00 1977-08-07 00:00:00 (32 hr)	1944-08-15 00:00:00 1977-08-07 00:00:00	Tephra: 100 VEI 2	Idem

Table 1. (*Continued.*)

	Volcano	Magma (SiO_2 wt per cent)	Run-up time (yyyy-mm-dd hh mm ss)	Repose time (yyyy-mm-dd hh mm ss)	Volume (bulk) 10^6 m^3	References
73	USU 2000 (Us3)	Dacite 68.89 per cent	2000-03-27 08:00:00[ee] 2000-03-31 13:10:00	1977-08-07 00:00:00 2000-03-31 13:10:00	VEI 2	Idem

[a]Based on 1986 eruption where range of SiO_2 is 56–64 per cent wt
[b]Month and day of onset set as 07–02 by convention in absence of other information
[c]Bulk composition
[d]From Naranjo & Stern, (2004) other date 9430 ± 60, error one standard deviation
[e]Intrusion started end of December
[f]Day of onset set as 15th day of month by convention in absence of other information
[g]From Yokoyama (1988)
[h]From BGVN and Sigmarsson *et al*. (2000) for previous eruption in 1998.
[i]Swarm 3 h before eruption, probably increasing seismicity from 5–7 a.m. November 1(from BGVN 29:10)
[j]From Garcia-Aristizabal *et al*. (2007), onset is mid-September
[k]Start of summit eruptions 1995–2001
[l]Summit eruption with juvenile material
[m]Real onsets from Andronico *et al*. (2005)
[n]Data taken from www.volcano.si.edu
[o]Jessica Larsen (Personal communication, 2008), Geophysical Institute, Fairbanks, AK
[p]Real onset time for run-up is known (see caption).
[q]Magma composition not available for 1996 eruption, so used the 2007 magma composition
[r]1450 ± 50 from Global Volcanism Database
[s]Onset of dome extrusion, no information on previous juvenile material
[t]Lees *et al*. (2008)
[u]In Christenson (2000) the onset is not clear, but from www.volcano.si.edu BGVN (20:05) onset mid-April
[v]Last magmatic eruption from www.volcano.si.edu
[w]From Kokelaar (2002), mid-June, 1995 July 18 beginning of phreatic activity, poor information from seismicity before.
[x]1630 ± 50 from Global Volcanism Program
[y]Matrix glass composition
[z]Real onset
[aa]From Yokoyama (1964)
[bb]Problematic onset run up time, choose mid-September, but increase seismicity started in 1988 July from Okada *et al*. (1990)
[cc]Onset of both run-up and repose time are from www.volcano.si.edu
[dd]From Showa-Shinzan diary 1944 August 17 with some ambiguity
[ee]Real onset times

1985; De la Cruz-Reyna 1991; Burt *et al*. 1994; Bebbington & Lai 1996; Sandri *et al*. 2005; Marzocchi & Zaccarelli 2006). This choice is mainly motivated by the large uncertainties related to the assessment of the endpoint of an eruption, however, using the onset time can introduce a bias for long lasting, effusive and dome forming eruptions. The cited literature was supplemented by the GVP records to determine the eruptive history (Table 1).

For some data in Table 1, correct quantification of both run-up and repose time are affected by epistemic uncertainties. For most eruptions the onset time is well known with an error of at least 1 d, but for some historical eruptions it is impossible to know when juvenile material is ejected first. Similarly, for a few precursory sequences we did not find a precise starting date, but only the period of the month when the unrest began.

For eruptions without a clear onset in the literature (Bezymianny, Chaitén, El Chichón, Pinatubo and Soufrière Hills) we use the start date given by Smithsonian Institution–GVP data sets in Table 1. For cases where only year and month are specified, we use the 15th day of the month as starting date (14 events of 73 in Table 1). The relative error introduced by this approximation, that is, 15 days divided by the run-up or repose time, is always less than 10 per cent except for Pinatubo and Eyjafjallajökull volcanoes, where the error is 17 per cent and 15 per cent, respectively.

In addition, error is introduced into the repose time through dating methods of pre-historical eruptions. Although no pre-historical eruptions can be used for the run-up time date, sometimes the preceding eruption defining the repose interval is pre-historical or historical but without any written documentation. Based on the technique-based errors provided by the Smithsonian database, relative errors for repose times because of the dating error on the onset are less than 3 per cent for El Chichón, Pinatubo and Soufrière Hills, and less than 1 per cent for Chaitén volcano. For such cases with only a year determined, we use the midpoint of the year, that is, July 2, as the onset date. The relative error introduced by this approximation, that is, 180 d divided by repose time, is <0.1 per cent for all cases and therefore is always below the dating errors.

Finally we collected information for magma composition and silica content. However not all eruptions considered have direct petrologic data. This is, for example, the case of Pavlof and Grímsvötn volcano, where we do not know the exact magma composition of their eruptions and use the magma composition information from the most recent ones. Such cases are documented in Table 1. When more than one magma composition is given for a particular eruption we reported their value in Table 1 indicating the relative class of magma composition they belong to.

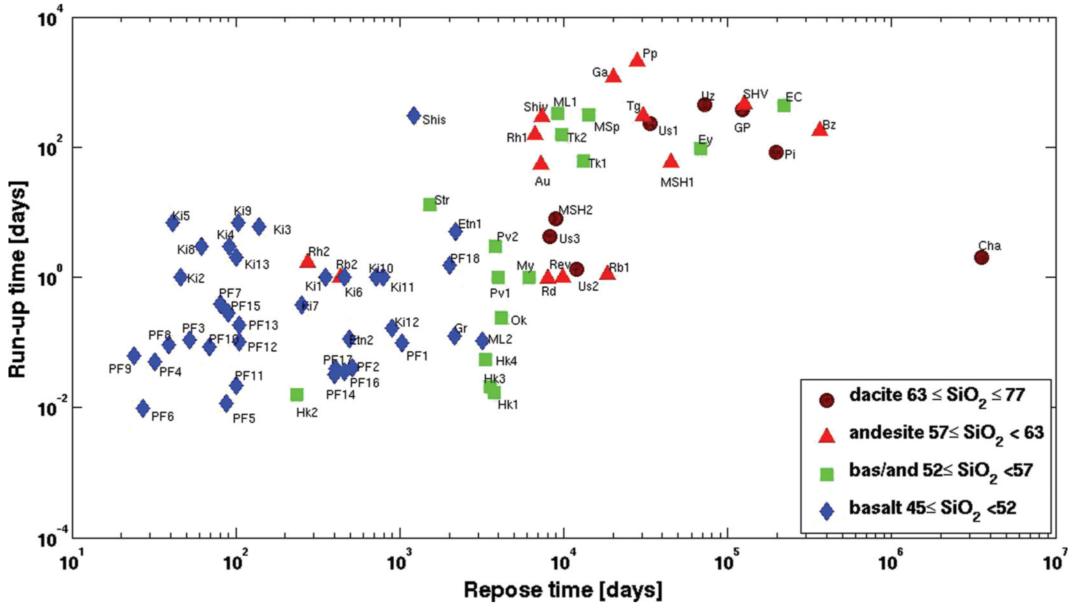

Figure 1. Repose time versus run-up time data. Labels of individual points correspond to each eruption documented in Table 1. Magma composition is based on the Le Bas *et al*. (1986) classification.

For each eruption included in this analysis we report the volcano name, silica content, run-up time, repose or interevent time, bulk volume erupted (tephra and lava) and Volcanic Explosivity Index (VEI) and references in Table 1. The 73 eruptions we collected are the 3 per cent of the 2326 eruptions reported in the GVP database. However, the Smithsonian Institution eruption definition encompasses phreatic events, which are excluded from this study. Furthermore, we require significantly more documentation of chemistry, run-up time and repose time. The total compilation here consists of 36 basaltic, 15 basaltic–andesite, 14 andesite and 7 dacitic eruptions and 1 rhyolitic eruption.

OBSERVATIONS

The repose times, run-up time and magma composition we have collected are shown in Fig. 1. Every eruption for which we could find documentation of all the three parameters is included. At first glance, it is easy to see that both run-up and repose times vary over about six order of magnitude. For basaltic volcanoes, repose times are of the orders of months to a few years and run-up times are of the order of minutes to a few days. For high silica volcanoes, repose times are of the order of several years up to several centuries and run-up time of the order of days to several months. The ratio between the run-up and repose times is always less than 10 per cent except for two events: Kilauea 1971 eruption (event number 17 in Table 1) and Shishaldin volcano which both run-up to repose time ratios of $\sim$0.25.

The interrelationship among repose times, run-up times and silica content

The main physical insight from Fig. 1 is that repose and run-up times seem to be positively correlated. To investigate the possible association between run-up and repose data, we will evaluate whether they are linearly correlated or not in log-log space and assess the statistical and physical validity of the correlation. We first check the power law dependency between run-up and repose times as the simplest case for quantities scaling of orders of magnitude (Draper & Smith 1998), than we use a three parameters exponential function to investigate whether or not the correlation is an artefact of the logarithm transformation. Later, we will investigate the interdependence of the two time quantities with the silica content.

The regression analysis of the logarithmic data in Fig. 2(A) show a positive linear association between repose and run-up times. The value of $R^2 = 0.41$ in log-log space means 40 per cent of the data are explained by the linear regression model. The validity of the regression is checked against the null hypothesis of uncorrelated values (i.e. slope equal to zero); this hypothesis can be rejected with an error of <0.01 (i.e. p-value of the hypothesis testing) according to an F-test (Draper & Smith 1998). The p-value is the risk associated with rejecting the hypothesis, so in this case the probability that we have inappropriately rejected the uncorrelated hypothesis is less than 1 per cent. The value of the best-fit line is $t_{\mathrm{run-up}} = 0.81\ t_{\mathrm{repose}} - 2.33$, although errors in the estimation of regressor parameters are given in the figure caption. The observed ratio of the run-up time and repose times in Fig. 2 ranges between 10^{-1} and 10^{-6}.

However, a regression with all data is not sufficient to fully prove the significance of the correlation. A close look at Fig. 1 shows a clear outlier for repose time data, that is, the Chaitén 2008 eruption. This one point has high leverage on the estimation of parameters of the regression. In addition, in Table 1 there are 18 eruptions pertaining to Piton de La Fournaise volcano and 13 to Kilauea volcano. Because we want to study globally the interrelationship among repose and run-up times and silica content, the presence of several eruptions of one volcano is justified from a physical point of view, but this leads to a problem of sensitivity and influence of those data on the estimation of regression parameters. To assess the robustness of the regression estimates, and check the influence of the above mentioned data into the regression analysis, we will repeat the regression excluding them.

In Fig. 2(A) we report the linear regression analysis excluding the Chaitén data and we find the expected improvement of the fit. In Fig. 2(B) we exclude only eruptions of Piton de la Fournaise

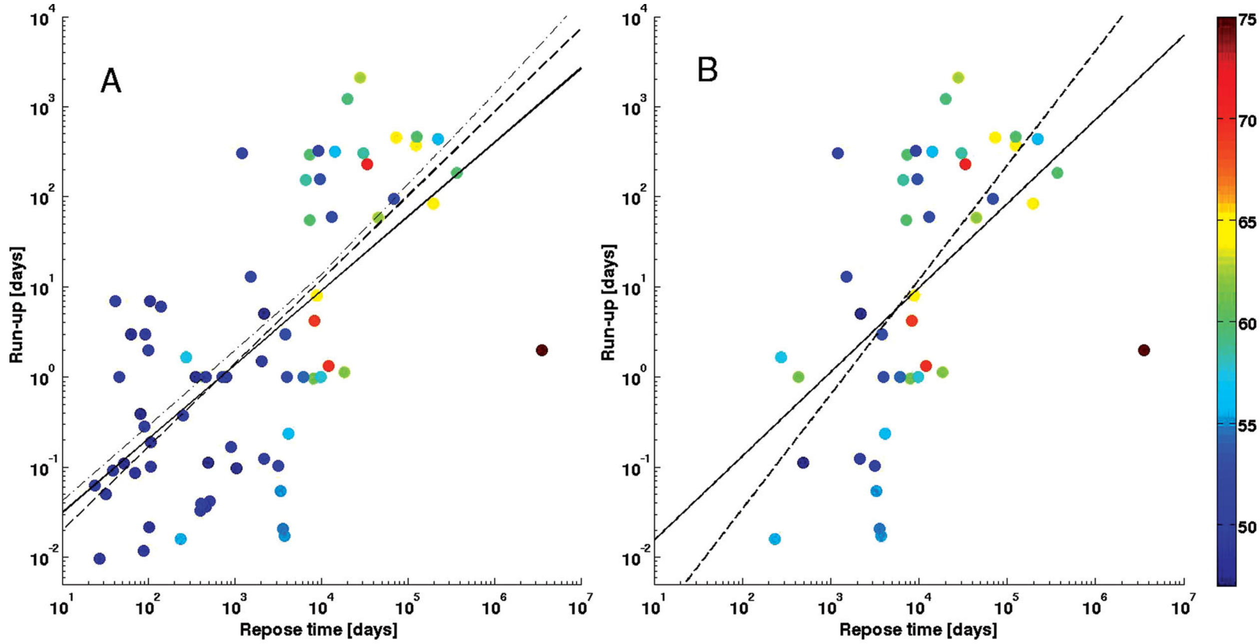

Figure 2. Regressions analysis for run-up and repose time with (A) All data in the catalogue of Table 1 and (B) Piton de la Fournaise and Kilauea eruptions excluded. Black solid and fine dotted lines are the regression lines with or without the Chaitén eruption, respectively. Colour bar is SiO_2 wt per cent. In panel A the regression line with Chaitén datum (solid) has equation $\log(t_{\mathrm{run-up}}) = (0.82 \pm 0.28)\log(t_{\mathrm{repose}}) - (2.33 \pm 0.13)$ with $R^2 = 0.42$, excluding Chaitén datum it becomes (dashed line) $\log(t_{\mathrm{run-up}}) = (0.93 \pm 0.26)\log(t_{\mathrm{repose}}) - (2.63 \pm 0.13)$ with $R^2 = 0.48$. In panel B the regression line is $\log(t_{\mathrm{run-up}}) = (0.93 \pm 0.66)\log(t_{\mathrm{repose}}) - (2.74 \pm 0.30)$ with $R^2 = 0.29$ (solid) and $\log(t_{\mathrm{run-up}}) = (1.27 \pm 0.59)\log(t_{\mathrm{repose}}) - (4.00 \pm 0.28)$ with $R^2 = 0.42$ (dashed) with or without Chaiten datum, respectively. In all cases the regression is statistically significant (F-test on the slope) with a p-value < 0.01. The finer dot-dashed line in panel A represents an exponential fit $t_{\mathrm{runup}} = a + b\exp(c\, t_{\mathrm{repose}})$; where $a = -8.9 \times 10^3$, $b = 8.5 \times 10^3$ and $c = 1.5 \times 10^{-7}$ and $R^2 = 0.89$. As discussed in the text the exponential fit is performed without Chaitén eruption.

and Kilauea volcanoes to understand their influence on the fit. Here the regression line is still significant, but the fit worsens according with the lower value of $R^2 = 0.28$. However when we exclude the Chaiten datum, the linear fit is again satisfactory with $R^2 = 0.41$. In the caption of Fig. 2, we report the value of the regression parameters for all tests, the p-value of the hypothesis testing, that is slope equal to zero, is ≤ 0.01 for each case according with F-test. Finally as the last check, we perform a regression with only Kilauea and Piton de la Fournaise data and they show no linear trend between repose and run-up times.

The multiple checks on the linear regression fit show that repose and run-up times relationship is valid even if we neglect multiple eruptions from a single volcano. At the same time, the linear trend is valid only if we consider all data ranging from low to high silica volcanoes. When we group eruptions by magma composition as in Fig. 3, we find that only volcanoes with intermediate composition have a significant linear association (i.e. basaltic–andesite and andesite volcanoes, panel B and C, respectively in Fig. 3). Furthermore, the dacitic eruptions are likely too few to perform such analysis for just this subset.

We have now shown how the data seem correlated by performing a robust statistical analysis. At this point, one can argue about the reliability of the data going back in the past and the related possible bias introduced in the analysis. Because of the difficulty of using a common criterion for all eruptions, for example the quality of monitoring network or its proximity to the volcano, we are pushed to use a time criterion. Further refinements of this data set have to include the quality of the monitoring set at each volcano and find a new criterion based, for example, on the distance of seismic and GPS stations from the volcano summit. Here the time criterion we use is to consider only eruptions after 1990 January 1, because all eruptions but Chaitén after that time have sufficient pre-eruptive recorded signals. Although arguable, this choice reduces the data available to 34 eruptions of 25 different volcanoes, which were all well-monitored at the time of the event. In Fig. 4 we present the analysis with and without Chaitén eruption. We find again a significant linear fit of the two time quantities considered here that eventually corroborates the interdependency of the run-up and repose times of eruptions.

As a final check for the validity of the correlation signal, we fit our data set using a three-parameter exponential function (Fig. 2A). We use a robust non-linear least square fit suitable in presence of outliers. The results of the fitting curve are shown as dot-dashed line in Fig. 2(A), although the value of the inferred parameters and R^2 are in the caption. The fit is significant only excluding the Chaitén volcano, because the non-linear algorithm does not converge in presence of this outlier datum. Because both run-up and repose time for Chaitén 2008 eruption do not meet the same stringent documentation criteria as the rest of the data set (See full discussion below), this last test seems to confirm that there is a correlation signal among our data.

At this point, we want to point out that the statistical analysis we carried out is only to show that there is a correlation between the two data sample. The fitted functional form has limited predictive power for four main reasons. First, half of the variance of the regression is not explained by data. Secondly, errors on run-up time are unknown so any resulting prediction could be biased. Thirdly, the present compilation is biased towards basaltic eruptions, which are 50 per cent of all eruptions listed. Basaltic eruptions are more frequent and consequently basaltic volcanoes are better monitored, thus naturally more events with this type of magma composition are included. This last problem may be remedied with the availability of new

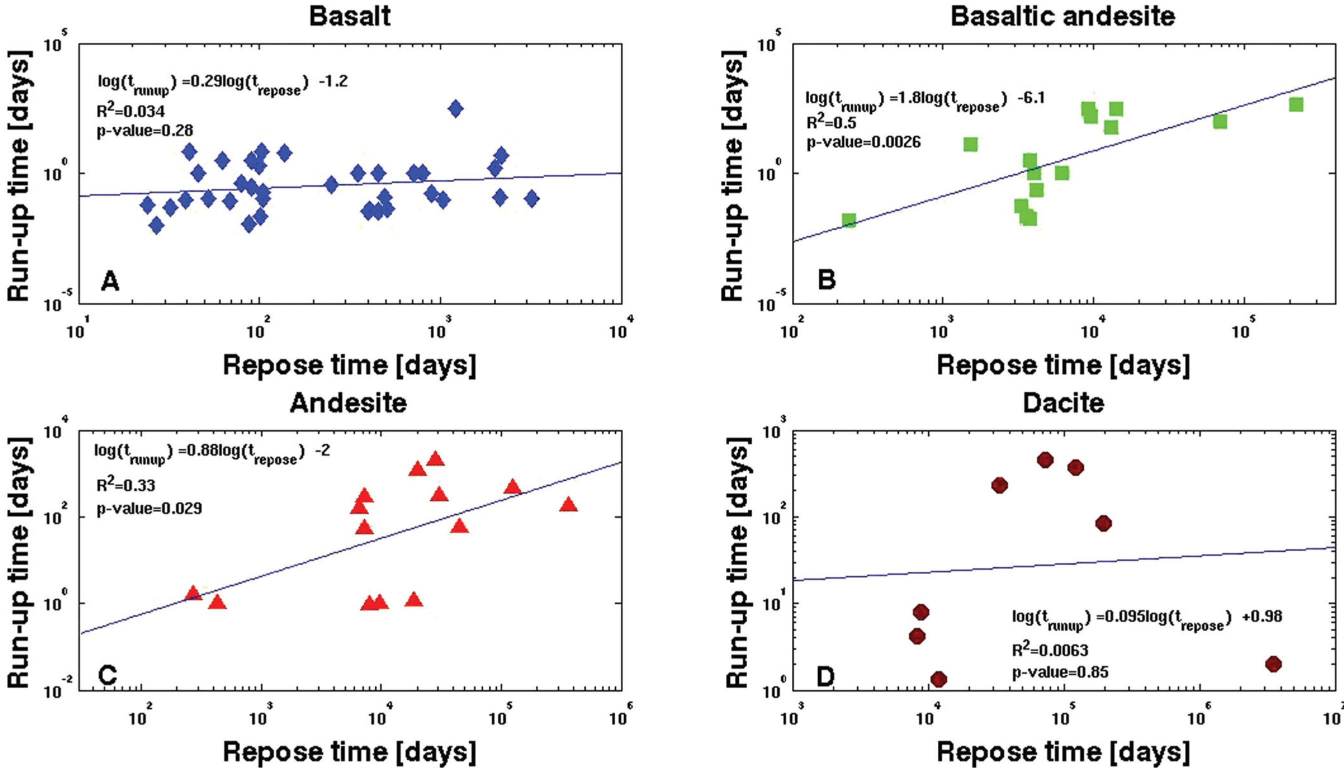

Figure 3. Regressions fits for eruptions grouped according with their magma composition. (A) Basalts, (B) basalt-andesites, (C) andesites and (D) dacites. Only eruptions of intermediate composition (B and C) show a significant linear association (See text). The trend that is the focus of this paper is a result of comparing across magma types, rather than within a small range of composition.

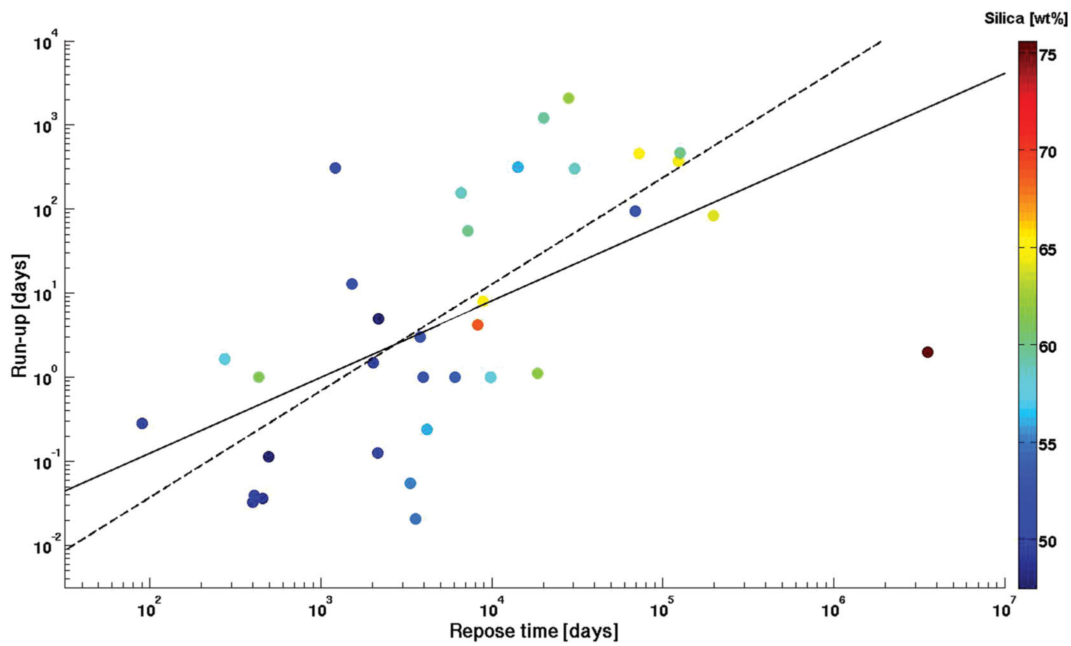

Figure 4. Regressions analysis for eruptions only after 1990 January 1. Black solid and dashed lines are the regression lines with or without Chaitén eruption, respectively. Colour bar is SiO_2 wt per cent. The regression line with Chaitén (solid) has equation $\log(t_{\text{run-up}}) = (0.90 \pm 0.61)\log(t_{\text{repose}}) - (2.71 \pm 0.28)$ with $R^2 = 0.33$, the one without Chaitén datum (dashed line) has $\log(t_{\text{run-up}}) = (1.27 \pm 0.54)\log(t_{\text{repose}}) - (3.97 \pm 0.26)$ with $R^2 = 0.49$. In both cases the regression is statistically significant (F-test on the slope) with a p-value <0.01.

databases, such as WOVOdat that has a projected release data of 2013 (Antonius Ratdomopurbo; personal communication, 2011). And finally, this correlation has no information at all on whether or not unrest at a particular site will ultimately culminate in an eruption. This study by design is limited only to eruptions that actually occur.

Despite the problems, the correlation we find can be an useful additional tool after volcanic unrest starts. It can help to estimate the

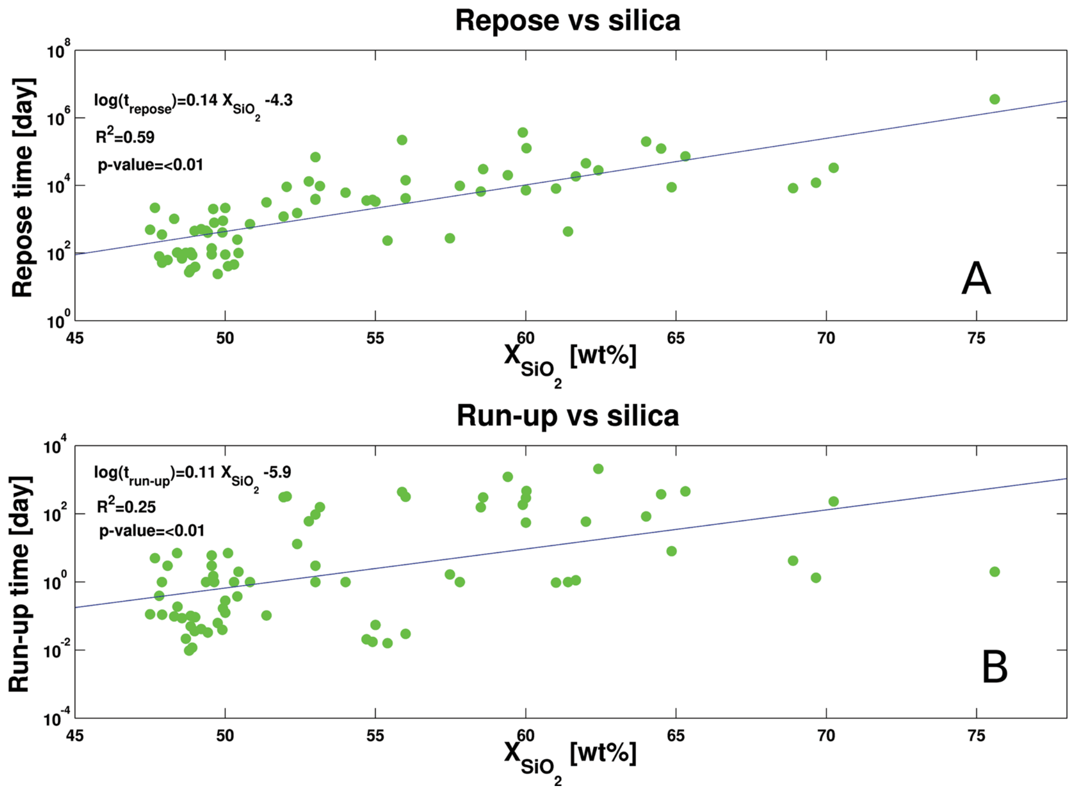

Figure 5. Regression analysis for repose times versus silica content (panel A) and run-up times versus silica content (panel B). In the inset of each plot are indicated the value of the regression line, the correlation coefficient R^2 and the p-value of the F-test made on the slope of the regression line, for more details please refer to the text.

time period over which concern should be maintained for a particular system. Most specifically, existing Bayesian event tree models can benefit from incorporating our findings about the correlation between repose time and length of precursory signals (Newhall & Hoblitt 2002; Marzocchi *et al*. 2008).

In Figs 2–4 we also colour code the silica content for each eruption. However, it is not easy to discern the degree of correlation of the SiO_2 data with the repose and run-up times. Thus, we check the linear dependency of both the repose and run-up time with the silica content. In Fig. 5, upper panel, we show the strong interrelationship of log-repose time and silica content. Value of the regression parameters are shown in the inset of the figure together with the R^2 that states that 60 per cent of the data are explained by the linear fit. The linear equation inferred indicates that repose time increases by a factor of about 3 for each 3 wt per cent increase in silica, which is quantitatively consistent with the findings of White *et al.* (2006) using a different set of data. Possible explanations for the correlation between silica and repose time include: (1) the time required for fractional crystallization processes increases with silica content and (2) high silica magma is less mobile because of the high viscosity and thus takes longer to leave the chamber.

A weaker linear relationship is found between run-up time and SiO_2, where the regression parameters are given in Fig. 5(B). Interestingly, the final eruptive process is somewhat less sensitive to bulk magma composition than the interevent recharge process. The weaker linear association between run-up times and the silica content needs further investigation, but may be because of the drastic changes in rheological properties of the magma during the upwelling process from the shallow reservoir to the surface. During the last part of the magma's path to the surface, the decreasing pressure may promote volatile loss and crystallization which both lead to an increase in its viscosity. In addition, the weaker relationship for run-up time and silica content may be indicative that precursory signals because of the magma transport processes, in the upper part of its way to the surface, are not only controlled by the magma compositions but by other processes such as friction and brittle failures on the boundary magma conduit walls (Costa *et al.* 2007; LaVallée *et al*. 2008 and reference therein).

The observation indicates that using the silica content as a fundamental parameter in describing the pre-eruption dynamics may be productive. But it is also a warning that other physical parameters like variable magma supply rate, magma mixing, the crystal content, temperature, tectonic and local stress distribution must be taken into account as more fully explained in the final discussion section of this paper.

Unusual individual eruptions

Much of the scatter in Fig. 1 is likely because of the great variability of individual eruptive circumstances. It is helpful to outline the limits of the proposed relationships by reviewing some of the peculiarities of the individual data points that lead to significant departures from the trend.

The 2008 eruption of Chaitén volcano is the first Holocene eruption for this volcano (Naranjo & Stern 2004; Carn *et al*. 2009) and is also the first dacitic–rhyolitic eruption to be recorded by geophysical instrumentation globally (Lara 2009). The repose time appears to be long, as expected for a high silica system, however Pallister *et al.* (2010) and Alfano *et al*. (2011) raise doubts about this long period of dormancy and suggested more recent activity of Chaitén volcano in between the 2008 May eruption and the pre-historical one (i.e. 9600BP).

Chaitén gave very little forewarning before the explosive eruption start on 2008 May 2. According to the available satellite data, no deformation was detectable until 2 weeks before the eruption (Fournier *et al*. 2010; Matt Pritchard; personal communication, 2010) and earthquakes with magnitude range 3.0–5.0 were only registered starting from 3 d before the eruption. Thus, this eruption showed an unprecedented little warning for high silica systems. Because Chaitén has the highest silica content of any eruption in the data set, it is possible that the relationship between precursory activity and magma chemistry studied here breaks down at very high silica content. However, Chaitén volcano was not monitored before the start of the eruption, and the seismic records of the pre-eruptive stages refer to a station 250 km far from the volcano (Basualto *et al*. 2008). In addition, in the past, a swarm of volcano-tectonic events with maximum magnitude of 3.6 were detected beneath the Chaitén volcano during 11 months of seismic acquisition made along the Liquine–Ofqui fault zone during 2004–2005 (Lange *et al*. 2008). Although the petrological evidence seems to indicate a very rapid ascent of magma underneath this volcano (Castro & Dingwell 2009), we can not be certain that Chaitén volcano was totally noiseless before 3 d since the start of the climax eruption.

Shishaldin volcano 1999 eruption shows a very long pre-eruption activity compared with other basaltic volcanoes with a run-up time that is one-fourth the repose time. This unusual ratio goes with an unusual sequence that includes a hiatus in the middle of the precursory activity. The precursory activity we consider here starts in late June 1998 with a series of small low-frequency earthquakes that continued until the end of 1998 October. After October, the volcano became quiet until the new increase in the precursory activity in early February, possibly indicating a new or renewed intrusion (Moran *et al*. 2002; Nye *et al*. 2002). Measuring the precursory interval from February results in a ratio of 1/40, which is still higher than other volcanoes with similar magma composition, but less extraordinary. In Fig. 1 and subsequent interpretations, we maintain consistency with the operational definition of Section 2 by choosing 1998 June 15 as the onset time, although it is possible that a shorter one would have been more appropriate physically.

Less easy to explain are Hekla and Okmok eruptions. These voluminous basaltic–andesite eruptions have repose times consistent with their moderate silicate composition, but run-up times more typical of low silica systems, that is, shorter than expected. The anomalously short warning was anecdotally noted for both systems as a cause for consternation to local observatories (Soosalu *et al*. 2005; Prejean *et al*. 2008; Johnson *et al*. 2010). Magma mixing for Hekla (Sverrisdottir 2007) and high supply rate for Okmok (Fournier *et al.* 2009) together with a favourable local fault and stress distribution result in relatively fast magma migration to the surface.

A particular mention is needed for Stromboli volcano. Even though it is not a statistical outlier from the linear trend, we have to clarify the presence of only one eruption in our catalogue for this very active volcano. Stromboli is an open conduit volcano with permanent crater activity lasting more than 1000 yr (Barberi *et al*. 2009). Because we cannot consider events during continuous small explosion because of the impossibility of defining a clear interevent time, we decide to focus our investigation on the effusive eruption of this volcano. The two last effusive events at Stromboli were in 2002 and 2007. For the 2002 lava outpouring eruption, the pre-eruptive activity did not make clear signals associated with the dyke emplacement (Bonaccorso *et al*. 2003), so we decided not to use this event. The 2007 eruption showed a clear onset phase associated with a dyke emplacement (Barberi *et al*. 2009) and we included this eruption in our data set. We define the repose time for this event as the time elapsed since the last effusive eruption occurred in 2002.

Interrelationship between repose times and volume erupted

We have presented so far a statistical analysis of the interdependencies among the repose times, run-up times and the silica content of each eruption in Table 1. In this section we investigate the possible association of the repose times with the volume erupted. This exercise could reveal systematic co-variation between these two physical observables and provide insight into the magma accumulation process in the crust.

The observed eruptive volumes have much larger relative errors than either the repose or run-up times. As documented by Passarelli *et al*. (2010a) and reference therein, the relative errors on volume can be estimated to be as much as 25 per cent. Because of these large uncertainties, we use a more sophisticated means of evaluating the correlation than was necessary for the earlier work. Passarelli *et al*. (2010a) developed a Bayesian method to consistently use the errors in the physical observables throughout the statistical evaluation.

The model assumes that the repose time and volume data are log-normally distributed or equivalently that the logarithm of the data are normally distributed with standard deviation calculated using the data errors. The variables are linked to each other through a linear equation, that is $R = bV + K + \sigma_R{}^2$, where $R = \ln(t_{\text{repose}})$, $V = \ln(v)$, v is the volume, $\sigma_R{}^2$ is the misfit of the model and b and K are parameters. Simulation of posterior distributions for variables and parameters of the model (i.e. R, V, $\sigma_R{}^2$, b and K) are obtained using Monte Carlo Markov Chain–Gibbs sampling. To infer the slope, the intercept and error of the repose times–volume linear equation we run the model for 10 000 iterations. Results of the posterior distribution for b, K and $\sigma_R{}^2$ are presented in Fig. 6. The distributions of the slope b and intercept K have average values equal to (0.88 ± 0.13) and (4.06 ± 0.49), respectively, (errors are one standard deviation); the median for the skewed distribution of error model $\sigma_R{}^2$ is 4.44 in log units.

Distributions in Fig. 6 show that b is indistinguishable from 1, that is, there is a linear relationship between repose times and volumes even if the high values of the misfit parameter distribution $\sigma_R{}^2$ reveal a high variability in the data set. The positive linear trend is consistent with previous work suggesting that high silica systems, with long repose intervals, tend to erupt larger volume of material compared with low silica systems with relatively short repose times (White *et al*. 2006).

The observed trend can be attributable to a supply rate effect, that is $t_{\text{repose}} = V/Q$. The correlation is consistent with quasi-steady magma accumulation rate Q. Such an inference is surprising in the light of the many potential physical factors affecting the magma supply rate. Magma accumulation rate should scale with magma mobility as we infer later in the paper using the observed repose times and volume data. However, particular local features of the stress field or changes in mechanical and physical properties of the hosting rocks may hinder the magma propagation at depth impeding a steady magma accumulation.

We also have checked possible association of run-up times and volumes. Unfortunately we cannot use the previous approach because the run-up time data are not log-normally distributed as

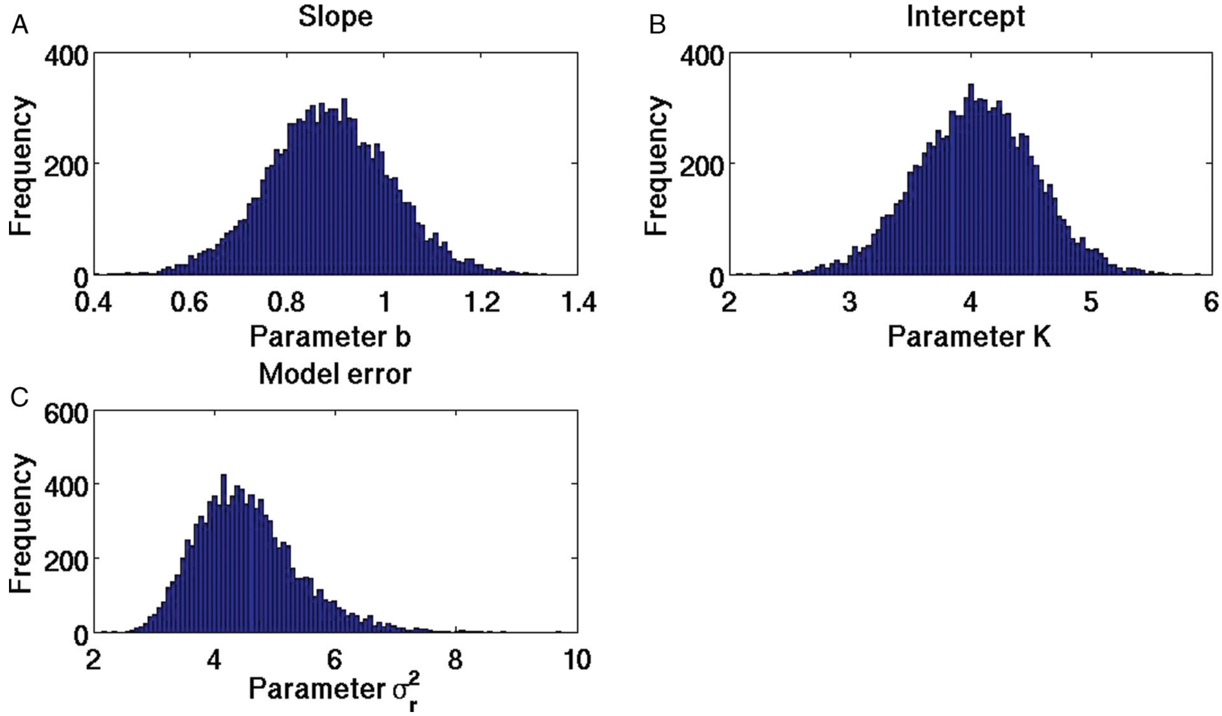

Figure 6. Histograms are the simulated posterior distributions for parameters of the Bayesian linear regression analysis between repose time and volume erupted discussed in the text using the Passarelli *et al* (2010a) model. (A) Distribution of the slope b of the regression line, (B) distribution of the intercept K of the regression and (C) distribution of the error model $\sigma_R{}^2$. The distributions are based on 10 000 simulations obtained using a Monte Carlo Markov Chain–Gibbs sampling.

it is required in the Passarelli *et al.* (2010a) model. Testing the co-variation through linear regression of volumes–run-up times data shows a very poor correlation and so was not investigated further statistically.

This lack of an observable correlation between volume erupted and precursory activity may be fruitful subject for future physical studies. A possible explanation might be related to the fact that the volume is not conserved from the shallower reservoir to the surface (Rivalta & Segall 2008) and thus the volume itself is not a good metric for testing the correlation with precursory activity. Other explanations include secondary effects controlling the run-up time. For instance, a separate gas phase can extend the precursory signals (Menand & Tait 2001) or the stress condition on a system of faults can control the timing of a sequence of seismicity independently of the volume of magma involved. However, we confine ourselves in this first study of the relationship to simply noting the statistical observation of an extraordinarily weak correlation.

These results are distinct from previous work on the correlation between repose times and erupted volumes for different volcanoes associated with the time-predictable model (De la Cruz-Reyna 1991; Burt *et al.* 1994; Sandri *et al*. 2005; Marzocchi & Zaccarelli 2006; Bebbington 2008; Passarelli *et al*. 2010a, b). In these previous model-driven studies the unknown time to the forthcoming eruption is proportional to the volume erupted in the last eruptions, whereas in Table 1 the listed volumes refer to the considered eruption although the repose time is calculated with respect to the previous eruptive event. In other words, in the time-predictable model the volume v_i of the ith eruption beginning at time t_i is related to a repose time defined as $r_i = t_{i+1} - t_i$ whereas in our data set the repose time corresponding to v_i is defined as $t_{\mathrm{repose}} = t_i - t_{i-1}$.

Viscosity as a tool for interpretation

The results thus far suggest that magma composition plays a role in both precursory and repose times. The magma composition mirrored in magma viscosity is one of the main controlling parameter on the velocity of magma-filled dykes propagating within the crust (Rubin 1995; Costa *et al*. 2007). Thus it can be worthwhile to try to gain an insight into the correlation between the eruptive time controls with the silica content in the light of a physics-based magma propagation model.

It is well known that the silica content and viscosity co-vary and generally higher silica content results in larger viscosity for the magma. Therefore, correlation observed with silica content may be reflected in the magma viscosity. However, the viscosity does not only correlate non-linearly with silica content, but also with crystal, water and volatile contents. The abundance of one of the latter parameters might increase or decrease the viscosity of magma even by orders of magnitude. Therefore, the correlation between bulk magma viscosity and bulk silica content is strongly non-linear and cannot be parameterized easily (Takeuchi 2011). For this reason it is not straightforward to translate the eruptive silica content in Table 1 into magma viscosity and use these viscosities for discerning whether the observed magma run-up and repose times are compatible with a simple model of magma uplift velocity.

We tackle this problem using a pre-existing database of viscosities calculated for a range of magma composition that overlaps our range of composition. We use the database published in Takeuchi (2011) consisting in 86 viscosity calculations for magmas spanning from basaltic to rhyolitic composition. We use this database of viscosity and a simplified model of magma velocity to calculate the resulting run-up times and compare them with our database. Of course, the Takeuchi (2011) examples are distinct from the eruptions studied here and so can simply be used to delineate the range of possible behaviours.

Similarly, we also show that the observations analysed here are consistent with previous inferences of the viscosity-dependence of recharge processes. Finally, we discuss other possible complicating factors affecting the magma uplift process not accounted in the simple physical model we use. We carefully discuss those factors highlighting their possible influence onto the scatter we observe in the correlation between run-up/repose time and silica content.

Possible consistency of standard dyking scalings and run-up time observations

We defined run-up time as a proxy for the time necessary for magma to travel from the magma chamber to the surface. Their relationship between magma migration and precursory seismicity is likely a complex process. Magma propagation can directly cause failure of the wall rock, generate indirect effects through gas release and thermal interactions and have internal brittle failure events (Menand & Tait 2001; Kilburn 2003; Burlini *et al*. 2007, Benson *et al*. 2008, LaVallée *et al*. 2008). Given these complexities, the scatter in the observations is hardly surprising. However, if the run-up time is in any way related to the magma migration, we would expect that a simple model of dyke propagation to the surface should match the order of magnitude of the observed for reasonable variations in viscosity. If an unrealistic range of viscosities is required to match the data with a dyking model, then magma migration through brittle rock is likely not the underlying process. To this end, we will calculate dyke propagation time (and hence run-up time) as a function of viscosity by considering the movement of a pressure-driven, magma-filled crack.

A standard model of a dyke is a 2-D planar pressure-driven elliptical crack propagating in an elastic medium subjected to a regional stress with a Poiseuille flow (Rubin 1995). If the host rock stresses and the displacement because of the dyke opening depend only upon the difference between internal magma pressure and the ambient compressive stress, the order of magnitude dyke propagation velocity under a linear pressure gradient p_0/L, assuming a laminar flow in the height direction, is given by

$$u = (1/3\eta)(p_0^3/M^2)L, \tag{1}$$

where η is the viscosity, p_0 is the magma pressure at the dyke entrance, M is the elastic stiffness, L is the dyke height and $w = (p_0{}^3/M^2)L$ is the half dyke thickness (Rubin 1995).

The time necessary for ascent from the magma chamber to the surface is the propagation time of a dyke with height L equal to the depth of magma chamber below the surface. Therefore,

$$t_{\mathrm{run-up}} = L/u = 3\eta M^2/p_0^3. \tag{2}$$

For typical values of $p_0 = 5$ MPa and $M = 3 \times 10^{10}$ Pa, and a range of viscosity of 10^1–10^9 as the one published in Takeuchi (2011) results in a range of 10^{-3}–10^6 d. The range of run-up times that ensues from this calculation matches the run-up times in Table 1 that span 10^{-2}–10^5 d.

We can conclude that the consistency between the simplistic magma ascent model and the range of the run-up time data for a reasonable range of viscosities confirms that magma mobility is a plausible explanation for the correlation.

Possible consistency of recharge models and repose time observations

Between eruptions, the magma chamber is recharged by a series of intrusions from depth. The speed of each individual intrusion is again related to viscosity through some combination of dyking, diapirism and porous media flow (Annen *et al*. 2006; Karlstrom *et al*. 2009). In all of these processes, recharge rate is inversely proportional to viscosity, therefore the higher silica systems are expected to take longer to fill a magma chamber and accumulate sufficient overpressure for an eruption. Studies of the duration of magma transfer in the crust based on uranium-series disequilibria show that magma differentiation time (i.e. cooling and crystal–liquid separation) is a function of silica content with high silica magma having greater intervals storage in crustal magma reservoir than low silica magma (Reid 2003). Storage time from crystal ages for basaltic system are generally longer or equal to repose times; for higher silica systems the storage times are comparable or slightly shorter than repose times (White *et al.* 2006).

A complete model of magma chamber recharge processes is beyond the scope of this paper. One simple conceptualization of magma reservoir is a storage system to which mass enters with a particular rate Q_i and is extracted at particular rate Q_e. In such cases when input and output are equal, that is $Q_\mathrm{i} = Q_\mathrm{e}$, it may attain quasi-steady-state condition and the magma residence time could be defined as V/Q_e (Reid 2003). Only fewer than 30 per cent or likely only the 10 per cent of the subaerial volcanoes approximate these conditions (Pyle 1992). For other volcanoes, eruption is not the only output of magma reservoir: there is also subsurface magma solidification as plutonism. In these non-steady-state cases, $Q_\mathrm{i} \le Q_\mathrm{e}$ and the relationship between residence times and volumes is only approximate (Reid 2003).

Here, we simply show that the observed repose time trend is consistent with recharge rates inferred by other means and thus appears to be reflecting the dynamics of deep crustal magma flow. We can make this connection by converting the repose time information into volcanic eruption extrusion rates, which is a quantity previously studied. The repose time is related to the extrusion rate Q_e by

$$Q_\mathrm{e} = V/t_{\mathrm{repose}}, \tag{3}$$

where V is the volume of an individual eruption. From the information in Table 1, the average Q_e for the basaltic volcanoes is $(5.4 \pm 0.1) \times 10^{-2}$ Km^3 yr^{-1}, for basaltic–andesites is $(3.3 \pm 0.8) \times 10^{-2}$ Km^3 yr^{-1}, for andesites is $(8.2 \pm 2.0) \times 10^{-3}$ Km^3 yr^{-1} and dacites is $(4.8 \pm 1.0) \times 10^{-3}$ Km^3 yr^{-1}. Errors for the extrusion rates are calculated averaging out the errors of Q_e obtained using the error propagation formula with relative error for repose times and volumes equal to 1 per cent and 25 per cent, respectively.

The average output rates here calculated are of the same order of magnitude of those presented by White *et al.* (2006). Despite some discrepancy given by using different definition of repose time, both data sets show a decreasing trend in repose time with silica content. As a first order approximation, it should be seen as the role played by the viscosity in the magma reservoir recharging process (Reid 2003).

This simple comparison highlights how the low silica systems take shorter time to refill the magma reservoir than high silica systems, assuming the output rate as a rough measure of the magma recharge rate. For low silicic volcanoes with relatively low viscosity the recharge rate is higher; high silica systems show very low recharge rate compatible with their higher viscosity.

Other complicating processes

The rest of the variance not explained by the regression analysis between the silica content and magma run-up time can be interpreted in two overlapping ways: (1) the viscosity is not the only control in the dynamics of the dyking process but the stress field induced by the magma propagation or the tectonic stress and topographic load the magma undergoes may play an equal important role in magma movements (Hamling *et al*. 2010; Maccaferri *et al*. 2011) and (2) the magma, in its path to the surface, can experience drastic increase in the viscosity because of volatile exsolution and crystallization so that the silica-based inferences are not accurate representations of the rheology (e.g. Costa *et al.* 2007). A drastic increase in viscosity, for high viscosity volcano, may eventually lead to a situation in which magma transport is dominated by processes separate from dyking as proposed by recent fieldwork on eroded conduit walls (Tuffen & Dingwell 2005) and numerical modelling of the lava-dome eruption (Costa *et al*. 2007). Furthermore, exsolution of volatiles can generate precursory activity migrating faster than magma movement. Menand & Tait (2001) have shown how the duration of precursory activity is in part related to a gas phase propagating in front of the dyke tip in laboratory experiment and the consequent cracking velocity is mainly driven by the very low viscosity of gases.

Similarly, the stronger correlation between repose time and silica content may be indicative of the slower recharge rate for high silica systems compared with the one of low silica system, as discussed in the previous section. However, additional processes also co-vary with silica content. For instance, magma storage time, inferred by crystal age and crystal size distribution, is a power law increasing function of the silica content. As a consequence the volume of stored magma increases (Reid 2003; Hawkesworth *et al*. 2004) and high silica volcanoes tends to have larger magma reservoirs (Annen *et al*. 2006). In addition, non-steady magma supply rate for a particular volcanic system may yield to shorter or longer repose and run-up time. In particular for those high silica eruptions driven by mixing with more primitive mafic magma, the run-up time could be shorter than other system of the same class of magma composition, because the first eruptive product is almost always the mafic magma (Takeuchi 2011).

Moreover, the supply rate is also controlled by the tectonic stress. In compressive settings the supply rate can be low and the repose time could be long compared with extensional environment. As a consequence, the run-up time can also be lengthened as the pressure needed to break the rocks has to be high. In extensional settings on the contrary, the magma erupted is usually mafic and less viscous, leading to short repose and run-up times that are both strongly dominated by the deep magma recharge rate. At the same time in these systems, multiple magma intrusions may occur before an eruption complicating the estimation of the magma run-up possibly yielding to an overestimation of this time.

Finally, the magma composition and differentiation can play an equal important role in the correlation we observe. Because crystal content and magma temperature co-vary, the freezing processes tend to slow down the magma uplift velocity and consequently lengthen the repose and run-up time. Finally the presence of local and shallow stress features or favourable system of faults can ease the magma to reach the surface, shortening the magma run-up time regardless the magma composition.

In conclusion, this paper presents possible physical interpretations of repose and run-up times on the ground of the silica/viscosity parameter. At the same time we bear in mind that a full physical description of the pre-eruptive dynamics must take into account all processes above discussed.

CONCLUSIONS AND IMPLICATIONS FOR ERUPTION FORECASTS

In this work we show the interrelationship between repose time, run-up time and silica content. The data presented suggest a positive correlation between repose and run-up time for all classes of magma composition volcanoes. The inferred power law relationship between repose and run-up time together with the magma silica content indicates similar dependency on the magma rheology. At the same time, the scatter of the data represents the difficulty of measuring the magma run-up time using the duration of the precursory activity. Most likely the precursory activity and thus our measure of the run-up time is also strongly influenced by other factors such as the tectonic setting, the volcano stress history, the role of the magma differentiation and volatile exsolution.

The high correlation we found between repose time and silica/viscosity, it seems to point out the role played by magma viscosity in the dynamics of the magma chamber refilling. This last result is also corroborated by the power law association we found between repose time and volume erupted that may represent how high viscous systems are less mobile than low silica systems but they tend to store and erupt larger volume of magma. Both magma chamber and magma migration models may benefit from these findings. Finally this work can be incorporated into probabilistic models for long- and short-term eruption forecast such as event trees. The findings and the interdependency we found can be implemented in such models to better constraint the alert window during a real volcanic crisis period.

Using the relationships between run-up–repose time and repose time–silica observed here provide a way to design a prediction window appropriate to a particular magmatic system. For instance, if unrest begins on a low silica system with short quiescent period, one should expect an eruption to occur within hours to days, if it is going to happen. On the other hand, for a high silica system that has experienced a very long quiescent time, an alert period should remain open for a much longer period of time from days to years. Furthermore, the inferred correlation between magma silica content and repose time suggests high viscosity systems have longer quiescent period and tend to erupt very large amount of magma then low silica systems.

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