Global volcanic unrest in the 21st century: An analysis of the first decade ☆

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ABSTRACT

We define volcanic unrest as the deviation from the background or baseline behaviour of a volcano towards a behaviour which is a cause for concern in the short-term because it might prelude an eruption. When unrest is preceded by periods of quiescence over centuries or millennia it is particularly difficult to foresee how a volcano might behave in the short-term. As a consequence, one of the most important problems is to assess whether unrest will culminate in an eruption or not. Here, we review and evaluate global unrest reports of the Smithsonian Institution Global Volcanism Program (GVP) between January 2000 and July 2011. The aim of the evaluation is to establish the nature and length of unrest activity to test whether there are common temporal patterns in unrest indicators and whether there is a link between the length of inter-eruptive periods and unrest duration across different volcano types. A database is created from the reported information on unrest at 228 volcanoes. The data is categorised into pre-eruptive or non-eruptive unrest indicators at four different subaerial volcano types and submarine volcanoes as defined by the GVP. Unrest timelines demonstrate how unrest evolved over time and highlight different classes of unrest including reawakening, pulsatory, prolonged, sporadic and intra-eruptive unrest. Statistical tests indicate that pre-eruptive unrest duration was different across different volcano types. 50% of stratovolcanoes erupted after about one month of reported unrest. At large calderas this median average duration of pre-eruptive unrest was about twice as long. At almost five months, shield volcanoes had a significantly longer unrest period before the onset of eruption, compared to both large calderas and stratovolcanoes. At complex volcanoes, eruptive unrest was short lived with only a median average duration of two days. We find that there is only a poor correlation between the length of the inter-eruptive period and unrest duration in the data; statistical significance was only detected for the pair-wise comparison of non-eruptive unrest at large calderas and stratovolcanoes. Results indicate that volcanoes with long periods of quiescence between eruptions will not necessarily undergo prolonged periods of unrest before their next eruption.
Our findings may have implications for hazard assessment, risk mitigation and scenario planning during future unrest crises.

1. Introduction and background

Currently, about 200 million people globally reside within a 30 km radius and >47 million people within a 5 km radius of approximately 1300 Holocene volcanoes (Chester et al., 2001; Siebert et al., 2010). As the human population continues to grow exponentially, an increasing number of people will be living in areas with heightened levels of vulnerability to volcanic hazards, particularly in the less developed countries (LDC) of Latin America and SE Asia (Small and Naumann, 2001). Volcanic eruptions and knock-on effects have the potential for significant socio-economic impact. In the spring of 2010 the eruption at Eyjafjallajokull Volcano led to the closure of Europe's airspace incurring more than US$2.5 billion in lost revenue to the airline industry (Airports Council International, 2010) and a total impact on global GDP caused by the first week's disruption amounted to approximately US$4.7 billion (Oxford Economics, 2013). Equally compelling are the figures available for implications of 'false positives' related to volcanic unrest, meaning that action was taken as a response to an imminent threat of an eruption which did not manifest as expected. In the case of volcanic unrest the imminent threat is generally defined as a magmatic eruption, although the multi-hazard nature of volcanic unrest (e.g., ground shaking, ground uplift or subsidence, ground rupture,

ground instability, gas emissions, phreatic explosions) makes the definition of "imminent threat" rather complex. Examples include:

(1) Evacuation and rehousing of 40,000 inhabitants of Pozzuoli in the Campi Flegrei volcanic area of Italy resulted as a response to intense seismicity and ground uplift in the early 1980s. Decision-makers did not define an eruption as the imminent threat due to disagreements among scientists regarding the cause of the unrest (Barberi et al., 1984).
(2) The 1983–5 unrest at Rabaul Volcano in Papua New Guinea (LDC) had significant adverse implications for both the private and public sectors. Considerable economic costs were incurred, estimated at over US$22.2 million at the 1984 rate of exchange, although an eruption did not occur until 10 years later (Benson, 2006).
(3) A major evacuation over a period of four months in excess of 70,000 individuals on Guadeloupe in the French West Indies in 1976 was initiated as a result of abnormal levels of volcanic background activity, which culminated in a series of phreatic explosions before waning. Not a single life was claimed by the activity, however, the estimated cost of the unrest was about US$300 million at the 1976 exchange rate (J-C Komorowski, personal communication, compiled from Tazieff (1980), Baunay (1998), Lepointe (1999), Annen and Wagner (2003)), which translates to more than US$1 billion at present. Of these costs, 90% were incurred by the evacuation, rehabilitation and salvage of the French economy. This in turn suggests that had the outcome of the unrest on Guadeloupe been predicted "correctly" the financial cost of the unrest crises would have been almost negligible. Nevertheless it is now acknowledged that the "proportion of evacuees who would have owed their lives to the evacuation, had there been a major eruption, was substantial" (Woo, 2008).

Although it appears vital that scientists are able to decipher the nature, timescale and likely outcome of volcano reawakening following long periods of quiescence early in a developing unrest crisis, the volcanological community still faces major challenges when assessing whether unrest will actually lead to an eruption or wane with time. According to Newhall and Dzurisin (1988) the nature, frequency, duration, outcomes and possible causes of past caldera unrest are considered to "provide a context in which future episodes of unrest can be interpreted".

Following this principle we collated available data on global volcanic unrest during the first decade of the 21st century across several types of volcanoes with an aim to audit these reported unrest episodes. Evaluating the catalogue this paper attempts to establish relationships between several key parameters of unrest (e.g., unrest duration vs. length of inter-eruptive period) as well as exploiting the nature, type and temporal evolution of unrest for a categorisation of unrest episodes. This is in view of testing the potential value of unrest parameters as indicators for an eruptive or non-eruptive evolution. McNutt (1996) proposed an unrest scheme for the evolution of volcanic earthquake swarms. Following a similar, yet, perhaps broader characterisation scheme we attempt to establish different unrest indicators across a variety of volcano types. To our knowledge, there has not been such a systematic study of historical unrest.

The key objectives of our study are:

(1) an identification and classification of repeated patterns of unrest to establish
(2) whether particular types of volcanoes display preferred patterns of unrest,
(3) whether the length of repose affects preferred patterns of unrest, and
(4) whether pre-eruptive patterns can be distinguished from non-eruptive patterns of unrest.

2. Methods and database creation

2.1. Data collection

In this study we primarily used information provided by the Smithsonian Institution Global Volcanism Program (www.volcano.si.edu/reports/usgs/; Venzke et al., 2002–2011). The GVP provides up-to-date information of volcanic activity worldwide on a weekly basis describing significant unrest activity and eruptions. In a first step, all volcanoes that had reported unrest activity in the GVP catalogue during the first decade of this century, 2000–2011 were investigated with a cut-off date of 31/7/2011. For greater in-depth analysis we also exploited other available information in the published literature for some activities reported in the GVP. This was particularly necessary for establishing inter-eruptive periods for those volcanoes where the last documented eruption dated back several decades or centuries.

2.2. Database creation and definition nature of variables

A database was created which includes 228 volcanoes (Fig. 1, Table 1 and online Supporting material) from which response and classification variables are obtained for statistical analyses. Although the GVP groups unrest under ten different types of volcanoes (Siebert et al., 2010), we have concentrated on the four primary subaerial types based on large scale morphology following the classification provided by the GVP. In addition to simplicity, the four-fold classification allows each category to contain a number of volcanoes that is significant. The type classifications are: large caldera, complex, shield, and stratovolcano. Submarine volcanoes have their own classification but are not further subdivided. Definitions of all volcano types in our database can be found in the GVP and are not repeated here. Type classification of individual volcanoes in the database is according to the GVP.

Classification variable *unrest outcome* is subdivided into:

(1) Pre-eruptive unrest: unrest culminating in a volcanic eruption involving the explosive ejection of fragmental material, the effusion of lava, or both.
(2) Non-eruptive unrest: unrest not associated with a volcanic eruption; either the unrest merely waned or an eruption had not occurred by the cut-off date (31/7/11).

We have further introduced the following definitions for response variables:

(1) Unrest duration: the number of days during the inter-eruptive period with recorded unrest.
(2) Unrest indicators: the geophysical and geochemical indicators of reported unrest.
(3) Inter-eruptive period: the time in days between two successive eruptions.

2.2.1. Unrest indicators

We recognise five primary observational (predominantly geophysical and geochemical) indicators of volcanic unrest and categorise the information from the GVP as follows (see also Table S1 in online Supplementary material):

(1) ground deformation: comprises inflation, deflation and ground rupturing.
(2) degassing: comprises gas plumes from vents and changes in the fumarolic activity.
(3) changes at a crater lake: includes variation in temperature, pH and water levels, increases in gas discharge or bubbling and changes in water chemistry or colour as well as shifts in the position of the crater lake.
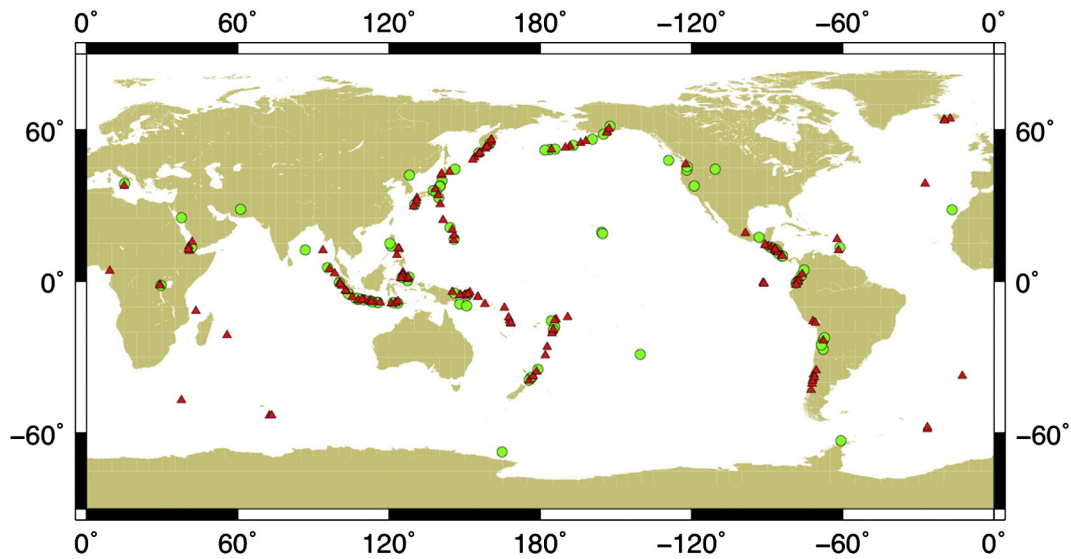(4) thermal anomaly: includes increases in fumarole temperature and hot spots identified by satellite remote sensing.

Fig. 1. Location map of volcanoes with documented unrest between 01/01/2000 and 31/07/2011. Green circles show volcanoes with unrest not followed by eruption within reporting period, while red triangles show those with eruption. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(5) seismicity: comprises shallow/deep volcanic events, tremors, tornillos, hybrid events, single event earthquakes and volcano-tectonic events.

2.2.2. Inter-eruptive period (IEP)

In the literature, the inter-eruptive period has been calculated in two ways: either as the time from the cessation date of an eruption to the onset date of the next eruption (Sandri et al., 2004; Siebert et al., 2010); or from the onset date of one eruption to the onset date of the next eruption (Sandri et al., 2005; Furlan and Coles, 2011; Passarelli and Brodsky, 2012). The 'onset date' approach creates a large bias towards persistently active volcanoes or long-lasting dome-forming eruptions with episodes of magma extrusion separated by pauses of eruptive; for example, using the onset date the inter-eruptive period at Stromboli would be more than 77 years, when, realistically, it has been practically continuously erupting since 1934 (Venzke et al., 2011). Here we apply the 'cessation date' definition to calculate the inter-eruptive period between the last reported eruptive activity (explosive or effusive) and the next. However, there is still a degree of uncertainty when establishing the exact end of a volcanic eruption from the consulted archives and temporal uncertainties may be of the order of days. Furthermore, there is no systematic definition available for the end of an eruption period. Table S2 in the online Supplementary

material summarises the length of the inter-eruptive periods per volcano type and unrest mode derived from the consulted data.

2.3. Sample data

The objective of the study is to identify possible temporal patterns in unrest and repose duration across different types of volcanoes. We interrogate data from 134 and 198 volcanoes to inform response variables *unrest duration* (UD) and *length of the inter-eruptive period* (IEP), respectively (Table 1). There are data from 118 volcanoes which simultaneously inform both the UD and IEP, however, for the purpose of this paper we will study both response variables independently. These response variables are evaluated against classification variables to explore their characteristics during reported pre-eruptive and non-eruptive unrest at subaerial and submarine volcanoes as well as at different types of subaerial volcanoes.

2.4. Statistical methodology and visualisation

We employ standard procedures to calculate mean, median and standard deviation of the data (Rice, 1995) and use boxplots to visualise the results. Boxplots graphically display several important statistical parameters describing the data: median (50th percentile or second quartile) $Q2$, interquartile range IQR, lower quartile (25th percentile) $Q1$, higher quartile (75th percentile) $Q3$, and smallest and largest observations. Horizontal lines are drawn at the median and at the upper and lower quartiles and are joined by vertical lines to produce the box. Then a vertical line is drawn up from the upper quartile to the most extreme data point that is within a distance of 1.5 (IQR) of the upper quartile. A similarly defined vertical line is drawn down from the lower quartile. Short horizontal lines are added to mark the ends of these vertical lines. Each data point beyond the ends of the vertical lines is marked with a circle, and they are considered abnormal or unusual data (outliers) for this particular distribution. Boxplots are therefore very useful to identify both deviations from normal data distributions and outliers.

This study aims to test several hypotheses surrounding the nature of volcanic unrest whereby we are interested to test if there is a dependency between different permutations of response variables and classification variables across the sample data (Table 1).

Comparing one unique dependent response variable (e.g., *length of the inter-eruptive period*), against one classification variable (e.g., *volcano type*) which has two or more categories, we call the design a one-way

Table 1
Variables of the database, their nature, number of entries that inform each variable and missing data. Hypotheses are formulated regarding the dependency between response and classification variables.

Variable	Nature	Volcanoes	Missing
Volcano number	Informative	228	
Volcano name	Informative	228	
Latitude	Informative	228	
Longitude	Informative	228	
Volcano type	Classification	228	
Setting	Classification	228	
Unrest outcome	Classification	228	
Inter-eruptive period	Response	198	13%
Unrest duration	Response	134	41%
Unrest indicator: seismicity	Response	121	47%
Unrest indicator: deformation	Response	27	88%
Unrest indicator: thermal anomaly	Response	32	86%
Unrest indicator: degassing	Response	58	75%
Unrest indicator: crater lake changes	Response	16	93%

analyses of variance (ANOVA). If each classification group has unequal numbers of entries, we call the experiment unbalanced, as opposed to a balanced experiment where the number of entries is equal for all groups. If observations in a response variable are assumed to be independent from each other, but lacking enough evidence to assume a particular distribution such as a normal distribution (due to insufficient data or strong skewness of the data), we then need to use nonparametric procedures to perform an ANOVA analysis.

As we will show in Section 3, the underlying data distributions considered in this study are not normal, some of the data counts are very small (less than 5 in some categories), and there are a significant number of outliers in some groups. Given these characteristics of the data set, we chose to test the hypotheses applying nonparametric one-way unbalanced ANOVA using the Kruskal–Wallis test (Rice, 1995).

The Kruskal–Wallis test pools and ranks the observations after which the observations are replaced by their ranks. This replacement has the effect of moderating the influence of outliers (see (Sobradelo et al., 2010, and references therein) for further details on this methodology).

Let R_{ij} be the rank of observations Y_{ij} in the combined sample, and let

$$\bar{R}_{i.} = \frac{1}{J_i} \sum_{j=1}^{J_i} R_{ij} \qquad (1)$$

be the average rank in the ith group. Let

$$\bar{R}_{..} = \frac{1}{N} \sum_{i=1}^{I} \sum_{j=1}^{J_i} R_{ij} = \frac{N+1}{2} \qquad (2)$$

where N is the total number of observations. Let

$$SS_B = \sum_{i=1}^{I} J_i \left(\bar{R}_{i.} - \bar{R}_{..} \right)^2 \qquad (3)$$

be a measure of the dispersion of the $\bar{R}_{i.}$. Under the null hypothesis that the probability distributions of the I groups are identical, the statistic

$$K = \frac{12}{N(N+1)} SS_B \qquad (4)$$

is approximately distributed as a Chi-square random variable with $I - 1$ degrees of freedom. This test statistic is then used for hypothesis testing: "Assuming that the null hypothesis is true, what is the probability (p-value) of observing a value for the test statistic that is at least as extreme as the observed value?".

A result is "statistically significant" if it is unlikely to have occurred by chance. Therefore, after a result has been proven to be statistically significant, we have statistical evidence to reject the null hypothesis that the observed difference is due to random variability alone. In this case the alternative that the difference is due to the specific characteristics of each group holds true. The amount of evidence required to accept that an event is unlikely to have arisen by chance is known as the significance level or critical p-value. Popular levels of significance are 5% (0.05), 1% (0.01) and 0.1% (0.001); the lower the derived p-value scores below the significance level, the greater the statistical evidence for rejection of the null hypothesis (Rice, 1995).

For illustration, one null hypothesis of this study is that the length of the inter-eruptive period is the same across volcano types, and the alternative hypothesis is the opposite, i.e., the length of the inter-eruptive period is different across volcano types. We apply the same procedure to test all hypotheses involving the different permutations between all response and classification variables.

We choose a significance level of 10% and therefore any p-value < 0.1 indicates statistical significance for the rejection of the null hypothesis in favour of the alternative. We used the software package SAS 9.1.3. to perform all tests of the study.

We also created 'volcano timelines' using floating bar charts in Microsoft Excel, which serve the purpose to visualise the evolution of reported unrest activity over time and aid the evaluation of unrest classes at individual volcanoes. Representative timelines are shown in the main text and additional examples can be requested from the authors.

2.5. Biases

2.5.1. Reporting bias

Although substantial efforts have been directed over the past decades towards improving volcanic monitoring programmes, one must recognise that available data and information on unrest in the GVP is incomplete and at times unreliable. Not only is the historical record of volcanic unrest largely incomplete but also in the cases of some well-studied volcanoes observations and data are only available for a couple of decades (Newhall and Self, 1982; Aoyama et al., 2009). We must therefore acknowledge that the knowledge base regarding occurrence, nature and duration of volcanic unrest is very limited. Whether or not unrest activity is reported is largely dependent on the subjective judgement of observers of geophysical or geochemical activity at a volcano as to whether it constitutes a deviation from background activity and thus may be termed unrest (Marti et al., 2009). There appears a lack of agreement regarding the terminology associated with volcanic unrest. Terms such as "precursor" and "unrest" are only poorly defined and semantics of these terms in different languages may play an important role for communication and reporting, or lack thereof.

Numerous definitions of the term unrest are available in the published literature, and encompass notions of "unusual non-eruptive activity" or "anomalous activity" above normal background levels (Newhall and Hoblitt, 2002; Hill et al., 2003; Parfitt and Wilson, 2008; Diefenbach et al., 2009). However, background levels of activity differ between volcanoes and what is classified as unrest or anomalous behaviour at one may be considered 'normal' behaviour at another (Diefenbach et al., 2009). Since there is no common baseline activity across all types of active volcanoes either, defining a threshold level of activity that must be met to call an unrest is extremely difficult and will affect the degree of reporting of unrest. For remote locations with difficult access for ground-based monitoring surveys or those that lack any monitoring instrumentation remote sensing surveys are often the only source of information of anomalous behaviour and at some volcanoes the only evidence for volcanic unrest is through satellite data; e.g., thermal anomalies (Wright et al., 2004) or ground deformation (Biggs et al., 2009; Fournier et al., 2010). This hindsight identification of unrest indicators often occurs only several years after the unrest and is generally not reported in the GVP. Some geophysical or geochemical variations that may be related to shallow magma migration and may hence indicate potential precursory activity such as changes in the chemistry or level of groundwater are perhaps less likely to be reported compared to anomalous seismic behaviours due to the relatively wide distribution of seismometers compared to other monitoring instrumentation (Sandri et al., 2004). In addition, there may be a reporting bias towards areas that are more densely populated or have a high concentration of essential assets in the vicinity of active volcanoes and which therefore benefit from a better monitoring infrastructure and a larger awareness of risk from hazardous volcanic phenomena.

Unrest activity could be disguised by other activity: hydrothermal buffering can mask changes in the release of gas or other processes (Newhall and Dzurisin, 1988) and uncertainties in estimating wind speeds can cause anomalous readings in gas emission rates (Olmos et al., 2007; Salerno et al., 2009). There is a notable absence of reported unrest for the investigation period for submarine eruptions, which is most likely related to an observation bias of submarine volcanism due to the difficulty associated with monitoring volcanic activity in a submarine setting.

There is also evidence for inaccurate reporting and inconsistencies in different sources of information; for example Olmos et al. (2007)

Table 2
Distribution of missing data for inter-eruptive period and unrest duration.

	Studied	Informed	Missing	% missing
Inter-eruptive period				
Large caldera	23	19	4	17%
Complex	24	22	2	8%
Shield	14	13	1	7%
Strato	150	133	17	11%
Submarine	17	11	6	35%
Total	228	198	30	13%
Unrest duration				
Large caldera	23	16	7	30%
Complex	24	13	11	46%
Shield	14	9	5	36%
Strato	150	93	57	38%
Submarine	17	3	14	82%
Total	228	134	94	41%

report that Santa Ana erupted on 1/10/2005 with pre-eruptive activity recorded from June 2005 onwards, whereas the GVP reports that the eruption began on 16/6/2005 and ended on 1/10/2005. Furthermore, it is at times difficult to establish precisely when an eruptive period is over from reports. As an example, the GVP reports eruptive activity at Papandayan between 11/11/2002 and 8/12/2002, whereas others report the eruption to have ended on 19/12/2002 (Abidin et al., 2006).

While the former uncertainty affects the accuracy of unrest duration, the latter has implications for the calculation of the length of the inter-eruptive period.

Finally, an anomalous activity that does not lead to an immediate eruption or some other significant volcanic event may be less likely reported consistently.

2.5.2. Statistical bias

Some unrest periods can be very short lived and it is possible that reported unrest durations are over-estimated. Seismic swarms can last a few hours but may be documented as lasting a full day. For example, a thermal anomaly at Pagan was reported in the GVP database to have lasted for 2 h but it is logged in the timeline as lasting 1 day. Unrest at Irazu was described as a crater lake altering its colour in February 2007, but it was unclear whether unrest was observed for the entire month, just one day, or maybe a few days on or off throughout the month of February. We recorded this unrest in our data inventory as lasting for 30 days. However, since the number of reported crater lake anomalies is rather small we do not associate any significance to this unrest indicator in our evaluation.

It is also possible that GVP reports include an under-estimation of the duration of unrest. Unrest may have been recorded as lasting a shorter duration than was actually the case due to an observation bias of spot measurements. The rate of volcano degassing, for example, is often not measured frequently or accurate enough due to instrumental
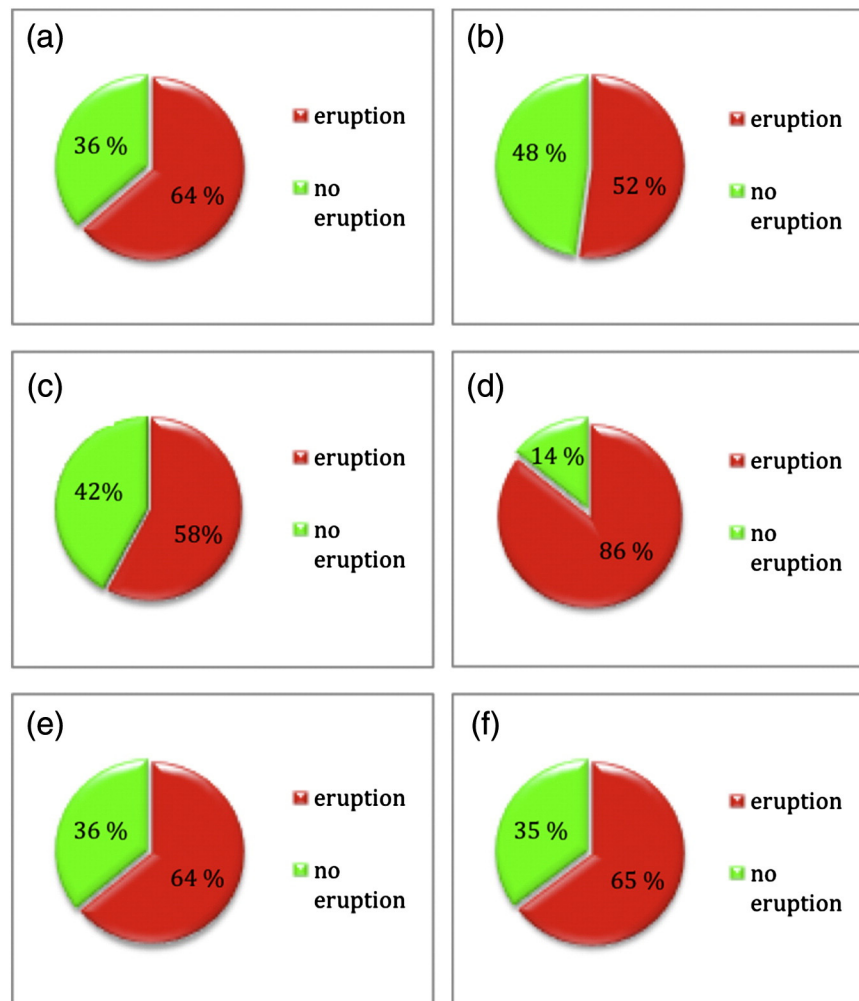

Fig. 2. Pie charts of the proportions of volcanoes with unrest leading and not leading to eruption; (a) all volcano types; (b) large calderas; (c) complex volcanoes; (d) shield volcanoes; (e) stratovolcano and (f) submarine volcanoes.

limitations or frequent changes in atmospheric conditions (Andres and Rose, 1995).

3. Results

This section reports key results for the identification and classification of unrest patterns reported during the investigation period to establish whether there are particular patterns for different types of volcanoes, whether the length of repose affects preferred patterns of unrest, and whether pre-eruptive patterns can be distinguished from non-eruptive patterns of unrest. We report results on the

(1) relative proportion of pre-eruptive vs. non-eruptive unrest and their respective reported durations,
(2) the duration of the inter-eruptive period prior to new pre-eruptive or non-eruptive unrest,
(3) the correlation between the type of unrest, its duration of unrest and the length of the inter-eruptive period, and
(4) the statistical significance of the findings for the correlation between response and classification variables and
(5) the patterns of unrest indicators at different volcano types.

3.1. Unrest duration

41% of the reported unrests do not allow the variable *unrest duration* (UD) to be established. These missing data are distributed evenly across the different categories of sub-aerial volcanoes (Table 2). Submarine volcanoes have the largest amount of missing data (for 8 out of 10 eruptions) and results should hence be interpreted with caution. The pie charts in Fig. 2 give details of the proportions of different volcano types that showed pre-eruptive or non-eruptive unrest over the investigation period. Figs. 3 (right) and 4 show the distributions of unrest duration (days) in the entire data set and grouped by volcano types. The numerical values informing Figs. 3 and 4 are presented in the electronic Supplementary material (Tables S1–S3). A mean unrest duration of 503 days, a standard deviation of 1295 days, and the presence of large extremes are found in the global data set.

A descriptive analysis of the data shown in Table S2 indicates that out of 93 stratovolcanoes undergoing unrest during the investigation period almost 50% erupted after about one month of reported unrest (median = 35 days). At large calderas this median average duration
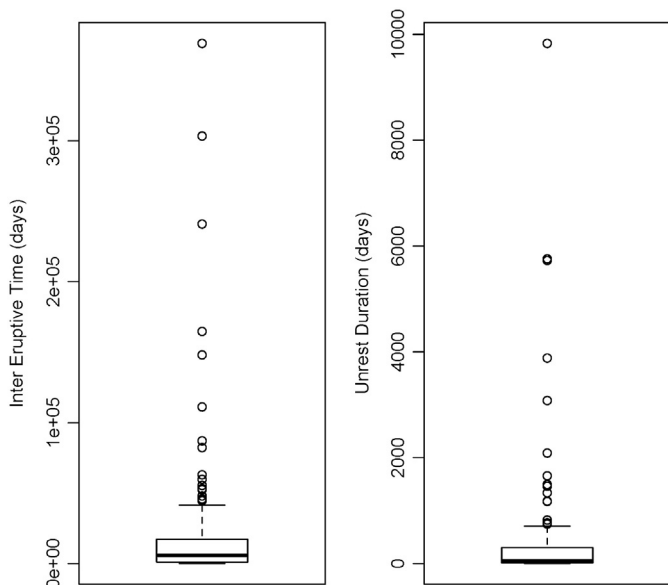
Fig. 3. Boxplots of inter-eruptive period (left) and unrest duration (right), in days. Note the different scales of the y axes. See text for explanation.
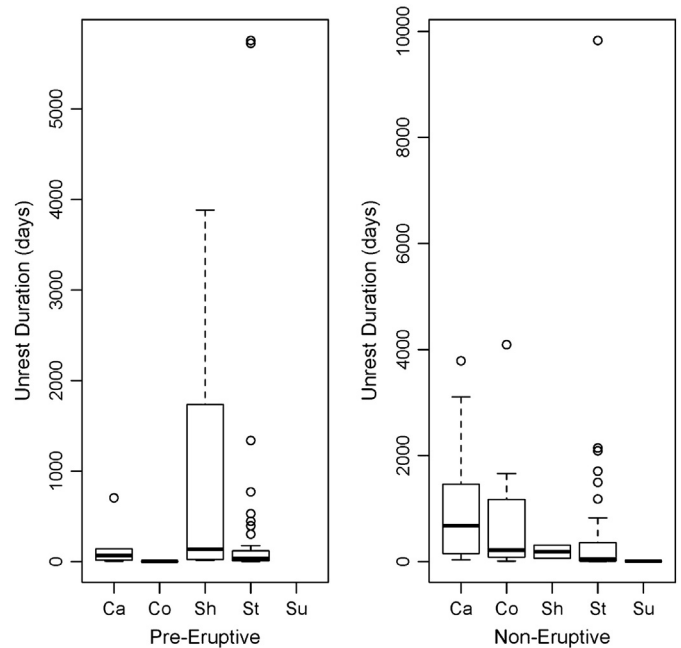
Fig. 4. Boxplots of unrest duration (days) for pre-eruptive and non-eruptive outcomes, segmented by volcano type (Ca = Caldera, Co = Complex, Sh = Shield, St = Strato, Su = Submarine). (Note the different scales in the y axes. See text for explanation.).

of unrest prior to eruption was about twice as long. Shield volcanoes have a significantly longer unrest period before the onset of eruption, compared to both large calderas and stratovolcanoes. Out of 9 shields investigated, 7 have erupted after a median duration of unrest of 137 days (about five months).

Non-eruptive unrest was dominant at complex volcanoes. However, if eruptive unrest did occur it was short lived with only a median average duration of two days.

The shortest unrest indicator is *thermal anomaly* with a mean duration of 36 days while *ground deformation* is the longest with a mean duration of 1001 days (Table S3).

The distributions of UD are different between pre-eruptive and non-eruptive unrest, as well as across different volcano types of volcanoes (Fig. 4). The outlier values for unrest duration primarily result from reports of unrest at stratovolcanoes.

Tables 3 and 4 show the results of the Kruskal–Wallis tests for unrest duration. The UD shows different temporal patterns depending on whether it is pre-eruptive or non-eruptive (p-value 0.0429) or whether unrest is subaerial or submarine (p-value 0.0523; Table 3).

Non-eruptive UD patterns are significantly different across volcano types (p-value 0.0089), with a significantly different pattern between subaerial and submarine unrest, and from stratovolcanoes compared to large calderas (p-value 0.0157) and complex volcanoes (p-value 0.0423), respectively (Table 4). For pre-eruptive unrest, there are also statistically significant differences in the UD at different types of volcanoes (p-value 0.0299), which stem predominantly from unrest data at complex volcanoes. They show a markedly different UD pattern compared to large calderas, shield- or strato volcanoes (Table 4).

Given the records considered here, we found no evidence of significant differences across classification variables for the duration of unrest indicators except for *seismicity*. Statistically significance is evident across volcano types during either pre- or non-eruptive unrest (Table 5). In particular, for non-eruptive unrest, the duration of reported seismicity at stratovolcanoes is shorter compared to non-eruptive seismicity at large calderas, complex and shield volcanoes (see Table S3). For pre-eruptive unrest, the duration of reported seismicity is statistically different (much shorter; Table S3) at complex volcanoes compared to any other volcano type.

Table 3

Results of the Kruskal–Wallis tests for unrest duration (days) for different segmentations (pre-eruptive and non-eruptive unrests, setting and volcano type, respectively).

Unrest duration					
Classified by outcome	N	*p*-Value	0.0429	Significant
Non-eruptive	73			
Pre-eruptive	61			
Classified by setting	N	*p*-Value	0.0523	Significant
Subaerial	131			
Submarine	3			
Pre-eruptive				
Classified by volcano type	N	*p*-Value	0.0299	Significant
Large caldera	7			
Complex	3			
Shield	7			
Strato	44			
Non-eruptive				
Classified by setting	N	*p*-Value	0.0262	Significant
Subaerial	70			
Submarine	3			
Classified by volcano type	N	*p*-Value	0.0089	Significant
Large caldera	9			
Complex	10			
Shield	2			
Strato	49			
Submarine	3			

3.2. Inter-eruptive period

As shown in Table 2, out of the 228 volcanoes in the data set, data from 198 volcanoes inform about the analysis of the IEP with about 13% of the total data set missing this information. The distribution of the missing data is spread across the different volcano types, with a larger amount in the large caldera and submarine categories.

Tables S1 and S2 show a descriptive analysis of the IEP. We find that the mean length of inter-eruptive period (days) is 18,326 with a large standard deviation of 42,710. This is in part due to the large maximum value of 369,100 days, suggesting either the presence of outlier data or the need for further segmentation. To describe this variable in more detail we have included a boxplot of the IEPs (left-hand side of Fig. 3) and the length of IEPs segmented by volcano type and unrest outcome (Fig. 5 and Table S2).

Fig. 3 shows a substantial amount of outliers for the IEPs. In Fig. 5 we find that outliers are mainly associated with stratovolcanoes for both pre- and non-eruptive unrests, as well as large calderas and complex volcanoes for pre-eruptive unrest. The distribution of the IEPs is significantly different for either pre-eruptive or non-eruptive unrest. While the length of the inter-eruptive periods is similar across the different volcano types for pre-eruptive unrest, they differ by several orders of magnitude for non-eruptive unrest. A *p*-value of <0.0001 supports the statistically significant difference of the temporal patterns (Table 6).

Tables 6 and 7 summarise the results of the Kruskal–Wallis tests for the IEP. We could not find sufficient statistical evidence to establish if the IEPs are different for subaerial and submarine volcanoes. This

Table 4

Pair-wise Kruskal–Wallis test for unrest duration (*UD*). Significant pairs are highlighted (*p*-values < 10%).

p-Values	Complex	Shield	Strato	Submarine
Non-eruptive				
Large caldera	0.6831	0.4795	**0.0157**	**0.0126**
Complex		0.5192	**0.0423**	**0.018**
Shield			0.4968	**0.0833**
Strato				**0.052**
Pre-eruptive				
Large caldera	**0.0167**	0.4062	0.5746	
Complex		**0.0167**	**0.0131**	
Shield			0.1648	

Table 5

Significant *p*-values from Kruskal–Wallis tests for duration of unrest indicator *seismicity*.

p-Values	Complex	Shield	Strato	Submarine
Non-eruptive seismicity				
p-Value by volcano type			0.0456	
Large caldera	–	–	0.0502	0.0167
Complex	–	–	0.0946	0.018
Pre-eruptive seismicity				
p-Value by volcano type			0.0377	
Large caldera	0.0366	–	–	
Complex	–	0.0076	0.0054	

also holds true for IEPs during pre-eruptive unrest at subaerial and submarine volcanoes (*p*-value 0.5824) and for different volcano types (*p*-value 0.8449), even during pair-wise comparison of the categories (Table 6). However, we find significant differences in IEPs for non-eruptive unrest for subaerial and submarine volcanoes (*p*-value 0.0359) and volcano types (*p*-value 0.0366). In particular, the difference is statistically significant for the pair-wise comparison of IEP between calderas and strato volcanoes (*p*-value 0.0345) and between strato- and submarine volcanoes (*p*-value 0.0159). A *p*-value of 0.0833 for the pair shield and submarine volcanoes indicates marginal statistical significance (Table 7).

3.3. Classes of unrest

We recognise five idealised classes of volcanic unrest, based on the temporal behaviour of the six most-commonly reported signals in the GVP (seismicity, ground deformation, degassing, thermal anomaly, and crater lake changes) depicted in unrest timelines. While the classes do not capture all unrest signatures of the 228 volcanoes investigated, they provide a general framework to group the nature and evolution of the documented unrests. Detailed background information on the construction of the timelines is given in the electronic Supplementary material.
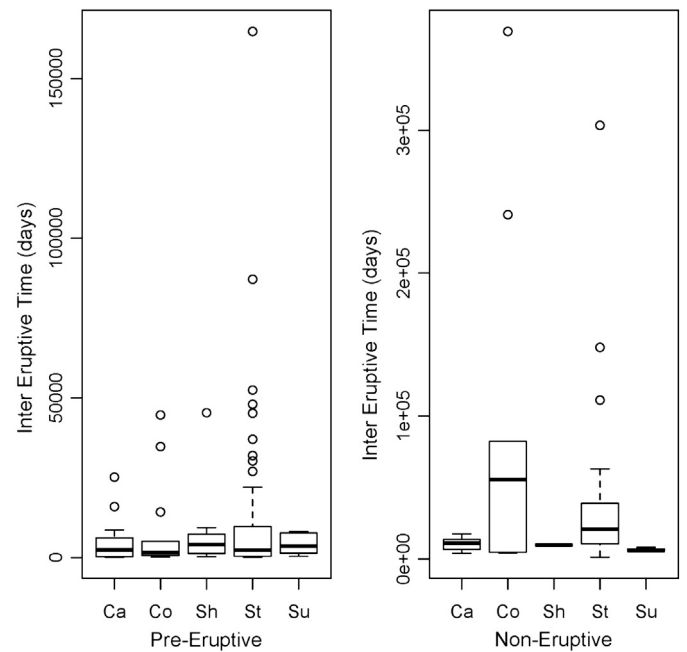

Fig. 5. Boxplots of inter-eruptive period (days) for pre-eruptive and non-eruptive outcomes, segmented by volcano type (Ca = Caldera, Co = Complex, Sh = Shield, St = Strato, Su = Submarine). (Note the different scales in the *y* axes. See text for explanation.).

Table 6

Results of the Kruskal–Wallis tests for the inter-eruptive period for different segmentations (pre-eruptive and non-eruptive unrests, setting and volcano type, respectively.).

Inter-eruptive period					
Classified by unrest	N	p-Value	<0.0001	Significant
Non-eruptive	63			
Pre-eruptive	135			
Classified by setting	N	p-Value	0.4632	Non-significant
Subaerial	187			
Submarine	11			
Pre-eruptive unrest				
Classified by setting	N	p-Value	0.5824	Non-significant
Subaerial	127			
Submarine	8			
Classified by volcano type	N	p-Value	0.8449	Non-significant
Large caldera	12			
Complex	13			
Shield	11			
Strato	91			
Submarine	8			
Non-eruptive unrest				
Classified by setting	N	p-Value	0.0359	Significant
Subaerial	60			
Submarine	3			
Classified by volcano type	N	p-Value	0.0366	Significant
Large caldera	7			
Complex	9			
Shield	2			
Strato	42			
Submarine	3			

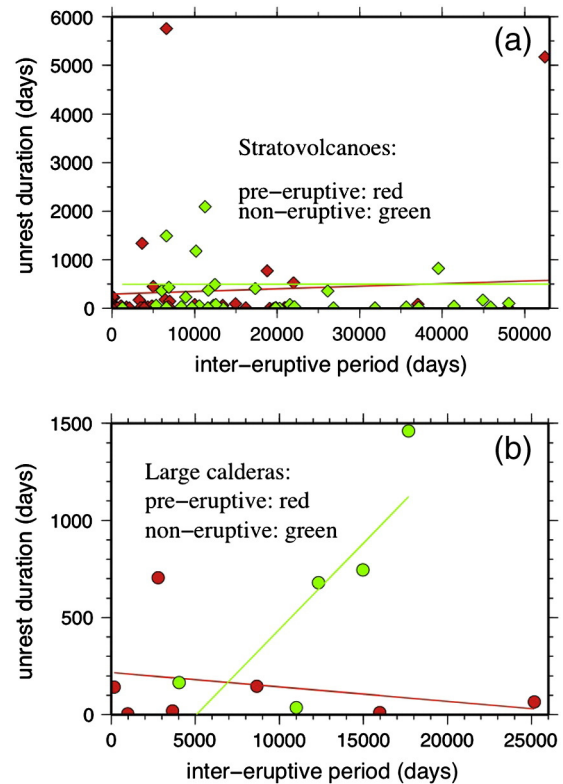

Fig. 6. Correlation diagrams between total unrest duration and inter-eruptive period for (a) stratovolcanoes, and (b) large calderas.

3.3.1. Reawakening unrest

Each of the timelines shown in Fig. 7 displays a clear period of reactivation from a period of prolonged quiescence which evolves into the reawakening of the volcano and its culmination in an eruption. Deformation and seismic activity appear to be key features of reawakening unrest and this may be explained by a model whereby a new pathway through which magma can ascend from depth needs to be established. A typical example for this unrest category is Redoubt, Alaska. Following an inter-eruptive period of 18 years, Redoubt erupted on 15 March 2009 at VEI 3 (Fig. 7 — top panel). Reawakening at Redoubt volcano consisted of short bursts of degassing, thermal anomalies and fumarolic activity, which began in September 2008. The period from the onset of reawakening to the eruption was about 6 months. This is only one example of reawakening out of its entire eruptive history and therefore cannot be suggestive as to how Redoubt will behave prior to the next eruption.

3.3.2. Prolonged unrest

A key feature of prolonged activity (Fig. 8) is long-term (years to decades) ground deformation which may only be identifiable at volcanoes with a long-term geodetic monitoring network or satellite remote sensing. This class of unrest does not always culminate in an eruption. A typical example showing prolonged unrest is the Sierra Negra shield volcano, Galapagos Islands, where cyclic ground deformation has been reported since the last eruption in 1979 (Geist et al., 2008) from ground-based observations.

3.3.3. Pulsatory unrest

Pulsatory unrest consists of episodes of unrest activity (lasting for days) separated by intervals of days without activity (Fig. 9). Pulsatory unrest appears to be mostly expressed by seismic activity, probably because of the widespread availability of seismometers even in rudimentary monitoring programs. From the timelines shown in Fig. 9 it appears that pulsatory unrest is usually a class of non-eruptive unrest. A typical example for this class is the unrest at Cotopaxi since its last eruption in 1940 with several pulses of non-eruptive unrest.

3.3.4. Sporadic unrest

Sporadic unrest is recorded as short-lived, intermittent activity with no apparent pattern to its behaviour. A typical example for this unrest class is shown in the timeline of Taal (Philippines). Neither of the sporadic unrests shown in Fig. 10 culminated in an eruption.

3.4. Intra-eruptive unrest

Eruptive episodes are complex and not always single events. The eruption of Soufrière Hills Volcano on Montserrat so far has been cyclic comprising five periods of effusion lasting from a few months to three years and separated by pauses of about 1.5–2 years (Odbert et al., 2013). Characteristic activity in between episodes of dome formation includes seismicity, ground deformation, and fumarolic degassing (Fig. 11). Activity between the five eruptive episodes could thus be termed intra-eruptive unrest.
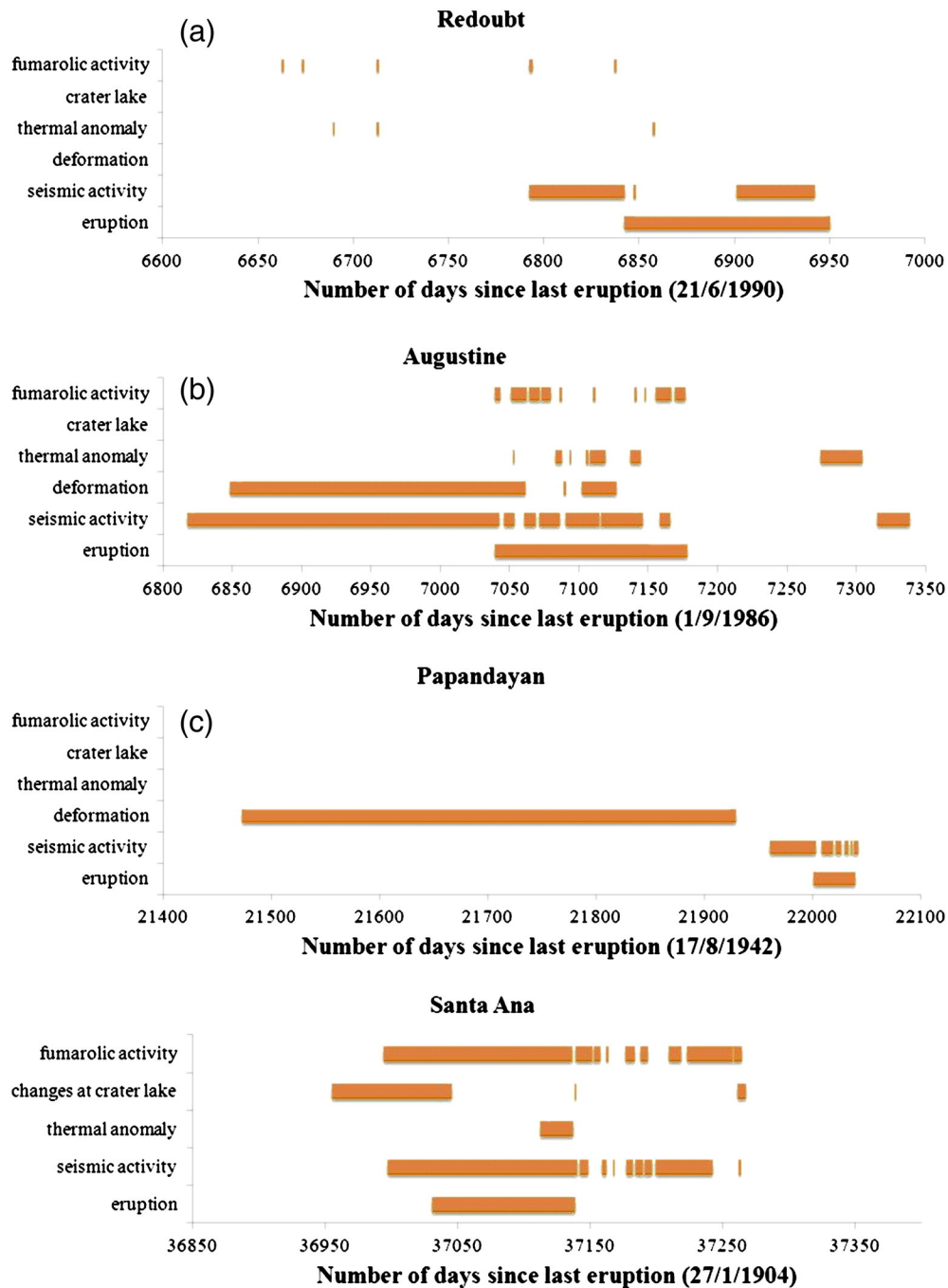
Table 7

Pair-wise Kruskal–Wallis test for inter-eruptive period. Significant pairs are highlighted in bold (p-values < 10%).

p-Values	Complex	Shield	Strato	Submarine
Non-eruptive				
Caldera	0.1248	0.7697	**0.0345**	0.3051
Complex		0.4795	0.3478	0.4054
Shield			0.159	**0.0833**
Strato				**0.0159**
Pre-eruptive				
Caldera	0.8278	0.2423	0.5649	0.4404
Complex		0.3692	0.8867	0.4689
Shield			0.4933	0.8044
Strato				0.5897

Fig. 7. Examples of reawakening unrest timelines. (a) Timelines of unrest activity at (A) Redoubt from 16/7/2008 to 20/8/2009, (b) Augustine from 14/4/2005 to 16/10/2006 and (c) Papandayan from 2/8/2002 to 9/1/2003. Additional information on the timelines and sources of data can be found in the electronic Supplementary material.

4. Discussion

4.1. Pre-eruptive vs. non-eruptive unrest duration

Although the basic physics of magma ascent beneath a volcano prior to an eruption are likely the same at all volcanoes, factors such as past activity and length of repose influence the stress distribution within the crust and the nature and evolution of unrest might therefore be different at different volcano types. For example, the high-viscosity magmatic systems of large silicic calderas evolve over much longer timescales (Jellinek and DePaolo, 2003) compared to those of other volcano types. As a consequence one might expect that the duration of pre-eruptive and non-eruptive unrest at large calderas are different compared to other volcano types. The test statistics in Table 4 provide strong evidence that this is true for some volcano types. Although unrest at both large calderas and stratovolcanoes culminated in an eruption in about 50% of all cases, there is a significant difference in the length of non-eruptive unrest at both volcano types. Pre-eruptive unrest durations, however, are not statistically different. An approximately even distribution between pre-eruptive and non-eruptive unrest at calderas was also found by Newhall and Dzurisin (1988) who identified pre-eruptive unrest at 48% of the calderas investigated in their study over a 40-year period.

By contrast shield volcanoes showed the highest proportion of pre-eruptive unrest (78%). This comparably high proportion of unrest leading directly to eruption may be explained by the particular volcano-
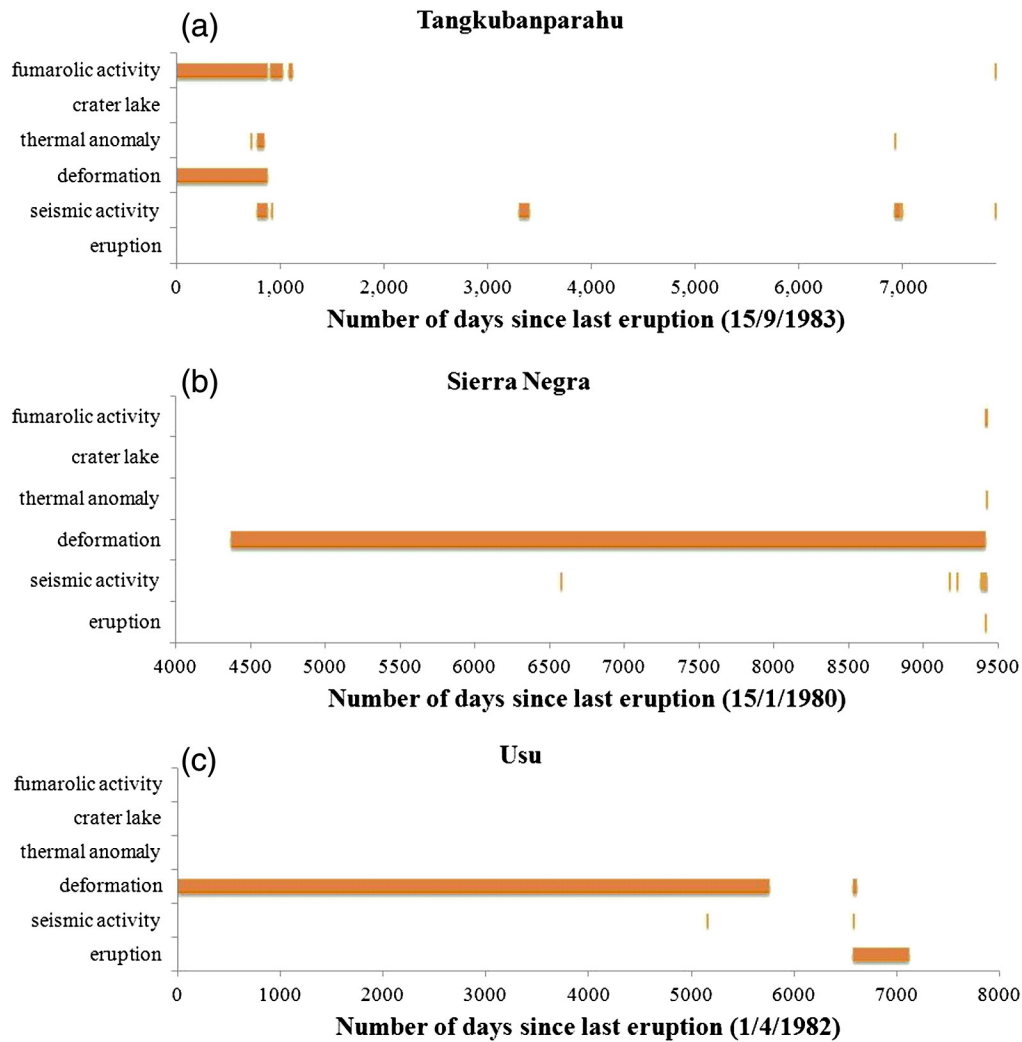
Fig. 8. Examples of prolonged unrest timelines. Timelines of unrest activity at (a) Tangkubanparahu from 15/9/1983 until 3/3/1986, (b) Sierra Negra, from 2/2/2005 until 18/1/2006 and (c) Usu from 22/3/2000 to 16/4/2000. Additional information on the timelines and sources of data can be found in the electronic Supplementary material.

tectonic and magmatic frameworks of shield volcanism. Magma supply at shield volcanoes is significantly higher than at typical strato-volcanoes and enough to sustain a hot pathway over long timescales (Walker, 1993). Extensional tectonics found in most areas of shield volcanism, mechanically compliant host rocks and high magma supply rate may be important factors that contribute to efficient magma transport towards the Earth's surface and eruption.

4.2. Correlation between inter-eruptive period and unrest duration

It has been proposed that there is a positive correlation between the length of repose and the size or explosivity of an ensuing eruption. De la Cruz-Reyna et al. (2008) and Thelen et al. (2010) proposed that this could be due to magma differentiation and longer recharge rates within the chamber. A positive correlation between repose time and silica content of eruptions has been noted in the literature (Thorarinsson, 1967; Santacroce, 1983; Passarelli and Brodsky, 2012). The global appraisal of volcanism shows that eruptions following repose periods on the timescale of centuries to millennia generally cause higher fatalities compared to those with shorter repose times since regions with short historical records tend to be the most unprepared for a large-scale eruption (Siebert et al., 2010).

One pertinent question arising from these observations is: Is there a correlation between the IEP and the UD in the data of this study?

Table 8 shows the Pearson correlation coefficients (Rice, 1995) between the IEPs and UDs from the sample data. There is a mildly negative correlation coefficient between both variables with a p-value of >0.9. This indicates that the null hypothesis ("the *UD* is independent of the *IEP*") is statistically acceptable. However, the statistical tests do not provide enough evidence to fully reject the alternative hypothesis. The correlation coefficient between IEP and pre-eruptive unrest duration with a p-value of 0.29 might hint that there is a correlation between the two response variables. A positive correlation between length of repose, eruption run-up times and silica content was found for eruptions at 34 different subaerial volcanoes investigated by Passarelli and Brodsky (2012). Their study focused on the exploitation of mostly seismic and limited deformation data for the calculation of the 'eruption run-up time', while our study also integrates other unrest indicators to quantify unrest duration. Although magma composition of individual eruptions is not a variable under consideration in our study, we can compare the length of reported pre-eruptive unrest at shield volcanoes, stratovolcanoes, and large calderas with the respective inter-eruptive periods as a proxy low, medium and high-viscosity systems, respectively. We do, however, not find any strong indication for a correlation between pre-eruptive UD, IEP and different pairs of volcano types (Tables 6 and 7; Fig. 6).

This lack of correlation is not surprising as specific volcano types do not exclusively erupt magmas of a narrow compositional range. For
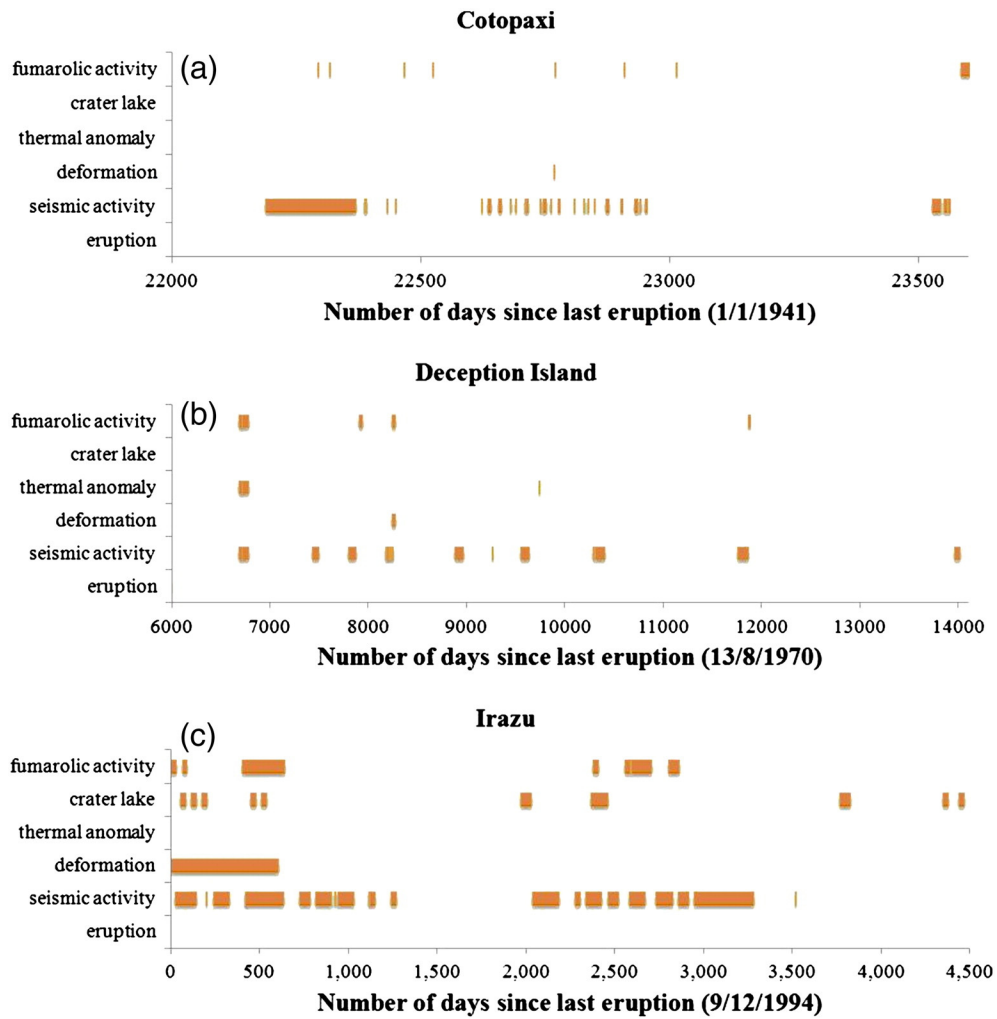
Fig. 9. Examples of pulsatory unrest timelines: Timelines of unrest activity at (a) Cotopaxi from 27/3/2001 to 21/11/2005, (b) Deception Island from 16/1/1987 to 11/12/2008 and (c) at Irazu from 9/12/1994 to 9/7/2004. Additional information on the timelines and sources of data can be found in the electronic Supplementary material.
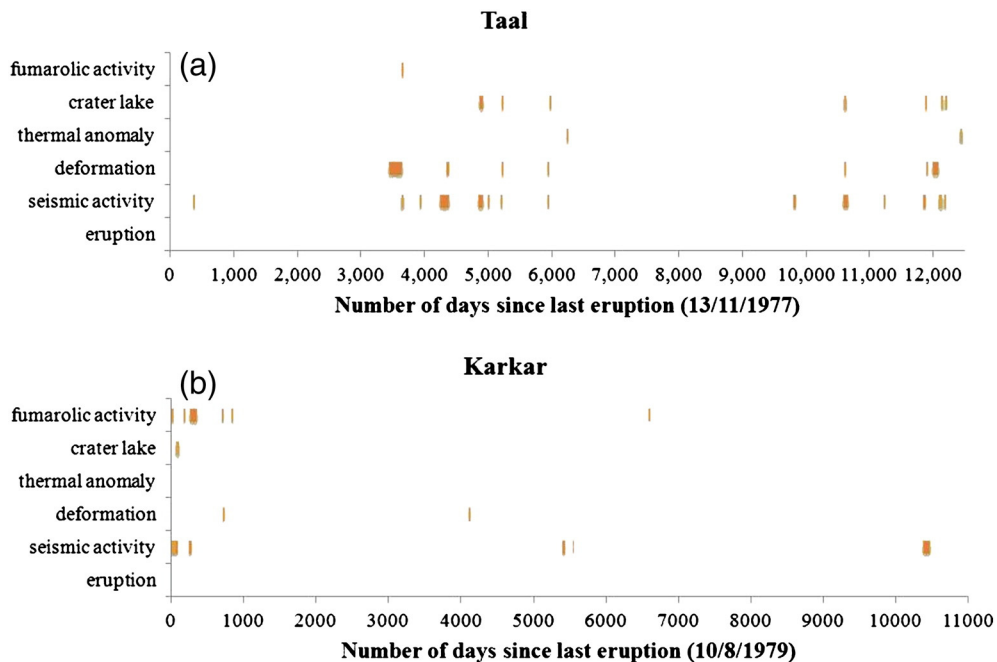

Fig. 10. Examples of sporadic unrest timelines. Timelines of unrest activity at (a) Taal from 9/9/1978 to 18/7/2011 and (b) Karkar from 10/8/1979 to 21/9/2009. Additional information on the timelines and sources of data can be found in the electronic Supplementary material.
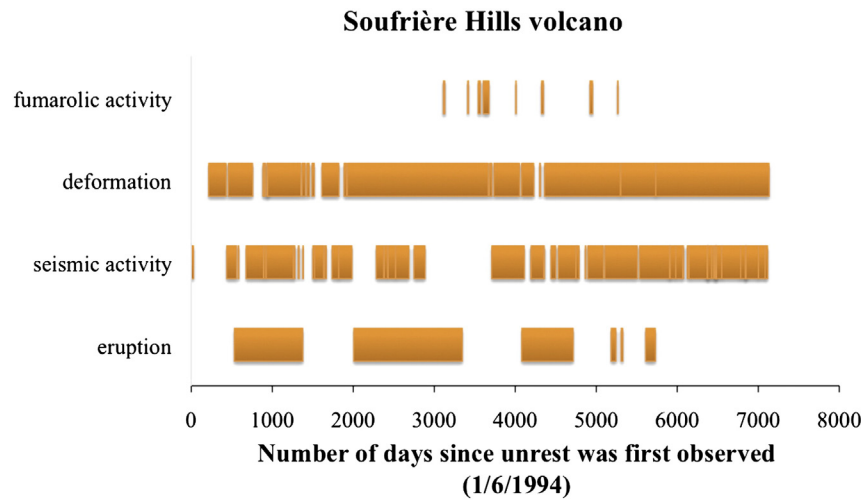
Soufrière Hills volcano

Fig. 11. Example of an intra-eruptive unrest timeline from Soufrière Hills Volcano. Additional information on the timeline and sources of data can be found in the electronic Supplementary material.

example, eruptions at large calderas cover wide ranges of magma composition that are different from the predominantly silicic magmas that formed the calderas.

Strong indications of statistically significant differences in the length of the IEPs between different pairs of subaerial volcano types are only derived for non-eruptive unrest, where, for example, large calderas appear to behave differently to stratovolcanoes (Table 7). One explanation for this observation could be the wide-spread presence of large active hydrothermal systems in large calderas. Non-eruptive hydrothermal unrest may be a key component characterising the IEP and UD at large calderas compared to stratovolcanoes.

To summarise, although volcanoes with lengthy inter-eruptive periods are more likely produce more explosive eruptions, this does not translate into longer pre-eruptive unrest durations.

4.3. Reactivation, reawakening and eruption

Any form of geophysical or geochemical activity above background levels should be regarded as a form of unrest. This is a particularly important consideration for volcanoes with a long period of quiescence as a result of long inter-eruptive periods and its associated frequent absence of reliable monitoring records (Gottsmann et al., 2006; Marti et al., 2009). Unrest should hence be treated as a sign of reactivation of the sub-volcanic system with the potential to trigger the reawakening of a volcano and eruptive activity. Hence, volcano

Table 8
Correlation matrix between inter-eruptive period (days) and unrest duration (incl. segments non-eruptive and pre-eruptive; days), showing the Pearson correlation coefficients and corresponding *p*-values. See text for explanations.

Pearson correlation coefficients		
Prob >|r| under H0: Rho = 0		
All unrest		
N = 118	IEP	UD
IEP	1	−0.00808
		p-value 0.9308
Non-eruptive		
N = 58	IEP	UD
IEP	1	−0.07137
		p-value 0.5945
Pre-eruptive		
N = 60	IEP	UD
IEP	1	0.16801
		p-value 0.1994

reactivation does not necessarily result in an immediate eruption, as many of the non-eruptive unrest timelines demonstrate. For example, Cotopaxi volcano last erupted in 1940 and had been in a state of quiescence until October 2001 when seismic and fumarolic activity heralded its reactivation with a pulsatory evolution of unrest activity. This reactivation did, however, not evolve to the reawakening of Cotopaxi and immediate eruption. It remains to be seen, though, how geophysical signals prior to a future eruption compared to those recorded during the 2001–2004 unrest, with a view to establish how close Cotopaxi was to erupting within a few weeks or months of the first observed unrest activity.

We show that eruptions at large calderas, complex- and stratovolcanoes typically occurred within a median reported unrest duration of between 2 days and 2 months, regardless of the length of the inter-eruptive period. These durations suggest that once a volcano reactivates, the reawakening phase may be rather short and an eruption could ensue relatively quickly. Seismicity and ground deformation appear to be the key indicators for reawakening unrest and the transition from dormancy to eruptive activity. Brittle deformation of rocks causes seismic signals as does the non-steady movement of the magma through newly generated fractures (Kilburn, 2003). This pre-eruptive fracturing process is a common feature of volcanoes after periods of repose (Kilburn and Sammonds, 2005; De la Cruz-Reyna et al., 2008) accompanied by an acceleration of the fracture rate shortly before eruption. In these cases, ground deformation must at least be partly caused by the migration of magma towards the surface. In contrast, pulsatory unrest in the examples above was exclusively non-eruptive. A change in the unrest behaviour from a pulsatory to a continuous nature with acceleration of the fracture rate may hence be an indicator for an eruption in the short term.

4.4. Unrest identification and classification: open questions

Although we have identified some common patterns of unrest from the timelines, we do not propose that all unrest patterns can be categorised into the unrest classes proposed above. One complication arises from the notion that a volcano will not immediately return to a quiescent state following an eruption. Post-eruptive unrest is likely to be recorded while activity returns to a baseline level; e.g., at Santa Ana volcano (Fig. 7). The inter-eruptive period may not be sufficiently long to determine exactly when an eruptive period has reached its conclusion (Sparks, 2003). Furthermore, a scientific reaction to the development of volcanic unrest is to extend the monitoring network so the progression of unrest can be studied. This leads to heightened recorded

levels of unrest that, in reality, may be the result of a more sensitive network and is not necessarily due to a real increase in the unrest activity. Over the past 20 years there has been a growing increase in the number of reported number of unrest episodes, which may partly be due to the advances in telecommunication technology.

An important issue for future tracking of unrest activity is the integration of remote sensing data. The GVP generally lacks the post-facto integration of unrest indicators from satellite-remote sensing data (e.g., Fournier et al. (2010) for deformation and Carn et al. (2011) for degassing). As a result these data have not been evaluated in this study. The same applies for unrest episodes that are reported in the scientific literature only, but are not listed in the GVP (e.g., the recent unrest at Santorini; Newman et al., 2012). Substantial efforts are dedicated currently to collate world-wide volcano monitoring data as part of the WOVOdat project (Venezky and Newhall, 2007). Contrary to the WOVOdat initiative, our analysis relied on the available qualitative information on volcanic unrest events, rather than the exploitation of individual geophysical or geochemical timeseries. A global geophysical/geochemical data repository on volcanic unrest will provide an unprecedented opportunity to significantly improve and share the knowledge-base on past unrest episodes and eruptions.

5. Conclusions

This study shows that 47% of reported unrest between Jan 2000 and July 2011 can be classified as pre-eruptive unrest; i.e., a causal link can be drawn between unrest and eruption during this reporting period. The median length of pre-eruptive unrest varies with volcano type: complex volcanoes showed the shortest duration of unrest before eruption (two days), and stratovolcanoes showed unrest for about one month before eruption. Pre-eruptive unrest at large calderas lasted for about two months and for about four months at shield volcanoes. By comparison, non-eruptive unrest periods are recorded at stratovolcanoes for less than two months while the median duration is between half a year and almost two years for shield volcanoes and large calderas, respectively. While non-eruptive and eruptive unrest occurred with almost equal frequency at large calderas and stratovolcanoes, non-eruptive unrest dominated complex volcanoes while eruptive unrest was a relatively rare occurrence at shield volcanoes.

We also find that there is only a poor correlation between the length of the inter-eruptive period and unrest duration in the data.

Therefore, the hypothesis that volcanoes with long periods of quiescence between eruptions undergo prolonged periods of unrest before eruption is not supported by our analysis. Most eruptions during the investigation period occurred within a relatively modest amount of time after the first documented unrest, with a median average unrest duration of 79 days across all volcano types considered, regardless of the length of the inter-eruptive period.

A globally-validated protocol for the reporting of volcanic unrest and archiving of unrest data does not exist. However, a concerted effort by the volcanological community to consistently report unrest would significantly reduce the uncertainties encountered in this study and would help improve the knowledge base on unrest behaviour. Towards this end, we propose a globally applicable "operational" definition for unrest and threshold for official reporting: "The deviation from the background or baseline behaviour of a volcano towards a behaviour is a cause for concern in the short term (hours to few months) because it might prelude an eruption."

Although data of up to a century had to be consulted to establish unrest timelines for some volcanoes, this study focused on a relatively short period of documented unrest between 2000 and 2011. The findings may not be representative of unrest behaviour over longer intervals such as centuries, but may have implications for hazard assessment, risk mitigation and scenario planning during future unrest crises. There are still substantial uncertainties regarding the causative links between subsurface processes, resulting unrest signals and imminent eruption which deserve future attention.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jvolgeores.2013.08.004.

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