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Volcanic activity before and after large tectonic earthquakes: Observations and statistical significance

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ABSTRACT

The study of volcanic triggering and interaction with the tectonic surroundings has received special attention in recent years, using both direct field observations and historical descriptions of eruptions and earthquake activity. Repeated reports of clustered eruptions and earthquakes may imply that interaction is important in some subregions. However, the subregions likely to suffer such clusters have not been systematically identified, and the processes responsible for the observed interaction remain unclear.

We first review previous works about the clustered occurrence of eruptions and earthquakes, and describe selected events. We further elaborate available databases and confirm a statistically significant relationship between volcanic eruptions and earthquakes on the global scale. Moreover, our study implies that closed volcanic systems in particular tend to be activated in association with a tectonic earthquake trigger. We then perform a statistical study at the subregional level, showing that certain subregions are especially predisposed to concurrent eruption–earthquake sequences, whereas such clustering is statistically less significant in other subregions. Based on this study, we argue that individual and selected observations may bias the perceptible weight of coupling. The activity at volcanoes located in the predisposed subregions (e.g., Japan, Indonesia, Melanesia), however, often unexpectedly changes in association with either an imminent or a past earthquake.

1. Introduction

Volcanoes are systems that may interact with their environment at different scales. The concurrence of seismic and volcanic events in particular, and thus the clustering of associated hazards, has received special attention for a long time. Historical descriptions of volcanic eruptions linked with major tectonic earthquakes are numerous, and evidence increasingly shows a mechanical relationship between these events (see Hill et al. (2002) and references therein). Nevertheless, the manifestations of volcanic activity related to earthquakes can differ significantly in space and time, i.e., a sequence of events can be separated by a few seconds to several decades at distances of a few to hundreds of kilometers and can be explained by permanent and transient changes in crustal stress and strain (Hill et al., 2002; Manga and Brodsky, 2006). Global databases of eruptions and earthquakes allow for testing of subregions that have been susceptible to volcano–earthquake interactions (Fig. 1). However, the degree to which eruptions and earthquakes concur in specific tectonic and regional settings is not well understood. After reviewing the existing literature, we detail a temporal and spatial statistical study that provides new insights into the regional distribution and timing of clustered events, suggesting that the interaction of volcanic eruptions with large earthquakes is common in some subregions and rare in others.

1.1. General observation of concurrent eruptions and earthquakes

Scientific descriptions of volcanic eruptions concurrent with large earthquakes date back to at least the 19th (Darwin, 1840) and early 20th centuries (Rockstroh, 1903). However, a thorough analysis and discussion of the processes involved and mechanisms responsible for the clustered occurrence of eruptions and earthquakes did not begin until much later.

A well-known sequence occurred in South America wherein the volcanoes Cordón Caulle and Puyehue erupted in Chile just one day after the large 1960 Valdivia earthquake (Barrientos, 1994; Lara et al., 2004). Other prominent examples of volcanoes that have been active in association with major tectonic earthquakes are Mount Vesuvius and Mount Etna in Italy (Sharp et al., 1981; Nercessian et al., 1991; Marzocchi et al., 1993; Nostro et al., 1998; Gresta et al., 2005), the Santa Maria volcano in Guatemala (Rockstroh, 1903; Williams and Self, 1983; White and Harlow, 1993), the New Hebrides (Blot, 1976), various volcanoes in Japan (Koyama, 2002), Alaska (Sanchez and McNutt, 2004) and Kamchatka (Walter, 2007), Mount St. Helens in the USA (Lipman and Mullineaux, 1981), volcanoes in Iceland (Gudmundsson and Andrew, 2007), and Kilauea and Mauna Loa in Hawaii (Swanson et al., 1976; Lipman et al., 1985; Walter and Amelung, 2006).

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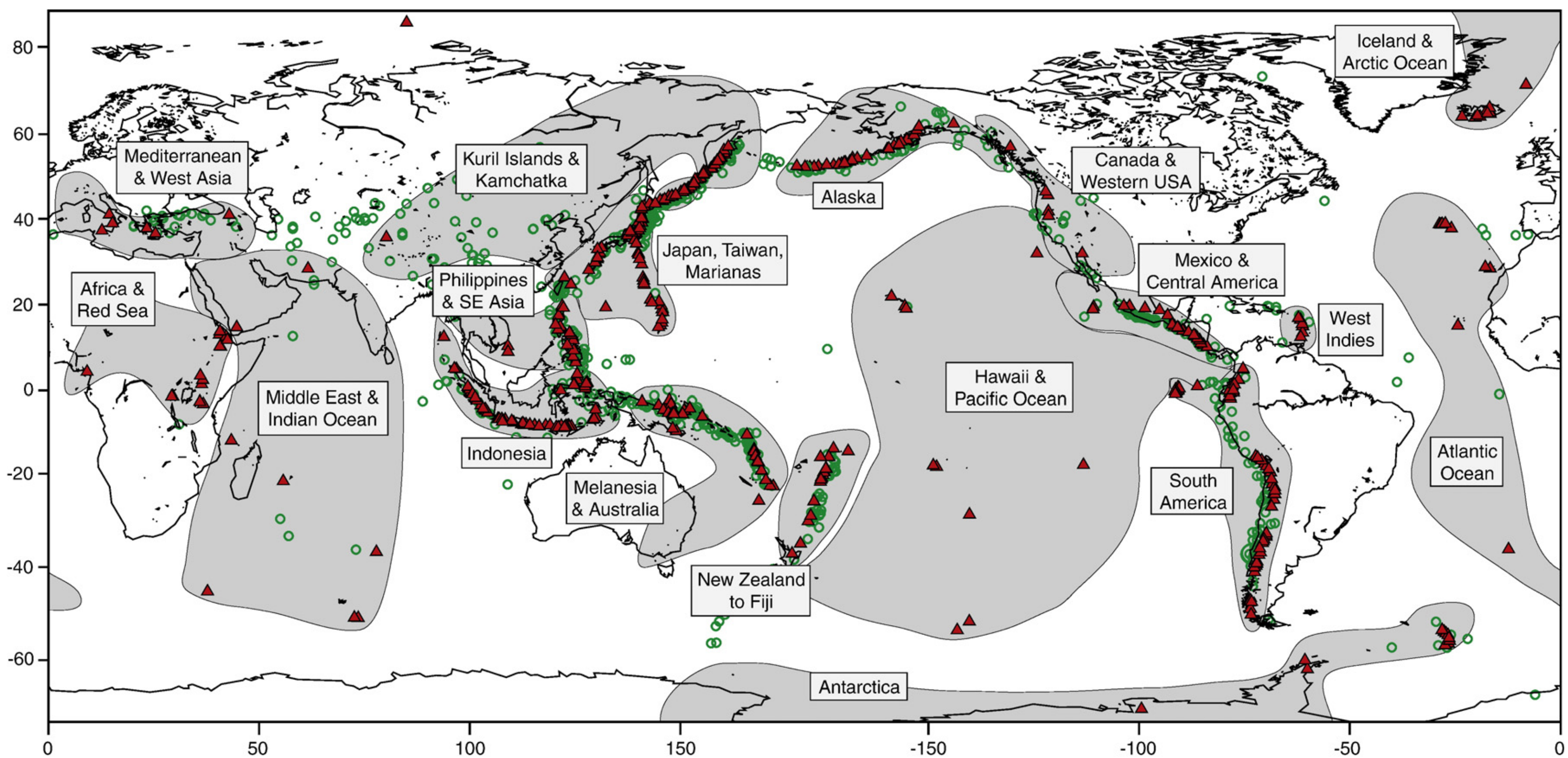

Fig. 1. World map showing considered active volcanoes (red triangles) listed in the updated eruption catalog after Siebert and Simkin (2002), and earthquakes Ms>7 (green circles) after Pacheco and Sykes (1992). Grey shaded regions are 19 subregions as defined by Simkin and Siebert (1994). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
List of selected previous works.

	b/a	Region	Author
General observations			
Probably the first description of volcano–earthquake interaction	a	South America	Darwin (1840)
Review of occurrence and processes involved	b/a	Global	Hill et al. (2002)
Destructive earthquakes and volcanism	a	Several volcanoes, Central America	White and Harlow, (1993)
Dormant volcano erupts after earthquake	a	Santa Maria, Guatemala	Rockstroh (1903), Williams and Self (1983)
Two volcanoes (one dormant) erupt simultaneously after tectonic earthquake	a	Karymsky and Akademia Nauk, Kamchatka	Izbekov et al. (2004), Walter (2007)
Eruption triggered by earthquake	a	Shishaldin, Alaska	Moran et al. (2002)
Sector collapse and eruption triggered by earthquake	a	Mt. St. Helens, USA	Christiansen and Peterson (1981), Lipman and Mullineaux (1981)
Fissure eruption after earthquake	a	Cordon Caulle, Chile	Lara et al. (2004)
Volcanism at convergent plate boundaries	b/a	Asal–Ghoubbet Rift	Lepine et al. (1980)
Mechanism			
Review of mechanical processes	b	Global	Nakamura (1971)
Review of mechanical and fluid-dynamic mechanisms	a	Global	Manga and Brodsky (2006)
Static and dynamic mechanisms	b/a	Global	Gomberg et al. (1998)
Mechanical coupling (flask model)	a	Japan	Koyama (2002)
Stress transfer due to earthquake	a	Japan	Rikitake and Sato (1989)
Coulomb stress change triggers earthquake	b	Iwate Volcano, Japan	Nishimura et al. (2001)
Decompression leads to eruption	a	Cordon Caulle, Chile	Barrientos (1994)
Decompression leads to eruption	a	Cerro Negro, Nicaragua	La Femina et al. (2004)
Dynamic triggering due to seismic waves	a	Merapi, Indonesia	Walter et al. (2007)
Stress triggering by gravitational loading and magma overpressure	b	Global	Kilburn (2003)
Stress triggering by dike propagation	a	Mt. Etna	Gresta et al. (2005)
Magma inflation leads to earthquake	b	Izu Peninsular, Japan	Thatcher and Savage (1982)
Rectified diffusion as mechanism	a	Yucca Mountain, Nevada	Brodsky et al. (1998)
Increased pressure from bubble growth	b	Long Valley, California	Linde et al. (1994)
Groundwater pressure changes	a	Global	Brodsky et al. (2003)
Triggering at geothermal fields	a	Bandai Volcano, Japan	Yamamoto et al. (1999)
Triggering at geothermal fields	a	The Geysers, California	Gomberg and Davis (1996)
Triggering at geothermal fields	a	Long Valley, California	Brodsky and Prejean (2005)
Temporal separation			
Few years to decades	a	Global	Marzocchi (2002)
Months to years	b/a	Pinatubo, Philippines	Bautista et al. (1996)
Days to a few years	a	Global	Mellors et al. (2007)
Days to months	a	Izu–Oshima, Japan	Nakamura and Yamashina (1975)
Hours to days	a	Alaska	Moran et al. (2004)
Seconds to minutes	a	Long Valley, California	Hill et al. (1995)
Spatial separation			
Far field (3500 km)	a	US West coast	Prejean et al. (2004)
Far field (3500 km)	a	Alaska	Sanchez and McNutt (2004)
Far field (2000 km)	a	Iwo Jima, Japan	Ukawa et al. (2002)
Near field (400 km)	a	Long Valley, California	Sturtevant et al. (1996)
Local (50 km)	a	Karymsky, Kamchatka	Gordeev et al. (1998), Zobin et al. (2003)
Local (50 km)	a	Merapi, Indonesia	Walter et al. (2007)
Few kilometers	a	Kilauea and Mauna Loa, Hawaii	Swanson et al. (1976), Lipman et al. (1985)
Statistical studies			
General observation of correlation at convergent plate margins	a	Global	Carr (1977)
Analysis of histograms of earthquake–eruption pairs	b/a	Global	Linde and Sacks (1998)
Analysis of histograms of earthquake–eruption pairs	a	Mt Etna	Feuillet et al. (2006)
Probability tests for earthquake–eruption pairs	a	Alaska	McNutt and Marzocchi (2004)
Regression and correlation analysis	b	Japan	Alam and Kimura (2004)
Correlation analysis of time and distance	a	Global	Marzocchi (2002), Marzocchi et al. (2004)
Correlation analysis of time and distance	a	Hawaii	Furumoto (1957)
Correlation analysis of time and distance	a	Mauna Loa, Hawaii	Decker et al. (1995)
Correlation analysis of time and distance	b/a	Mt Vesuvius	Nostro et al. (1998)
Correlation analysis of time and distance	a	Iceland	Gudmundsson and Saemundsson (1980)
Correlation analysis of time and magnitude	a	Chile, Central America, Kamchatka	Acharya (1982)
Correlation analysis of time and earthquake swarms duration	a	Global	Benoit and McNutt (1996)
Correlation analysis of earthquake and types of eruptions	a	Mt. Etna	Sharp et al. (1981)
Spatial correlation analysis	b	Global	Acharya (1987)
Cross-correlation analysis	a	Mt Vesuvius	Marzocchi et al. (1993)
Correlation analysis and stress transfer modeling	b/a	Mauna Loa, Hawaii	Walter and Amelung (2006)
Correlation analysis and viscoelastic modeling	a	Mt Etna	Marzocchi et al. (1993)
Fractal dimension analysis	a	Mt Etna	De Rubeis et al. (1999)

First column provides group categorization (general observations, mechanism, temporal and spatial separation and statistical studies), second column b/a stands for volcanic activity before (b) and after (a) an earthquake, third column details the subregions studied, and fourth column provides reference.

Concurrent activation of volcanoes and fault zones has thus involved different volcano types in different regions and tectonic settings. Studies include composite volcanoes erupting dacite, andesite or rhyolite magmas, as well as shield or central volcanoes of basaltic composition, located at convergent plate boundaries in subduction zone settings, transform or transcurrent plate boundaries, divergent zones, and even hotspot volcanoes that are isolated from significant regional tectonic effects (e.g., Lepine et al., 1980; Christiansen and Peterson, 1981; Williams and Self, 1983; Hill et al., 1985; Larsen et al., 1998; Moran et al., 2002; Izbekov et al., 2004; Walter and Amelung, 2006). An extended list of these and other previous descriptions of concurrent eruptions and earthquakes is given in Table 1.

1.2. Mechanisms responsible for earthquake–eruption sequences

A number of different mechanisms have been proposed to explain the concurrence of eruptions and earthquakes, focusing on triggering processes related to permanent (static) and transient (dynamic) stress and strain changes (Hill et al., 2002; Manga and Brodsky, 2006).

Permanent changes at volcanoes are caused by static dislocation of the crust during an earthquake, which is the best studied and most commonly suggested mechanism. For instance, compressive permanent deformation at a volcano may lead to the so-called “toothpaste” or “flask” process, and affect the shallow magmatic system or even deeper reservoirs by squeezing magma out of a chamber, leading to a magma migration and finally to a volcano activity change. Rikitake and Sato (1989) used such a process to explain eruptions at the Izu–Oshima volcano and major inter-plate earthquakes occurring at the Sagami trough west of Japan. The toothpaste model, however, has been debated because a) the volumes of magma mobilization in a simple elastic medium may not be sufficient to lead to eruptions and b) compression and extension have both had detectable effects. The latter was demonstrated by volcanoes that began erupting after earthquake-induced compression (e.g., Mount Pinatubo (Bautista et al., 1996), Mount Vesuvius (Nostro et al., 1998)), while there are also plenty of examples that suggest that volcanoes became active due to earthquake-induced decompression (e.g., Cerro Negro in Nicaragua (La Femina et al., 2004)). On a larger scale, subduction megathrust earthquakes that usually induce volumetric decompression along the volcanic arc are followed by an increase in volcanic activity (Walter and Amelung, 2007). Intriguingly, permanent deformation may promote volcanic activity even if the thrust earthquake is aseismic (silent) (McNutt and Marzocchi, 2004). Historical records suggest that, in the case of earthquake-induced decompression, open system volcanoes are less affected by remote earthquakes than volcanoes that are closed and have had a long period of quiescence (Walter, 2007; Walter and Amelung, 2007). Material heterogeneities may also contribute to these mechanisms, as shown for Iceland, where soft volcanic zones are subject to large deformation during loading of a seismic zone, whereas stiff zones concentrate stress (Gudmundsson and Brenner, 2003).

Volcanic activity may also influence the occurrence of tectonic earthquakes. For instance, magma inflation periods on the Izu Peninsula, Japan, were followed by subsequent large (M ~ 7) earthquakes (Thatcher and Savage, 1982), and were explained by a significant increase in the Coulomb failure stress (Nishimura et al., 2001).

In addition to permanent (static) deformation and stress changes associated with the dislocation of a fault or intrusion, earthquakes send out mechanical (seismic) waves that travel great distances (r) without losing much of their energy (compared to the static effects) (Hill et al., 2002). Direct measurements of associated dynamic pressure changes within a volcanic system are rare and difficult to obtain (Linde et al., 1994), but empirical considerations suggest that dynamic stresses decrease by $1/r^{1.66}$ (Lay et al., 2005). If direct field measurements are not available, model simulations allow the frequency, amplitude and duration of fluctuating pressures during the passage of seismic waves to be estimated (Walter et al., 2007). These pressure changes typically exceed the values of the static changes but last only seconds. Hill et al. (2002) suggested that dynamic shaking of a volatile-rich system may have a major effect on the pressure conditions within a magma chamber. While there is general agreement that the passage of seismic waves may be a major player, the details of the feedback mechanisms remain unclear. Several studies suggest that dynamic triggering of volcanic/hydrothermal activity is frequency-dependent, e.g., after the Landers earthquake in California or the Denali earthquake in Alaska (Hill et al., 1995; Gomberg and Davis, 1996; Moran et al., 2004; Brodsky and Prejean, 2005). Various successive chains and processes are proposed, e.g., triggered fracture formation or bubble growth within a magmatic system, including advective overpressure (Linde et al., 1994), rectified diffusion (Brodsky et al., 1998), and shear strain (Sumita and Manga, 2008). Some of these mechanisms may have limited relevance (Pyle and Pyle, 1995; Ichihara and Brodsky, 2006), and are thoroughly reviewed in Manga and Brodsky (2006).

In summary, no consensus exists on what might be the *ultimate* mechanism responsible for the observed clustering of events. It is likely that physical and chemical processes are jointly activated by earthquake-triggered stress and strain changes. We thus expect the answer to be found in a combination of solid mechanic and fluid dynamic effects and both permanent and transient triggering.

1.3. Spatial separation of earthquake–eruption sequences

There are several examples in the literature of the clustered occurrence of eruptions and earthquakes at both short and very large distances. For instance, earthquakes on the island of Hawaii frequently reach magnitudes exceeding Mw = 6 and correlate with eruptions ~ 10–20 km away at Kilauea (Swanson et al., 1976; Lipman et al., 1985) and Mauna Loa (Walter and Amelung, 2006), less than 20 km away. The 1996 twin eruption of the volcanoes Karymksy and Akademia Nauk on Kamchatka followed an earthquake about 50 km away (Walter, 2007). In 1992, the Landers earthquake triggered volcanic unrest at the Long Valley caldera, 450 km away (Linde et al., 1994; Hill et al., 1995; Gomberg and Davis, 1996; Sturtevant et al., 1996; Linde and Sacks, 1998). Microseismicity at the Iwo Jima volcano in Japan suddenly increased when major tectonic earthquakes occurred over 2000 km away (Ukawa et al., 2002). The 2002 Denali earthquake induced local seismic activity at volcanoes across western North America, including Mount Rainier, the Geysers geothermal field, Long Valley Caldera, and the Coso geothermal field, up to 3660 km away (Moran et al., 2004; Prejean et al., 2004).

Typically, because of the dimension of dislocation (fault size and earthquake magnitude or intrusion size and volume), volcanic eruptions and intrusions may be followed by an increase in seismicity in only the immediate surroundings (up to tens of kilometers), whereas large tectonic earthquakes may induce volcanic activity at distances of several fault lengths (up to thousands of kilometers) (Hill et al., 2002; Manga and Brodsky, 2006).

1.4. Temporal separation of earthquake–eruption sequences

Examples of clustered eruptions and earthquakes discussed in the literature include events that took place simultaneously as well as events separated by a considerable delay, thus of seconds, days, months or even years. While historical information on the timing of large earthquakes is often very precise, descriptions of volcanic eruptions or other activity changes in volcanic regions accurate to the hour or even day are rare. Much more precise data exist since modern instrumentation and monitoring have become available at some volcanoes, in a few cases with decade-long recordings of fumarole activity, deformation or volcanic seismicity. Such instrumental data, for example, showed within seconds an increased seismicity at western-US volcanic systems after distant earthquakes (Linde et al., 1994; Hill et al., 1995). Also on Alaskan volcanoes volcano monitoring data were analyzed after the 2002 Denali earthquake, and showed that triggered seismicity began on Katmai immediately after the earthquake waves passed (Moran et al., 2004).

Examples of more delayed events include the 1707 Mount Fuji eruption, which occurred 49 days after an earthquake of magnitude Mw = 8.4 (Nakamura, 1975) and the 1991 Pinatubo eruption 11 months after the magnitude Mw = 7.8 Luzon earthquake (Bautista et al., 1996). Viscoelastic model simulations suggest that increased volcanic activity may be evident even after tens of years following large earthquakes (Marzocchi, 2002).

1.5. Previous statistical tests of concurrent events

The many historical concurrent eruptions and earthquakes presented in the previous sections suggest a possible interaction of events. In order to investigate the significance of the proposed interactions, several statistical studies have focused on the occurrence of volcanic activity before and after a major earthquake. Studies have been performed on the local scale with individual volcanoes, on the regional scale considering a number of volcanoes in a tectonic setting, and on the global scale considering global eruption and earthquake databases; selected examples are described below.

1.5.1. Local scale

On the local scale, it was found that, e.g., volcanic activity at Mount Vesuvius, Italy, repeatedly correlated with tectonic earthquakes on Apennine faults in the past 1000 years with a 95% correlation confidence level (Marzocchi et al., 1993; Nostro et al., 1998). Similarly, the rate of earthquakes increases before a new sequence of flank and/or summit activity initiated at Mount Etna and can therefore be seen as a precursor to volcanic activity (Marzocchi et al., 1993); further details on the correlation of Etna eruptions with earthquakes are elaborated by a number of other authors (Sharp et al., 1981; Patane et al., 1994; De Rubeis et al., 1999; Gresta et al., 2005). For the Hawaiian volcanoes, local scale interactions are also suggested to occur (Furumoto, 1957), confirmed by later workers (Decker et al., 1995; Walter and Amelung, 2006). It was found that the probability of concurrence is very high if voluminous eruptions and earthquakes of M>6 are involved (Walter and Amelung, 2006). Numerous other case studies describe volcano-earthquake interactions on the local scale (see table 1), yet the databases are often not large enough to distinguish between coincidence and causality.

1.5.2. Regional scale

Some workers have investigated volcano–earthquake interactions on the regional scale. For instance, Icelandic volcanoes exhibit a statistically significant correlation to earthquakes (Gudmundsson and Saemundsson, 1980). A regression and correlation analysis was performed around Japan (Alam and Kimura, 2004), focusing on the volcanic and seismic activity along the Pacific and Philippine Sea plates. It was found that the time and distance of the events show a high correlation coefficient, being independent of the energy released by the earthquake. In the Pacific region, the timing of volcanic activity increase was found to be related to the magnitude of the subsequent earthquake (Acharya, 1982). In other words, the higher the earthquake magnitude, the earlier the volcanic activity changes prior to the earthquake. Moreover, it was noted that volcanic activity is localized, which means that volcanoes that are adjacent to one another often jointly interact with an earthquake. In a later study, the same author further analyzed the spatial relationship and found that the location of volcanic activity is often far from the earthquake (Acharya, 1987).

1.5.3. Global scale

One of the first global approaches to investigate the temporal correlation of volcanic eruptions and large subduction earthquakes was performed over thirty years ago (Carr, 1977). The analysis was based on a correlation diagram of historical earthquake–volcano databases. On a global scale, Carr proposed that volcanic eruptions are more frequent after earthquakes, and also observed a period of volcanic silence prior to large earthquakes. Another succinct statistical investigation of global datasets was performed by Linde and Sacks (1998). The authors used a frequency-distribution test and searched the eruption catalog for events within 1000 days before and after large (M>8) earthquakes; they found that eruptions occur in the temporal vicinity of large earthquakes. The study suggests a significant number of earthquake–eruption pairs on the same day, most pronounced at distances of 250–500 km. The global study by Linde and Sacks is often considered to be the first clear statistical evidence showing that eruptions and earthquakes are coupled in space and time, and was re-evaluated by us see Fig. 2 and the following paragraph. Manga and Brodsky (2006) also recalculated the statistics by Linde and Sacks and confirmed their results. A similar methodology applied for smaller earthquakes (M>5) and eruptions in the near-field also showed that the correlation is statistically significant within a range of a few tens of kilometers (Lemarchand and Grasso, 2007). For global catalogs, Marzocchi and co-workers showed that large earthquakes can modify the probability of a volcanic event (Marzocchi,

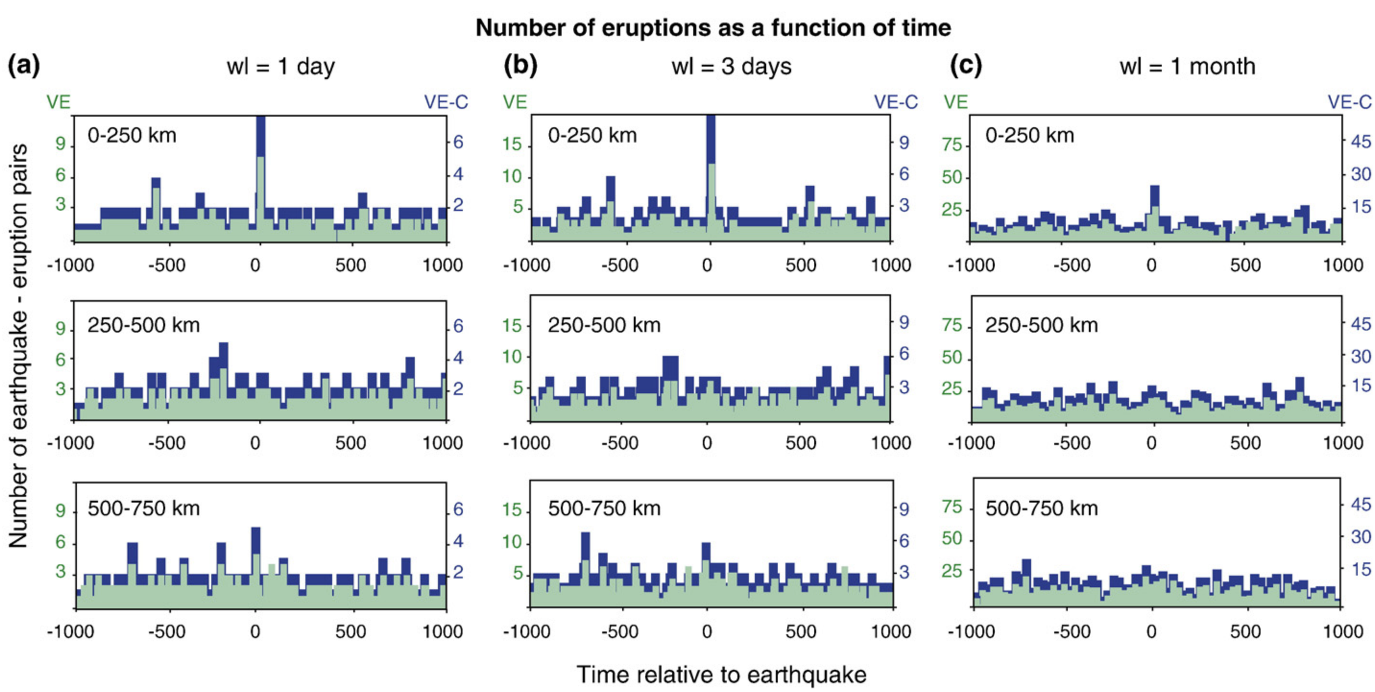

Fig. 2. Histograms showing the number of eruptions ± 1000 days of large earthquakes Ms ≥ 7.0 for a window length (wl) of (a) 1 day, (b) 3 days, and (c) 1 month at distances of 0–250 (upper row), 250–500 (center row) and 500–750 km (bottom row). The volcano database used for this plot includes all volcanoes (VE — in green) and the catalog without continuously erupting volcanoes (VE-C — in blue). Most earthquake–eruption sequences occur in spatial and temporal proximity.

2002; Marzocchi et al., 2004). The statistical significance and the correlation were calculated with a Spearman non-parametric test, revealing that the eruption rate increases for 0–5 years and 30–35 years after the earthquake (Marzocchi, 2002). Since the results do not fit into spatial-temporal clustering of events, it was suggested that the eruptions were triggered by large earthquakes (Marzocchi et al., 2004). The difference from the results of Alam and Kimura (2004) is explained by the different scale and the different region considered: Marzocchi and coauthors used global data, whereas Alam and Kimura (2004) used regional data for Japan only.

These preceding studies show that statistical evidence of volcano–earthquake interactions exists on the local, regional and global scales. In the next chapter, we perform a systematic investigation of the subregions showing significant interactions.

2. A new systematic study of the clustered occurrence of eruptions and earthquakes on the global and subregional scales

Most of the previous studies analyzed the concurrence of earthquakes and eruptions either on the global level or for few selected volcanoes. To obtain a more complete view of the phenomenon of eruptions promoted by earthquakes and to test the volcanic subregions susceptible to earthquake–volcano interactions, we develop statistical tests on various temporal and regional levels. First, we use an updated global eruption catalog to validate and extend a previous study (Linde and Sacks, 1998) on statistical correlation between earthquakes and volcanic eruptions. We then perform a regression and correlation analysis for the different volcanic "subregions" as defined in the standard reference volume "Volcanoes of the World" (Simkin and Siebert, 1994).

2.1. Data catalogs and quality of data

The earthquake data used in this work were taken from a published seismic catalog (Pacheco and Sykes, 1992) that includes 839 events at depths between 0 and 70 km. The database contains worldwide earthquakes of magnitude $Ms \geq 7.0$ from 1900 to 1989, and is the same catalog used by previous workers, e.g., Marzocchi (2002). The eruption data used in this work are from the new version of the catalog by (Simkin and Siebert, 1994), regularly updated and published by the Smithsonian Institution (Siebert and Simkin, 2002). The eruption catalog contains 2650 eruptions for the same time period occurring at 340 active volcanoes. The locations of the considered earthquakes and volcanoes are shown in Fig. 1.

Since the time frame considered begins in 1900 and the rates of reported earthquakes and eruptions generally remain constant for most of the century, we consider both catalogs to be nearly complete. Especially for the time after 1949, the global seismic network and recording instrumentation make the earthquake data very homogeneous (Pacheco

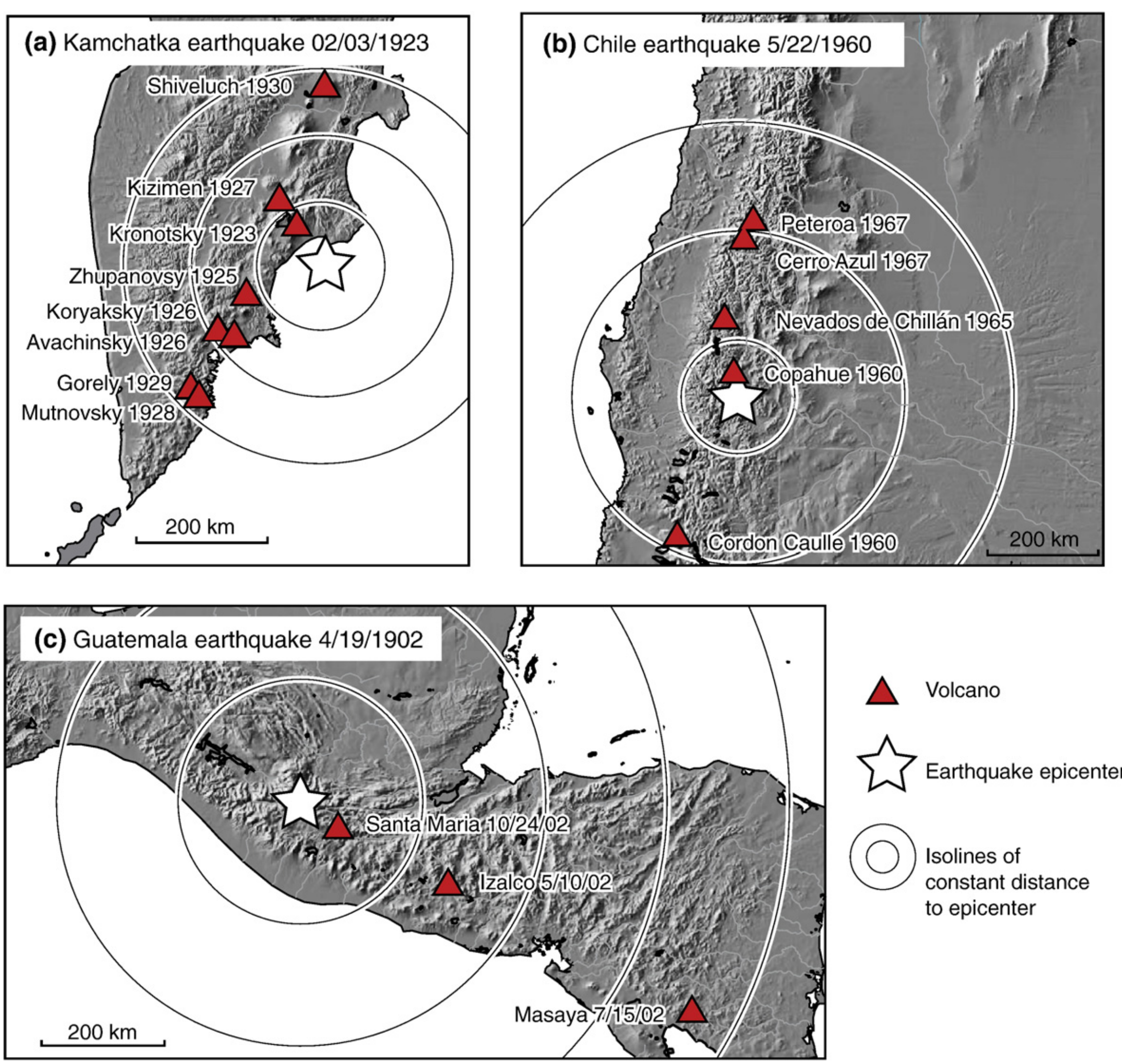

Fig. 3. Examples of eruptions following (a) the Kamchatka earthquake on 02/03/1923, Far East Russia, (b) the Valdivia earthquake on 5/22/1960, South Chile, and (c) the Quezaltenango earthquake on 4/19/1902, Guatemala. The distance of eruptions relative to the epicenters generally increases as a function of time.

and Sykes, 1992). Nevertheless, the awareness of, for instance, volcanic events or any other natural hazards is much higher after large earthquakes, so the catalog may be biased for these periods. Only for a few subregions of the world do historical descriptions explicitly emphasize an absence of volcanic activity (White and Harlow, 1993). In contrast, as described by Simkin and Siebert (1994), a considerable number of historical eruptions were never confirmed, especially if they happened after large earthquakes (L. Siebert, personal communication 2006). We attempt to minimize these limitations of the catalog by filtering the data, as described below.

The Pacheco and Sykes (1992) earthquake catalog summarizes the surface wave magnitude Ms for earthquakes larger than magnitude 7 since 1900. This has limitations, since the value for this kind of magnitude saturates at around 8.5. As a consequence, for example, the 1960 Chile earthquake, which has a seismic moment magnitude of Mw 9.5 is listed with only Ms 8.5 (Pacheco and Sykes, 1992). Nevertheless, this catalog is one of the most complete published global catalogs available for large tectonic earthquakes and is used here for statistical evaluation.

For the following analysis, the catalog data are filtered in two ways. First, only events with the exact date to the day (yr/mo/dy) are considered so that uncertain or unconfirmed eruptions and earthquakes are ignored. Second, clustered events are reduced to avoid double counting. We follow a previous study (Walter and Amelung, 2007) and consider eruptions that occur within less than six months at the same volcano as one event. Some events appear twice in the catalog; we de-cluster also these by considering only the first event listed.

To gain a more differentiated result, we extract two datasets from the filtered eruption catalog. The first contains all recorded events (dataset VE, Volcanic Eruptions). In a second list, we remove all continuously erupting volcanoes. This is done to test whether closed and open systems behave similarly in association with earthquakes. Thus, we then consider only those volcanoes that erupted less than 20 times since 1900 (dataset VE-C, Volcanic Eruptions without Continuously erupting volcanoes).

2.2. Methods

We apply two statistical approaches. The first of these (the so-called "frequency distribution") was chosen in order to evaluate earthquake–eruption sequences on the global scale, while the second ("regression/correlation analysis") is used for a subregional-scale study. The two methods are described below, and the results and data analysis are detailed in Section 2.3.

2.2.1. Frequency distribution approach

This approach has already been used in a variety of different studies of volcano–earthquake interaction, showing a correlation of, e.g., earthquakes with volcanoes (Linde and Sacks, 1998; Manga and Brodsky, 2006; Lemarchand and Grasso, 2007; see also Section 1.5) and earthquakes with mud volcanoes (Mellors et al., 2007). We follow this approach and calculate the number of earthquake–eruption pairs within distances of 250, 500 and 750 km and search for all earthquakes with Ms>7.0. We note that we perform the query once with all confirmed volcanic eruptions (VE) and a second time with the reduced catalog without continuously erupting volcanoes (VE-C). For each earthquake, we search the eruption catalog for events and obtain a histogram of the number of eruptions per day before and after the earthquakes. More details about this method are described by Linde and Sacks (1998).

2.2.2. Regression/correlation analysis approach

This method can be applied to analyze statistics with smaller numbers, and becomes necessary for studies in subregions. We conduct the statistical analysis for 19 volcanic subregions, as shown in Fig. 1. We first perform a regression analysis to examine the proportion of variability between distance and time. To obtain the strength and direction of this relationship, we then determine the correlation coefficient. This allows us to test regional differences of correlation between earthquake and eruption events. To perform the regression/correlation analysis, we consider only directly-related events. We set the frame to ten years before and after the earthquake at a distance up to 500 km, similar to what is used in the frequency distribution above after Linde and Sacks (1998).

We define that an eruption can be assigned to only one earthquake, and apply a filter that is based on the observations by Carr (1977) and Alam and Kimura (2004): In the period before an earthquake, the distance between earthquake and eruption increases as the time interval decreases; after an earthquake, the time interval increases with distance. As an example (Fig. 3), associated with the April 19 1902 Guatemala earthquake in Quezaltenango, the Santa Maria Volcano (30 km distance)

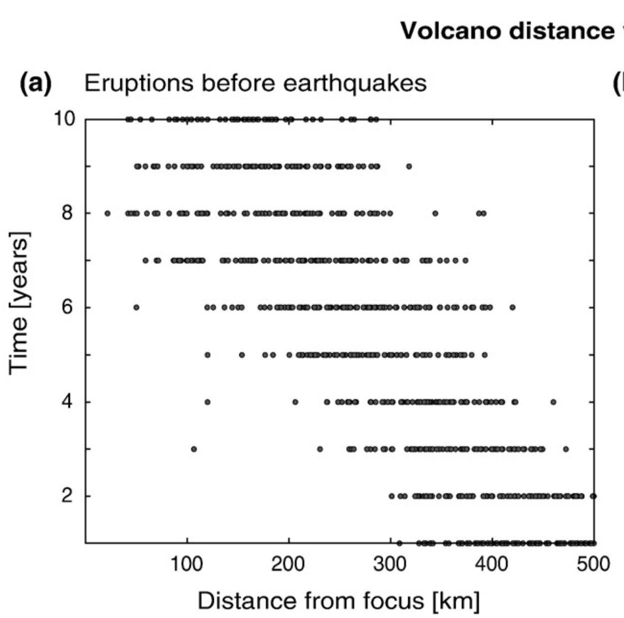

Fig. 4. Global scale study. Scatter diagram showing the relationship between eruption distance and time (a) before and (b) after large earthquakes. Before an earthquake, fewer eruptions occur in the near-field, whereas after the earthquake more eruptions occur in the near-field.

erupted, as did Izalco volcano (250 km) and Masaya volcano (600 km). Because another earthquake occurred on September 23, 1902, this example also illustrates that some of the associated events are ambiguous, as eruptions may be associated with more than one earthquake. We therefore count each eruption once only in the statistics, where (i) for the period before the earthquake, the oldest eruption considered is the one located nearer to the epicenter and the furthest eruption is the most recent one, and (ii) for the period after the earthquake, the youngest eruption considered should be the nearest one to the epicenter and the oldest eruption should be the furthest. In the example from the 1902 Guatemala clustered occurrence, applying the filter leaves us with only two eruptions (Izalco and Masaya). The Santa Maria eruption (October 1902) is attributed to the September earthquake and not the April earthquake. This and two other examples for Kamchatka and Chile are shown in Fig. 3. We applied this filter to each of the 19 subregions and then studied changes in the data expression.

As observed by Carr (1977) and Alam and Kimura (2004), the relationship between time and distance is almost linear, for which we apply a Kolmogorov–Smirnov goodness-to-fit test (Chakravarti et al., 1967) in order to obtain distance–time plots for each subregion, and the coefficients of determination by applying a regression analysis.

The applied log-linear regression analysis uses the least-squares method for all volcanic subregions. The obtained coefficient of determination provides the proportion of variance between the two variables. As we obtain a relationship between time and distance, the strength and direction of this relation is important. We therefore calculate the correlation coefficient by Pearson. Time and distance are highly correlated within the 1% level of significance if the correlation coefficient is higher than 0.8, which means that more than 80% of the variation of time can be explained by a log-linear relationship to distance. The distance–time correlation coefficient is <0 for eruptions occurring before an earthquake and >0 for eruptions after an earthquake.

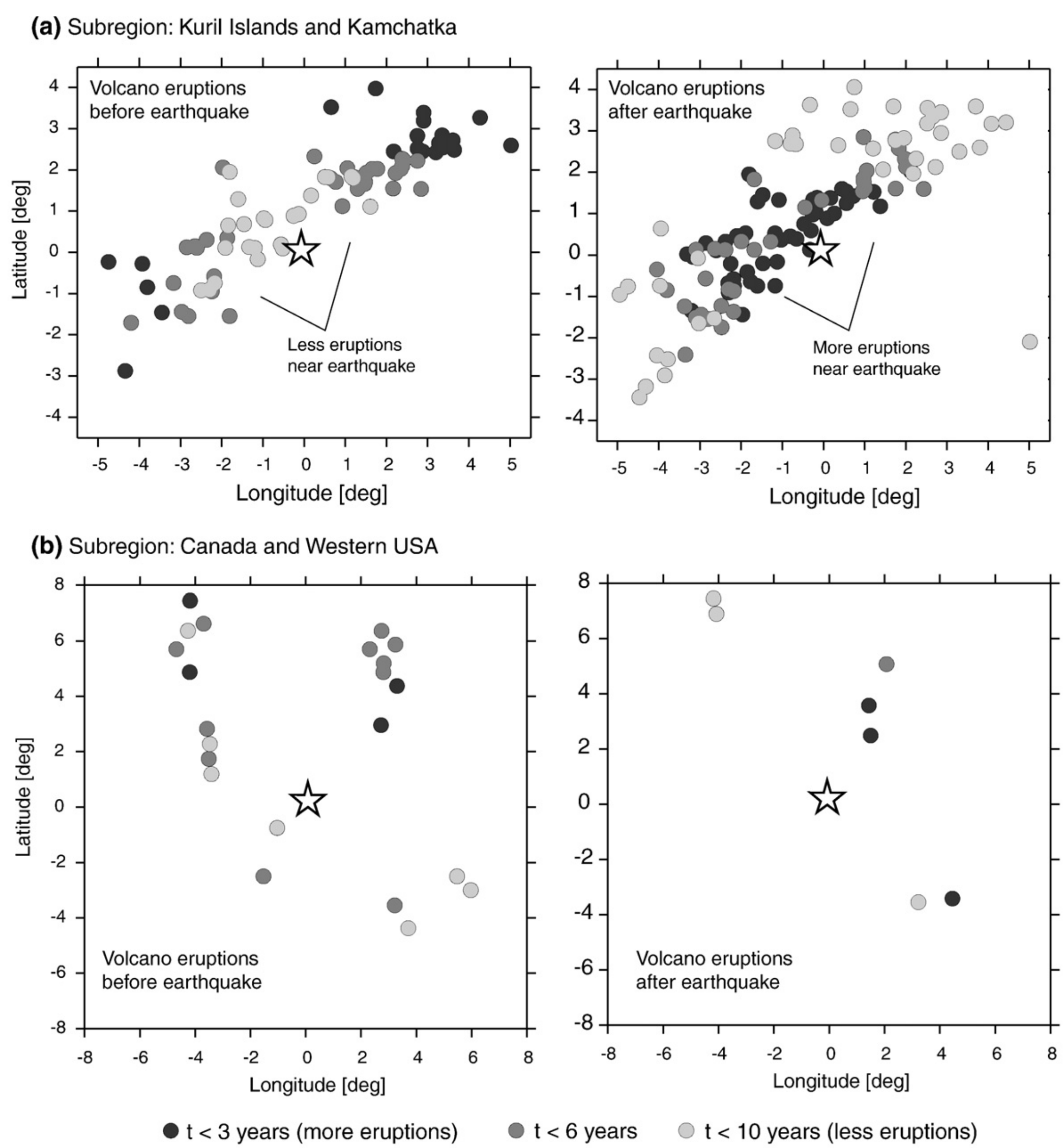

Fig. 5. Distribution of eruptions 10 years before (left) and after earthquakes (right) in (a) Kuril Islands and Kamchatka and in (b) Canada and the western USA. Axes are longitude and latitude; the earthquakes' hypocenters are set to the zero location. The volcanic eruptions are plotted as circles, grey-coded according to their timing (t) with respect to the associated earthquake (shown in three time classes, 3, 6, and 10 years). Examples illustrate the difference in data quantity and spatial-temporal changes of eruptions before and after tectonic earthquakes. See text for details.

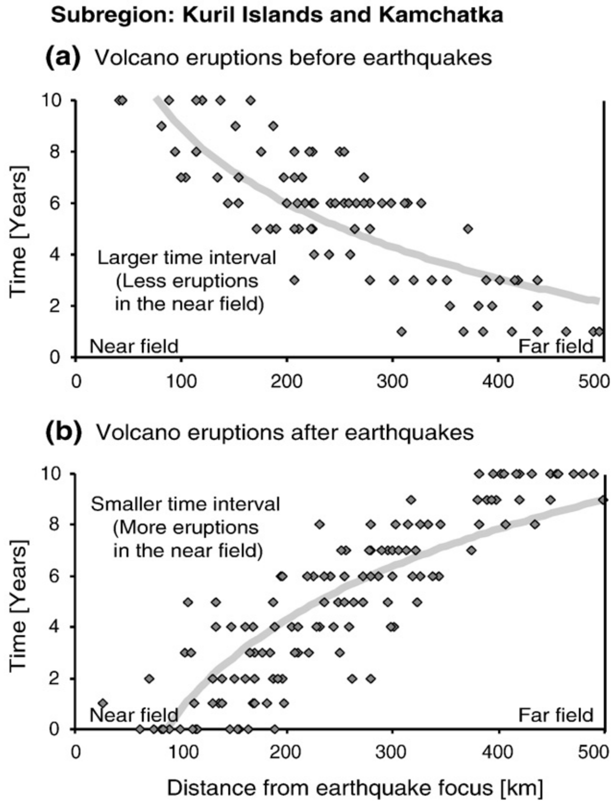

Fig. 6. Scatter diagram showing the relationship between distance and time before and after large earthquakes for the Kuril Islands and Kamchatka. (a) Before an earthquake, fewer volcanic eruptions occur in the near-field, i.e., the time interval between eruptions increases. (b) After an earthquake, more volcanic eruptions occur in the near-field, thus the time interval between eruptions decreases.

2.3. Results

2.3.1. Earthquake–eruption sequences on the global scale:

This method was applied to confirm and expand former studies on the interaction at the global scale with an updated catalog. Counts of the numbers of eruptions per day show a significant peak on the same day as the earthquake in the near-field (Fig. 2). Some smaller peaks are seen in the days following the earthquake and at around 550–600 days before and after the event. With greater distance, the results show another peak at around 200–250 days before and after the earthquake. Slight variations from the Linde and Sacks (1998) results are probably due to use of the updated catalog and the inclusion of earthquakes with magnitudes $Ms>7.0$. We observe more eruption–earthquake pairs in the near-field. Moreover, we observe a higher percentage of pairs in the VE catalog compared to the VE-C catalog, i.e. the proportion of the number of earthquake–eruption sequences to the number of eruptions is higher for the VE-C catalog than for the VE catalog (see Fig. 2). Since the peaks are more distinctive if continuously erupting volcanoes are ignored, an important implication is that volcanoes that have not been continuously erupting are more susceptible to changes associated with tectonic earthquakes. Although the higher number of eruptions occurring on the same day as an earthquake is solid evidence for global interactions of earthquakes and eruptions, this study does not clarify whether specific subregions are more susceptible to a clustering of events. This subject is the goal of the following paragraph.

2.3.2. Earthquake–eruption sequences on the subregional scale

The results of the regression/correlation approach suggest a relationship between the distance (km) and the time (years) of earthquakes and eruptions (Fig. 4). Setting all earthquakes to the zero location and plotting the related eruptions with their respective distance, we observe more eruptions in the far-field and fewer in the near-field in the time before the earthquake. Before the earthquake, a period of volcanic silence occurs near the earthquake. After the earthquake, we see the opposite situation, i.e., a period of higher volcanic activity in the vicinity of the earthquake. Fig. 5 provides an example for Kamchatka, the Kuril Islands, and North America. This dependency results from the filter applied (see above); varying expressions of this situation are also investigated and depend on the dataset considered (VE or VE-C).

Time–distance-plots suggest that a distance of up to 500 km and a time period of up to ten years around the earthquake form a good frame for our calculations, and that the resulting databases are large enough (cf. Fig. 6). Tests in the 19 subregions show that the observed trends are similar in the far-field and converge towards a limit in time and distance. For most volcanic subregions, we find that ~30 years is a good approximation to return to the *normal* state.

We analyze the relationship between directly-related events in time and distance using a log-linear regression model, and obtain a coefficient of determination higher than 0.5 before an earthquake for about 50% of the 19 volcanic subregions. For eruptions following large earthquakes, the coefficient is higher, often even exceeding 0.8 (Table 2).

We find that the subregions around the Pacific Ring of Fire show the most pronounced volcano–earthquake interaction, with a higher correlation coefficient for the period after the earthquake than before the earthquake. For the VE-C catalog, the highest distance-time correlation coefficients (before/after earthquakes) are found for Japan (–0.88/0.93), Kamchatka and the Kuril Islands (−0.85/0.89), New Zealand (−0.86/0.91), Indonesia (−0.89/0.91), Australia (−0.89/ 0.87), and South America (−0.83/0.88). Zones of moderate correlation are Southeast Asia (−0.83/0.84), Alaska (−0.75/0.81), North America (−0.71/0.81), Mexico (−0.74/0.81) and the Hawaii-Pacific zone (−0.66/0.73). Other subregions, like Europe (−0.71/0.56), the Middle East (−0.10/0.62), Africa (−0.74/0.69), Arctica (−0.42/0.22) and the

Table 2
Statistical analysis on the subregional scale.

	Coefficient of determination				Correlation coefficient				Correlation coefficient	
	for distance – time				for distance – time				for distance – magnitude	
	Before		After		Before		After		Before	After
	VE	VE-C	VE	VE-C	VE	VE-C	VE	VE-C	VE-C	VE-C
Africa	0.50	0.51	0.51	0.52	−0.72	−0.74	0.67	0.69	−0.12	−0.19
Alaska	0.39	0.41	0.57	0.59	−0.30	−0.75	0.78	0.81	0.02	0.01
Antarctica	0.38	0.38	0.46	0.49	−0.73	−0.74	0.74	0.77	0.18	0.06
Arctica	0.17	0.19	0.02	0.05	−0.40	−0.42	0.21	0.22	0.17	0.17
Atlantic	0.06	0.07	0.35	0.37	−0.66	−0.67	0.68	0.71	0.10	0.10
Australia	0.64	0.65	0.58	0.59	−0.86	−0.89	0.86	0.87	0.17	0.04
Europe	0.29	0.31	0.23	0.23	−0.69	−0.71	0.53	0.56	−0.04	−0.09
Hawaii and Pacific	0.16	0.16	0.50	0.52	−0.63	−0.66	0.70	0.73	0.16	−0.14
Indonesia	0.79	0.81	0.68	0.69	−0.86	−0.89	0.89	0.91	−0.25	0.12
Japan	0.66	0.67	0.65	0.67	−0.84	−0.88	0.90	0.93	0.19	0.12
Kamchatka and Kuril	0.63	0.65	0.60	0.69	−0.83	−0.85	0.88	0.89	0.14	0.08
Mexico	0.49	0.49	0.67	0.64	−0.72	−0.74	0.79	0.81	0.14	−0.05
Middle East	0.001	0.003	0.68	0.71	−0.10	−0.10	0.59	0.62	0.12	0.19
New Zealand	0.63	0.65	0.63	0.65	−0.85	−0.86	0.90	0.91	−0.03	0.13
North America	0.41	0.44	0.65	0.67	−0.69	−0.71	0.78	0.81	0.24	−0.16
Southeast Asia	0.74	0.77	0.64	0.65	−0.81	−0.83	0.82	0.84	0.20	0.14
South America	0.68	0.69	0.73	0.75	−0.80	−0.83	0.87	0.88	0.24	−0.004
Column (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)

First column describes the subregion after Simkin and Siebert (1994), columns 2–5 show the coefficient of determination between distance and time before and after earthquakes, and columns 6–9 show the correlation coefficient for the same dataset, columns 10–11 show the correlation coefficient between distance and magnitude. All values are given before and after earthquakes for both eruption catalogs, VE — statistical test using the entire volcano eruption catalog, VE-C — statistical test using the volcano eruption catalog without continuously erupting volcanoes.

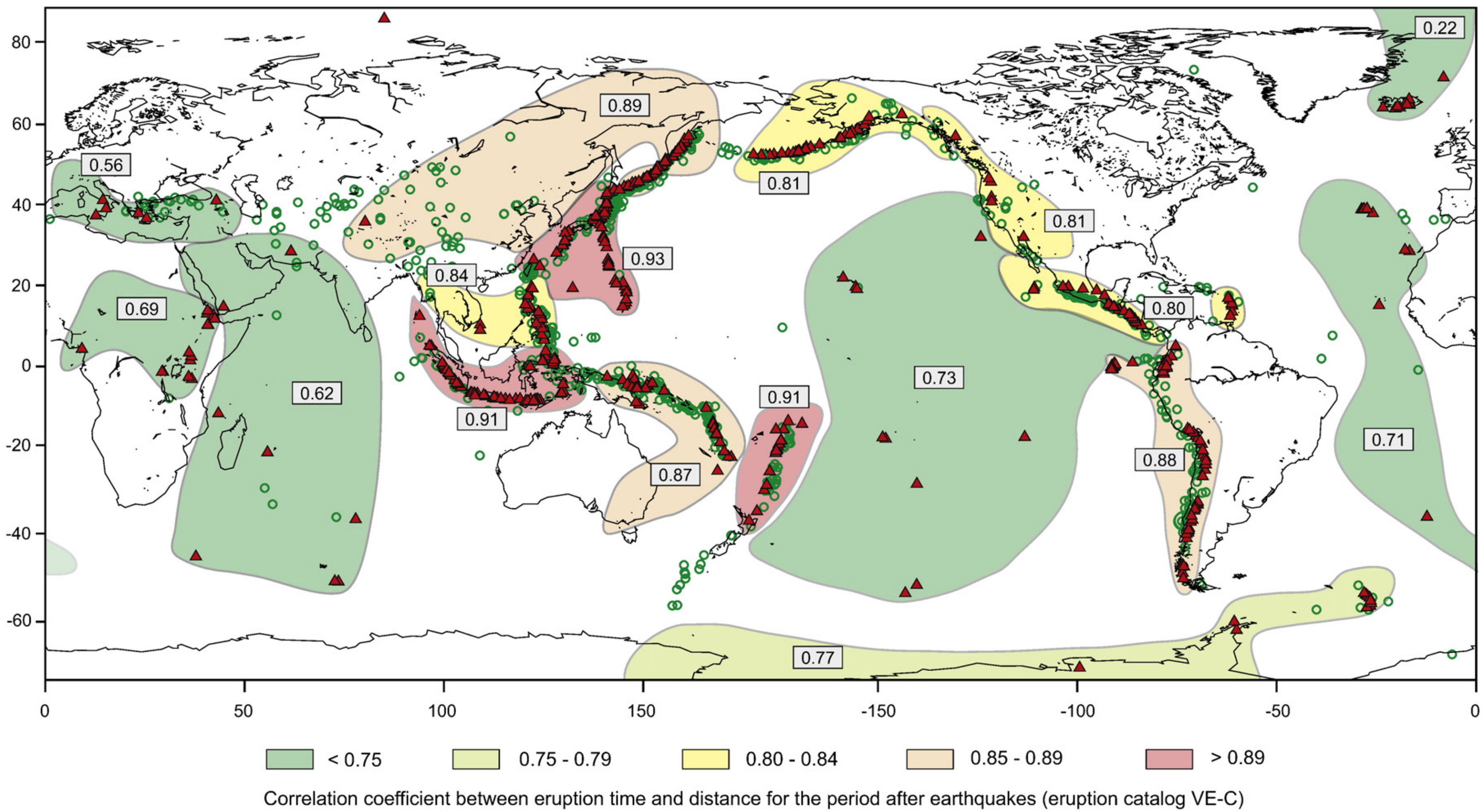

Fig. 7. Correlation coefficient map for the 19 subregions considered in this study. Red shading shows subregions with high correlation coefficients, i.e. statistically significant clustering of eruptions and earthquakes, while green shading shows subregions that have lower correlation coefficients, i.e. less pronounced clustering of eruptions and earthquakes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Antarctic Subregion (−0.74/0.77) show even lower correlation. The coefficient is generally slightly higher without continuously erupting volcanoes (Table 2).

3. Discussion

A number of previous studies could show that there is a significant temporal and spatial relationship between eruptions and earthquakes. Although this relationship has been studied at the local scale for individual volcanic centers, at the regional scale for selected countries and settings, and even at the global scale using available historical global databases, a systematic study for all 19 subregions has not yet been performed. Activity reports occasionally suggest that a subregion is subject to high eruption–earthquake correlation. However, such an observation may be locally biased by dense population, reporting and society-dependent natural hazard awareness. For instance, numerous reports and publications claim a correlation or even interaction of eruptions and earthquakes in Europe and Japan. As shown in this paper, statistical evidence proves this for Japan, but in Europe, a significant interaction is less evident on the subregional scale and may be true for individual volcanoes only. Fig. 7 shows a map of the correlation coefficient for the 19 volcanic subregions.

We analyzed the relationship between earthquakes and linked volcanic activity by applying standard statistical methods; the results show that time and distance are significantly related. Nevertheless, there are other factors that may have influenced the statistical results. The filters we applied to overcome the problems of data ambiguity and reporting also reduce the database. This leaves only small datasets for some volcanic areas (cf. Fig. 5b), which we try to overcome by applying a statistical method suitable for small datasets. In addition, eruptions that occur on the same day as an earthquake may have occurred slightly before or slightly after the earthquake, which is hard to decipher because the exact timing of eruptions is often available to the day only.

The input database is much smaller for subregions that are seismically and volcanically less active, such as Europe or Africa. However, since we used the same calculations and filters for each subregion, the relation of earthquake and volcanic activity and differences in correlation coefficients appear to be true. Some subregions, like Alaska, show low correlation coefficients, although numerous and very large earthquakes occurred there within the study period. Thus the regional presence of numerous (or few) large earthquakes and eruption events does not necessarily suggest high (or low) correlation coefficients.

In order to account for a larger number of major earthquakes in some subregions, we also investigated the influence of magnitude. We find that adding the earthquake's magnitude as a third variable to our calculations only slightly affect the results. The coefficient of determination increases by just ~0.01–0.03. The correlation coefficient between magnitude and distance is between −0.25 and 0.24, which means that they are statistically insignificant. These results suggest that the earthquake's magnitude may not have a clear and direct relationship with both time and distance. Since we consider only the surface wave magnitude and $Ms>7$, however, this does not mean that the earthquake size has no influence on the clustered occurrence of eruptions and earthquakes. Earlier studies about the correlation of earthquake with mud volcanoes or geyser activity have suggested magnitude dependency (Manga and Brodsky, 2006; Mellors et al., 2007).

Out of the entire dataset, only some eruptions concur with tectonic earthquakes and may have been triggered. However, we note that volcanic activity is probably in most cases non-eruptive, as shown by the observation that most dike intrusions never reach the surface (Gudmundsson and Philipp, 2006). Accordingly, triggered volcanoes may in many cases show only unrest, without an eruptive manifestation at the surface, so the interaction of volcanoes with earthquakes may be largely underestimated by our study. The expression of triggered volcanic activity may be largely dependent on the varying degree of criticality of the involved volcanoes (Hédervári, 1979). Further studies will be necessary to elaborate and understand this dependency for local, regional and global databases.

Although this paper elucidates that some volcanic subregions are more susceptible to earthquake triggering, the mechanisms of interaction remain unclear. Our study confirms and further details the results by Walter and Amelung (2007), that rarely erupting volcanoes show more significant correlation to earthquakes than continuously erupting volcanoes. Thus triggering may depend largely on the state of the volcano system involved, although all kinds of volcanoes (e.g. shield-, strato-, caldera volcanoes) have been involved. Further studies will be required to understand the importance of the different volcano types, and on the effects of compression or decompression as volcanic triggers, whether via the transient passage of seismic waves or due to permanent, sometimes aseismic, fault displacements. It was noted decades ago that dynamic and volumetric strains have effects that are "neither simple nor obvious" (cf. Yamashina and Nakamura, 1978). Many recent research initiatives have thus focused on the indirect consequences of earthquakes, affecting volatile phases, gas bubbles, pore pressures, microcracks and other processes and chains for which the feedback mechanisms are only marginally understood. Understanding these interactions may provide new insights into earthquake and eruption prognosis and the assessment of associated hazards.

4. Conclusions

In summary, our most important conclusions are:

- Numerous examples of the clustered occurrence of eruptions and earthquakes can be found in different volcanic areas, tectonic settings, and on different time and distance scales. Examples of earthquakes preceding volcanic activity can be found on local, regional and global scales. The time between a tectonic earthquake and a volcanic eruption may vary from a few seconds to years. The distance between the events can reach up to thousands of kilometers, but is most evident in the near-field.
- A period of volcanic silence is found before many earthquakes. After large earthquakes, there is an increase in volcanic activity. Most volcanic activity occurs on the same day as the earthquake.
- The coefficients of determination are <-0.5 before and >0.8 after large earthquakes for many subregions. The highest correlation coefficients are found for subregions around the Pacific Ring of Fire. The correlation coefficients are generally higher when continuously erupting volcanoes are not included, implying that systems with longer quiescence periods tend more to be promoted by earthquakes.

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