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ScienceDirect
Earth and Planetary Science Letters 264 (2007) 347–359
EPSL
www.elsevier.com/locate/epsl

How a tectonic earthquake may wake up volcanoes: Stress transfer during the 1996 earthquake–eruption sequence at the Karymsky Volcanic Group, Kamchatka

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Received 16 October 2006; received in revised form 10 April 2007; accepted 3 September 2007
Available online 18 September 2007
Editor: C.P. Jaupart

Abstract

A large tectonic earthquake occurred on Kamchatka peninsular on New Year's Day of 1996 along a SW–NE trending fracture system. Just two days after the earthquake and at a distance of about 10–20 km to the north, a simultaneous eruption of two separate volcanoes followed. These were Karymsky Volcano and Akademia Nauk Volcano, the latter having its first eruption in historical records. In this paper I use numerical models in order to elaborate the static stress transfer between the earthquake and the volcanic system during the sequence that culminated in the January 1996 volcano-tectonic events. The models were designed to consider (i) the geodetically identified pre-eruptive period of doming in order to calculate stress changes at the nearby SW–NE trending fracture zone, and (ii) the January 1996 Mw 7.1 earthquake in order to calculate the dilatation and stress changes at the magma plumbing system.

The results suggest that stress changes related to year-long inflation under the volcanic centers increased the Coulomb failure stress at the active faults and thus encouraged the earthquake. The earthquake, in turn, prompted dilatation at the magmatic system together with extensional normal stress at intruding N–S trending dikes. Also, field measurements confirmed the presence of N–S oriented fractures above the dike. Unclamping of the N–S oriented fractures allowed magma to propagate and eventually to trigger the twin-eruption at the volcanoes Karymsky and Akademia Nauk. These findings imply that successful hazard evaluations at volcanoes elsewhere require consideration of the seismo-tectonic framework and large earthquake cycles.
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Keywords: Karymsky volcano; stress triggering; caldera; eruption precursor; hazard

1. Introduction

The initiating mechanisms of volcanic eruptions commonly include magma influx from deeper reservoirs and an increase of the magma/gas pressure. Increasing evidence supports that stress changes play a fundamental role in triggering volcanic eruptions. Stress changes may vary in origin to include earthquakes, erosion and landslide processes, deglaciation, or tidal effects (Stein, 1999; Hill et al., 2002). Also, at volcanoes, the stress transfer may be of great importance in reawakening a dormant system. Previous work suggested a significant statistical correlation of large earthquakes and eruptions in time (Linde and Sacks, 1998) and space (Alam and

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0012-821X/$ - see front matter © 2007 Published by Elsevier B.V.
doi:10.1016/j.epsl.2007.09.006

Kimura, 2004). The interaction may be two-fold, where magma intrusions may change the stress at active faults and trigger earthquakes (Thatcher and Savage, 1982), while tectonic earthquakes may affect the volcano magma system and change the eruption activity (Lipman et al., 1985). In some cases, the magnitude of the events is also correlated, as probabilistic studies show that earthquakes preceded the most explosive eruptions (Marzocchi et al., 2002) and the most voluminous eruptions (Walter and Amelung, 2006). Sometimes volcano systems that are nested or closely located may become active in chorus; neighboring volcanoes may interact in a sense that one volcano triggers its neighboring volcano (Miklius and Cervelli, 2003). However, although there is ample evidence of concurrence, the processes of interacting volcanoes and earthquakes are not well understood, neither for the near-field nor for the far-field. Some studies suggest that volcanic eruptions are triggered if compressive stress acts at the magma system and "squeezes" out magma (Nakamura, 1975; Nostro et al., 1998). Other studies suggest that extensional stress fields facilitate magma rise and thus encourage eruptions (Bursik et al., 2003; Walter and Amelung, 2006), or that fluctuating compression and extension during the passing of seismic waves trigger eruptions (Hill et al., 1994; Brodsky and Prejean, 2005; Walter et al., 2007).

Here, I describe the simultaneous eruption of two volcanoes that may also represent a case scenario of an earthquake–eruption sequence, as recognized at the Karymsky Volcanic Group in Kamchatka, Russia. The 1996 earthquake–eruption sequence at the Karymsky Volcanic Group included the activation of a dormant or apparently extinct volcano, and therefore is of special interest for the evaluation of the volcanic hazard potential in similar tectonic environments elsewhere. The paper begins first with a review of the main development of the Karymsky Stratovolcano and the Akademia Nauk Caldera. In the following section, I then describe the events associated with the 1996 earthquake and simultaneous eruption at both volcanic systems. Finally, Section 3 is devoted to boundary element models that simulate the volcanic and tectonic events and quantify the stress and strain changes in order to understand better how the earthquake and the volcanic activity interacted.

1.1. Geological and structural background of two neighboring volcanic centers

Two volcanic chains developed on Kamchatka, the eastern of which is the more active one containing 14 historically active volcanoes. This chain is aligned along a SW–NE trending fracture zone (Fig. 1) that is thought to channel the magma to the surface (Masurenkov, 1991a,b). Slightly offset to the north of this fracture zone, the Karymsky Volcanic Center is about 30 km away from the Pacific coast. The Karymsky Volcanic Center comprises an area of ~ 2000 km^2 and contains two historically active volcanoes (Karymsky Stratovolcano and Maly Semyachik) and two small apical calderas (Karymsky caldera and Akademia Nauk Caldera). I will focus hereafter on Karymsky Stratovolcano and the Akademia Nauk Caldera.

Karymsky Stratovolcano represents the infill of an older $\sim$4.7-km-wide caldera that formed during an 11–12 km^3 pumice eruption 7900 yr ago (dacite dense rock equivalent DRE of 5–7 km^3, Braitseva and Melekestsev, 1991). The caldera collapse also affected the southern sector of the Dvor Volcano (150 ka old) in the north, parts of which collapsed into the newly formed caldera basin (Belousov et al., 2005). Following a 2500-year-long period of inactivity after the caldera collapse, eruptions restarted inside the caldera and the construction of the present-day Karymsky Stratovolcano began (Braitseva and Melekestsev, 1991). Today, Karymsky Stratovolcano is one of the most active and best monitored volcanoes, about 900 m high (1540 m above sea level), 4.6 km wide with 20–35° slopes, and over 20 historical eruptive periods, 9 of which occurred in the 20th century (Siebert and Simkin, 2002). The erupted rocks have andesite, dacite–andesite and dacite compositions (Fedotov, 1998). The main magma pathway over the past few hundreds of years has been the Karymsky feeder (Fedotov, 1998), where geophysical data indicate the presence of one or more shallow magma chambers under Karymsky, somewhere between 1.5 km (based on geodetic data) and 4–5 km (based on gravity and seismic data) below sea level. In the time period from 1970 to 1982, a DRE of $\sim 110 \times 10^6$ m^3 erupted at Karymsky Stratovolcano (Fedotov, 1998). Then, from 1983 to 1995, no major eruptive activity was reported, although significant inflation was detected (see below).

About 7 km to the SSE of Karymsky Stratocone is the center of Lake Karymskoye, a lake that infills the collapse caldera basin of the northern sector of the Akademia Nauk volcano, hereafter referred to as Akademia Nauk Caldera. Large-volume pyroclastic eruptions dated to 48,000, 40,000 and 28,000 yr ago reveal incremental evolutionary stages of caldera subsidence (Masurenkov, 1980). Akademia Nauk Caldera is about 615 m above sea level, has an area of about 11.5 km^2 and dimensions of $\sim 3.2 \times 4$ km slightly elliptic along NW–SE. After these caldera-forming eruptions in the Pleistocene, no significant eruption occurred at Akademia Nauk Caldera (Braitseva et al., 1994, 1995); however, two minor phreatomagmatic explosions have

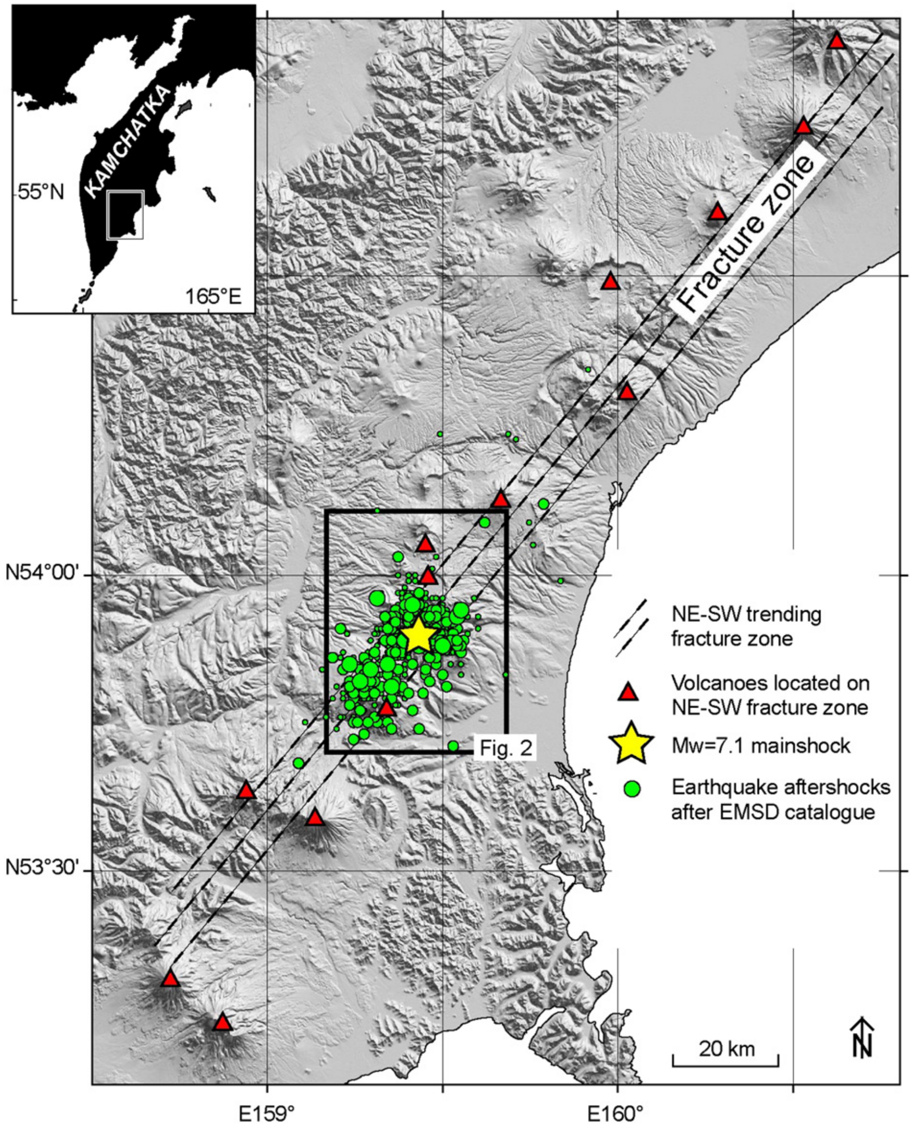


Fig. 1. Map of the study area and shaded relief map. Shown are the earthquake locations of the magnitude Mw = 7.1 mainshock (star) and the aftershocks (green circles). Included are the regional fracture zone trending NE–SW (Masurenkov, 1991a,b), the mainshock (Zobin et al., 2003), and other earthquake locations according to the Kamchatka EMSD catalogue (http://kbgs.kscnet.ru/); red triangles are active volcanoes (Siebert and Simkin, 2002). The black rectangle in shaded relief map indicates the close-up which is Fig. 2.

occurred within the past 5000 yr (Belousov and Belousova, 2001). Although deformation and seismic activity have been detected around Akademia Nauk Caldera for more than 30 yr, the volcanic system was considered to be extinct — until January 1996.

2. The 1996 earthquake–eruption sequence

The interaction between tectonic earthquakes and volcanic activity in the Karymsky area was already subject to debate even before the 1996 events took place (Maguskin et al., 1998; Shirokov et al., 1988). Earthquakes at Karymsky Volcanic Center generally occur within the upper 20 km of the crust, with the most pronounced earthquake swarms in 1964, 1971, 1975, 1978, 1985 (Shirokov et al., 1988) and, most recently, 1996. A $M = 5.5$ earthquake occurred during the 1978 swarm, with an east–west extension and strike-slip movement with one nodal plane parallel to the NE–SW oriented fracture zone (Zobin et al., 1983). However, geologic observation and geodetic measurements did not confirm this signal.

Prior to 1996, the last major eruption of Karymsky occurred between 1970 and 1982. The type of eruption was mainly explosive (vulcanian). Strong explosion earthquakes accompanied this activity (Ivanov et al., 1991). Following the end of the 1982 eruption, an intense doming period commenced. The 1996 eruptive episode can therefore be considered to have started with the pre-eruptive inflation period in 1983 (see Section 2.1), before the large tectonic earthquake occurred in 1996 (see Section 2.2), which was followed by a dike intrusion and eruption (see Section 2.3). The chronology of events is summarized below and in Fig. 4; further details are provided in the literature base (Maguskin et al., 1998; Gordeev et al., 1998a,b; Leonov, 1998; Muraviev et al., 1998; Zobin and Levina, 1998).

2.1. Pre-eruptive inflation

Repeated geodetic measurements since 1975 revealed ongoing activity in Karymsky Volcanic Center. The distance between the Karymsky volcanoes and Academy Nauk was measured by a triangulation network, suggesting that deformation took place at different scales. Locally, co-eruptive subsidence occurred at Karymsky Stratovolcano (Maguskin and Sharoglazova, 1993). On a larger scale, widespread extension was measured from Karymsky Stratovolcano to Akademia Nauk Caldera. The larger-scale deformation may have had an important effect in redistributing the stress field. The horizontal deformation data suggest almost continuous extension since 1975 (Maguskin and Sharoglazova, 1993). A distance increase was measured during the eruptive phase from 1975–1977; elongation then decreased and even reversed to become a slight distance shortening at the end of the eruptive period (1981–1983). After the eruptive period ended in 1983, a distance increase was measured again (Maguskin and Sharoglazova, 1993). The distance further increased until 1995, so that at least an 11-year period of extensional deformation preceded the 1996 eruption.

The spatial pattern of deformation was radial-extensional, suggesting accumulation of magma in the crust during an inter-eruptive period of inflation (Maguskin and Sharoglazova, 1993). The local and large-scale deformations are probably related to two different magma chamber sources. A small shallow reservoir is thought to exist at a depth of 4–5 km (Gordeev et al., 1998a,b), but various authors suggest the presence of an additional, much larger, potentially common source below Karymsky Volcano and Akademia Nauk Caldera. Fedotov (1998) calculated a pressure source and suggested that the bulk of the measured surface deformation is attributed to inflation of a large, deep magma reservoir at a depth of roughly 18 km, located halfway between Akademia Nauk and the Karymsky volcanoes. Other studies basically confirmed the idea of such a deep magma chamber (Maguskin et al., 1982; Shirokov et al., 1988). Also, geodetic measurements suggest that the main magma chamber responsible for the 1983–1996 inflation period is likely to be located at such deep levels (Maguskin and Sharoglazova, 1993; Zobin et al., 2003), maybe in a north–south elongated form (Pavlov et al., 2003).

2.2. Earthquake

On the 31 Dec 1995 an earthquake of magnitude 5.6 occurred 60 km SE of Karymsky offshore in Kronotsky Bay of the Pacific. The earthquake was relatively deep at 60 km and caused no reported damage, even though it was felt in the City of Petropavlovsk 140 km to the south. Then another, much larger earthquake occurred further north on 1 Jan 1996 (9:57 GMT) in the shallow crust, about 14 h before the first eruption. The regional seismic network of Kamchatka located the epicenter (KRSC event ID 2020739) at 53.88°N and 159.44°E at 0 km depth. Zobin and Levina (1998) noted that the depth may be inaccurate because of the large distance (>80 km) of the nearest seismic station operating in the region, and suggested a corrected depth at 10 km according to foreshock distributions (Zobin and Levina, 1998). Because of the overlapping recordings with a larger earthquake Mw=7.9 near Minahassa Peninsula, Indonesia, no Harvard CMT solution could be resolved for the Kamchatka event. For this work, magnitude estimations from the International Seismological Centre (Bulletin of ISC) were used; these estimates ranged between 5.8 and 7.2. The magnitude was determined by NEIC as Ms=6.7 (Mw=7.1). Curiously, no primary surface fractures could be found around the mainshock epicenter even though the earthquake was very shallow. Based on P-wave first motions recorded at 11 local stations and 69 teleseismic records, the focal mechanism solution suggests nodal planes with 14° strike, 81° dip and 14° slip, or 282° strike, 76° dip, 171° slip (Fig. 2). The 14° strike direction correlates with the NE–SW structural trend as suggested by geological evidence (Belousov et al., 1997). This was the largest earthquake ever measured in the eastern volcanic arc of Kamchatka. An intense swarm of aftershocks followed, two of which exceeded M=6 and many others larger than M=5 (Fig. 2). These aftershocks were too large to be attributable to magmatic origin in this volcanic area (Fedotov, 1998). Overall, 19 earthquakes larger than M=4.5 were detected about 5–10 km south of the extinct Akademia Nauk Caldera, most of which occurred along the NE–SW fracture zone (Fig. 1), and

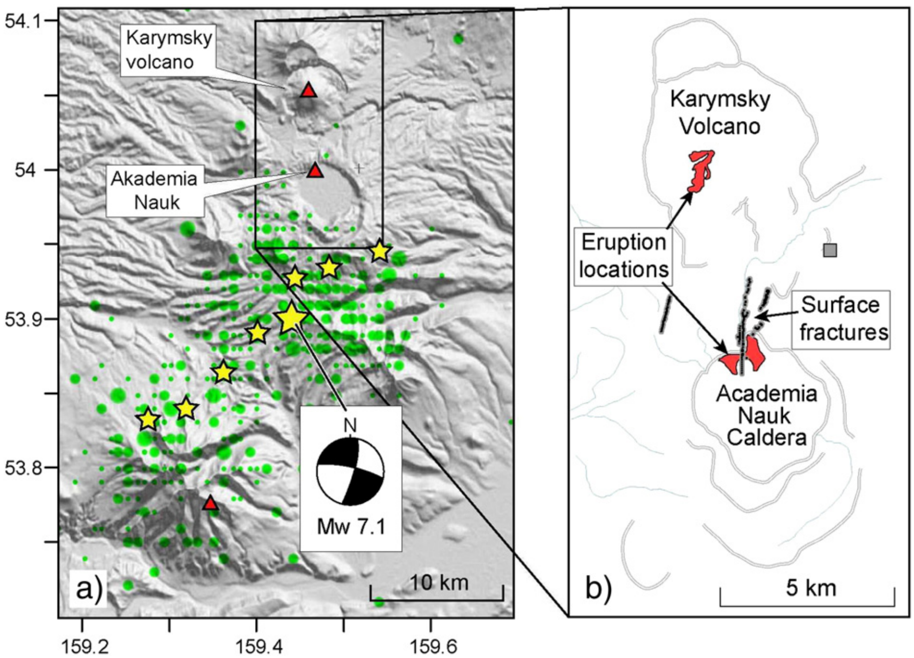


Fig. 2. Karymsky Volcano and Akademia Nauk Caldera. (a) Alignment of earthquakes along the regional NE–SW trending fracture zone. Yellow stars are the epicenters of the strongest earthquake aftershocks (Ms > 5) (Zobin et al., 2003); green dots are the same as in Fig. 1 (EMSD catalogue). Mainshock focal mechanism after (Zobin and Levina, 1998; Gordeev et al., 1998a,b). (b) Locations of surface ruptures mapped between Karymsky Volcano and Akademia Nauk Caldera [Leonov (1998), own observation].

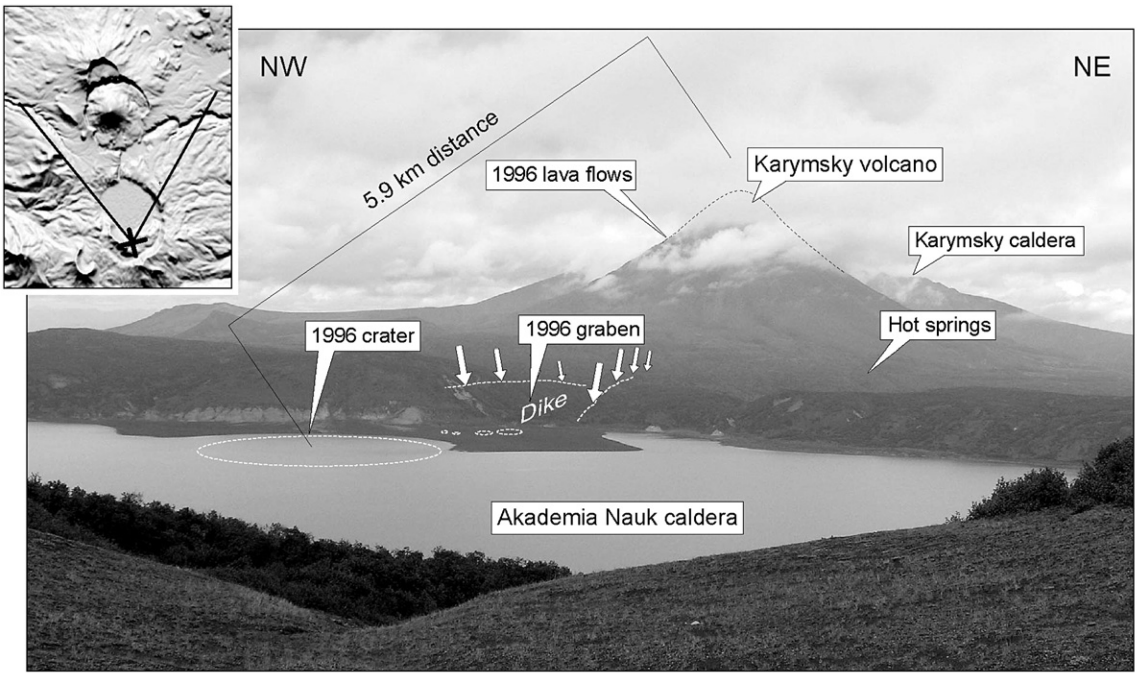


Fig. 3. Photograph of Akademia Nauk Caldera Lake and Karymsky Volcano in the background. Visible is the new phreatomagmatic explosion crater of the 1996 eruption, from which small pit holes and a fault-bound graben strike northwards to Karymsky Volcano (5.9 km distant). Picture taken from the south rim of Akademia Nauk Caldera, as shown in insert on upper left corner.

thousands of even smaller aftershocks followed (Fedotov, 1998; Zobin and Levina, 1998). An eruption at Karymsky Volcano was expected, but the simultaneous eruption at Akademia Nauk Caldera was surprising.

2.3. Dike intrusion and eruption

On 2 Jan 1996, Karymsky Stratovolcano started to erupt. Shortly afterwards, another eruption commenced at Akademia Nauk Caldera despite its long dormancy (Fedotov, 1998; Belousov and Belousova, 2001). The distance between the two eruption centers is 5.9 km. The main vent at Karymsky Stratovolcano formed 100 m below the summit where two weeks of gas, ash and periodic vulcanian explosions were followed for about 1 yr by strombolian explosions with andesite to dacite–andesite lava outflows at an average rate of discharge of 0.35 m^3/s (Fedotov, 1998). In the south, the main vent at Akademia Nauk Caldera was located in the northern part of the caldera lake and produced phreatomagmatic explosions, base surges and tsunami waves that eroded beach sand and plants of the opposite shore (Belousov et al., 2000). A new peninsula formed with a deep, incised explosion crater (Fig. 3). In association with the 1996 eruptions, just north of the new explosion crater several sinkholes formed. From their northward extension, a set of subparallel N175°±10° trending fractures developed (Figs. 2, 3) which can be traced as far as >1 km to the north (Leonov, 1998). Geodetic measurements detected ~2.3 m of extension across the fracture system that connects Karymsky Stratovolcano and Akademia Nauk Caldera (Maguskin et al., 1998). These fractures are about 15 km away from the epicenter and probably represent the surface expression of a dike intrusion. This hypothesis is also supported by petrological studies that clearly show that the double-eruption of Karymksy Stratovolcano and Akademia Nauk Caldera were initiated by a basaltic dike that intruded from a greater depth into a shallow andesite reservoir before the eruption (Fedotov, 1998; Eichelberger and Izbekov, 2000; Izbekov et al., 2004a,b). Considerable seismic evidence suggests that the earthquake and the volcanic activity were separate events (Gordeev et al., 1998a,b). Moreover, basaltic magma is otherwise uncommon at both Karymsky Stratovolcano and Akademia Nauk Caldera, and may have been facilitated or triggered by the preceding tectonic earthquakes, as I will illustrate below.

3. Stress modeling

The study of the stress field changes during the earthquake–eruption sequence may help to understand modes of activity and the relationship between the tectonic and volcanic stages. Using a three-dimensional numerical modeling method, I simulate the two main processes: (a) pre-eruptive inflation into the deep reservoir that is responsible for the pronounced uplift period from 1983–1996, and (b) static dislocation during the 1 Jan 1996 earthquake that may have facilitated the subsequent dike intrusion into the line between Karymsky Stratovolcano and Akademia Nauk Caldera. The computer code used is Poly3D, a boundary element modeling program based on displacement discontinuities in a linearly elastic medium (Thomas, 1993). Three angular dislocation solutions allow the construction of triangular dislocation elements (Comninou and Dundurs, 1975); a set of such elements allows for the approximation of complex dislocation shapes such as the topography or a magma

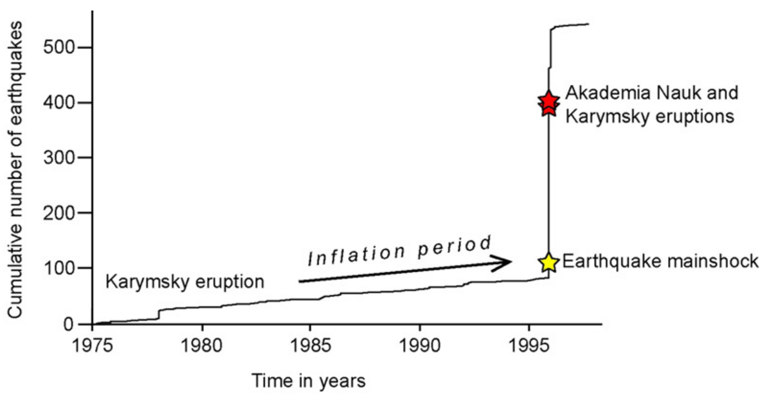


Fig. 4. Chronological summary of the volcanic and tectonic events. An inflation period followed the last major eruption at Karymsky Volcano. On 1 Jan 1996, the earthquake mainshock (Mw=7.1) occurred, followed by the double eruption at Karymsky Volcano and Akademia Nauk Caldera. Black line is the cumulative number of earthquakes versus time, yellow star is the 1 Jan 1996 mainshock, red stars are the beginning of the reported eruptions.

chamber (Walter and Amelung, 2006; Walter et al., 2005). In the case of the 1996 earthquake–eruption sequence, the fault dislocation is prescribed based on the work by Zobin and Levina (1998). The geometries are simplified (Fig. 4); the material is homogeneous and linearly elastic. The inter-eruptive inflation period was simulated by volumetric expansion of a sphere 4-km-wide in radius located at a depth of 18 km (Fig. 4). The depth is constrained based on geodetic data (Fedotov, 1998), though the radius is not constrained and may be different without affecting the quality of the results. Because the volume usually erupted during a single cycle at Karymsky Stratovolcano is 0.1 km^3 or less (Ivanov et al., 1991), I assume that a similar volume was stored in the deep reservoir before the 1996 twin-eruption sequence started at Karymsky Stratovolcano and Akademia Nauk Caldera. The crust is considered to be a Poisson solid with a Poisson's ratio of $\nu=0.25$ and a Young's Modulus of $E=70$ GPa. The Coulomb failure stress is calculated at shallow crustal depth (10 km below the surface) at the SW–NE trending fracture zone, according to $\delta CFS=\delta\tau_R+\mu\ (\delta\sigma_N+\delta P)$, where $\delta\tau_R$ is the shear stress change on a fault in the expected rake (slip) direction, $\delta\sigma_N$ is the normal stress change, δP is the pore pressure change in the fault zone, and μ is the coefficient of friction (Harris 1998). According to the used convention herein, shear stress is positive in the direction of fault slip, and normal stress on the fault plane is compressive if negative. The pore pressure change is defined by $\delta P=B\delta\sigma_M$; the parameter B is the Skempton's coefficient for which experimental determinations indicate $0.5<B<0.9$ (here used: $B=0.7$); and $\delta\sigma_M$ is the change in mean stress (Harris 1998). Some authors use instead an apparent coefficient of friction; the applications, assumptions and limitations of this approach

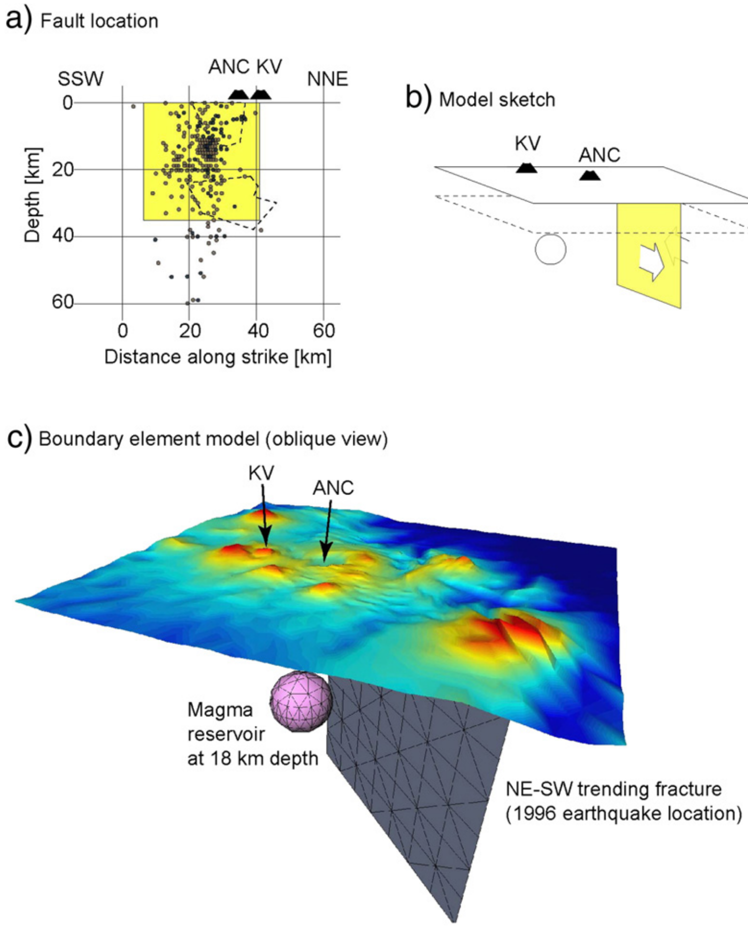
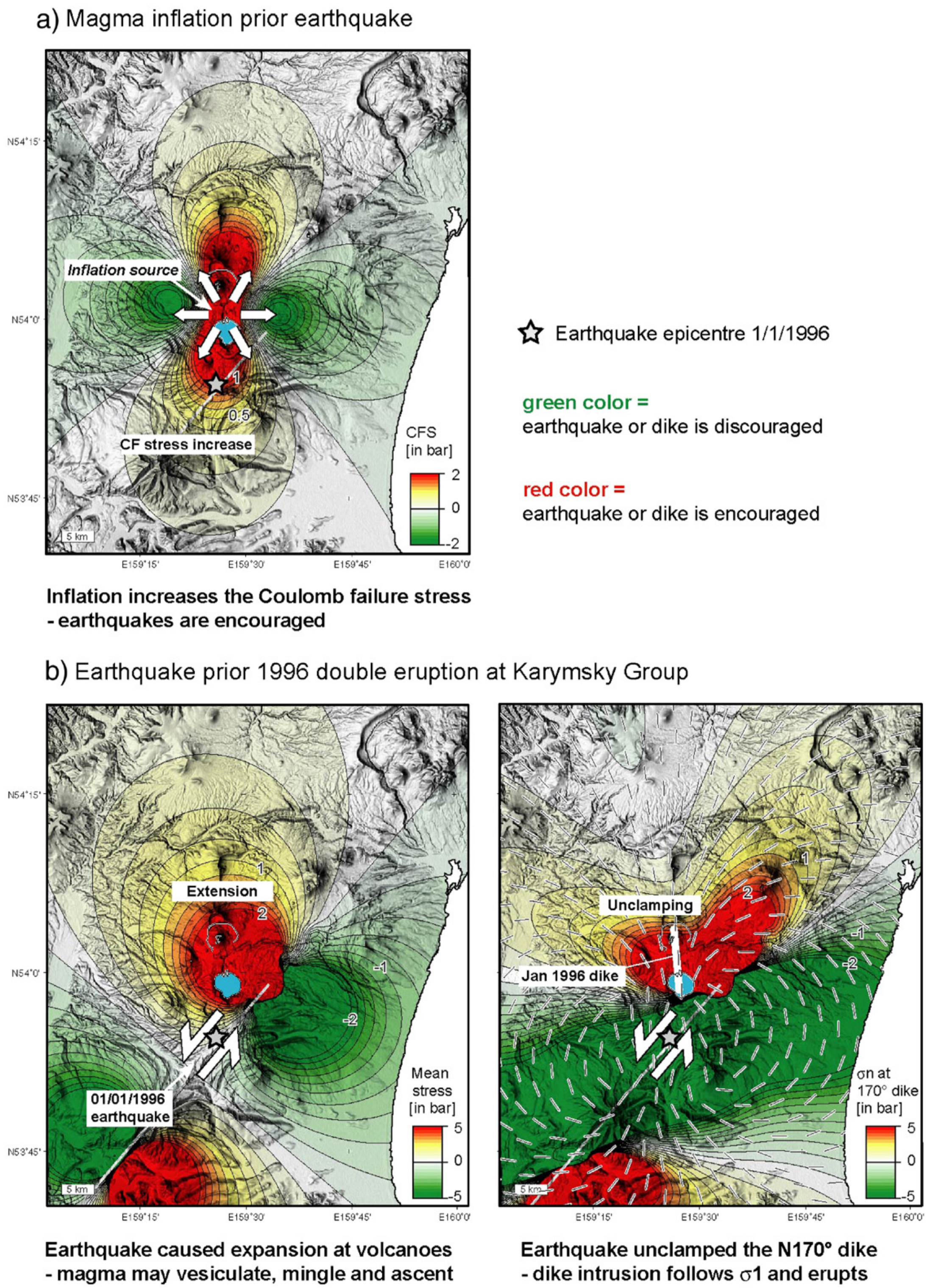


Fig. 5. Numerical model construction: (a) profile along fracture zone, where black dots show earthquake M>2 hypocenter distribution prior to the 1996 eruption, dashed black line shows asperity location (Zobin et al., 2003), yellow area shows the fault dislocation plane used in this paper: (b) sketch of the model setup with Karymsky Volcano (KV) and Akademia Nauk Caldera (ANC), where yellow area represents the fault plane and the circle represents the deep magma reservoir; (c) perspective view of the boundary element model setup.

are discussed in (Beeler et al., 2000). Simulation of a 0.1 km^3 volume change yields maximum surface vertical displacements of 4–5 cm, which is of the same order as those detected geodetically and correlates to a magma overpressure of about 7 MPa. Fig. 6a shows the results of the Coulomb failure stress, where warm colors indicate an



increase of the Coulomb failure stress to encourage earthquakes, while green colors reduce the Coulomb stress to discourage earthquakes. The Coulomb failure stress increase at the NE–SW regional fracture zone is more than 0.5 bars, and thus an important contributor to the total failure stress in view of the fact that even stress changes below 0.1 bar may trigger earthquakes (Stein, 1999). The highest increase of the Coulomb failure stress occurs in the position where the mainshock epicenters were located in 1996 (Figs. 2, 6). The models therefore suggest that inflation encouraged fault slip and the 1996 tectonic earthquake.

In the second model type, I simulate the 1996 earthquake and calculate the changes on the fissure system connecting Karymsky Stratovolcano and Akademia Nauk Caldera. Both, regional records and teleseismic data, suggest a NE strike, a subvertical dip and a left lateral slip, in agreement with the NE–SW trending fracture system (Masurenkov, 1991a,b). A variable-slip model was published by Zobin and Levina (1998). Here, I use a simplified-slip model in which the fault plane has a dimension of 35×35 km^2 and a constant slip of 0.7 m, yielding a moment release approximately equivalent to the 1 Jan 1996 earthquake. The model results are shown in two ways: first, the mean stress ⅓($\sigma 1 + \sigma 2 + \sigma 3$); second, the sigma 1 ($\sigma 1$) trajectories and the normal stress (σn) on the 170° dike direction. Fig. 5b (left side) shows that there are two main zones of positive mean stress change (decompression), the largest of which is in the area between Karymsky Stratovolcano and Akademia Nauk Caldera. A magma reservoir at this depth would have been subject to sudden decompression. The trajectories as shown in Fig. 6 (right side) show the orientation of the maximum compressive stress direction caused by the earthquake. The orientation of the $\sigma 1$ trajectories at Karymsky Stratovolcano and Akademia Nauk Caldera is N170°, which almost perfectly matches the direction of the co-eruptive fractures between the volcanic centers. This is in agreement with Anderson's theory, where propagating opening-mode dikes follow the direction of maximum compressive stress, $\sigma 1$. Additionally, a preexisting fracture zone may have become reactivated. For a quantitative result, the normal stress was computed in the direction N170° in order to assess whether the fractures were clamped or unclamped by the earthquake. The results show that unclamping occurred between both volcanic centers (red color in Fig. 6, right side).

The numerical models presented herein therefore help to explain the location and direction of the 1996 earthquake–eruption sequence, with several further implications for the magma ascent and eruption-triggering mechanisms, as discussed below.

4. Summary and discussion

Unusual volcanic activity after earthquakes is known in various regions around the world. Although the effect of destructive earthquakes on the correlating occurrence of volcanic eruptions was hypothesized back in the 19th century (Darwin, 1840), the mechanisms of earthquake and volcano interactions remained poorly studied. This subject attained further attraction when a July 1990 magnitude 7.8 earthquake in the Philippines preceded a seismicity increase near Mt. Pinatubo, initiating a reawakening that finally led to the climactic June 1991 eruption (Bautista et al., 1996). A subduction zone earthquake in the Andes in July 1995 was followed by surface deformation at various volcanoes, some of which had not been listed as active (Pritchard and Simons, 2004). Mount Vesuvius was having the largest eruptions shortly after earthquakes in the Appenines (Nostro et al., 1998). Also, in Kamchatka, Russia, earthquakes and eruptions have been identified as spatially–chronologically linked. For instance, following the megathrust earthquake of 3 Feb 1923 ($M = 8.5$), the two volcanoes Karymsky and Dzenzur erupted, the latter of which was erupting for the first (and last) reported time. Following the 5 Nov 1952 subduction earthquake near the southern shore of Kamchatka, on 12 Nov the Krenitsyn stratovolcano located in the Tao-Rusyr caldera (Paramushir Island, Kuriles) started to erupt (Walter and Amelung, 2007). Following the $Mw = 7.1$ earthquake in 1 Jan 1996, unusual volcanic activity occurred at Karymsky Stratovolcano as described herein, and again a volcano that was not considered active began a violent eruption.

Stress field models were presented in this paper in order to better understand the 1996 earthquake–eruption sequence. The models were set up to simulate dislocation

Fig. 6. Modeling results. (a) Model simulation of inflation of a deep magma reservoir. Coulomb failure stress change (CFS) calculated at faults parallel to the NE–SW (N040) fracture system (red = faults are brought closer to failure, indicating CFS increases; green = CFS decreases). Faulting is encouraged in exactly the area of the 1996 earthquake mainshock. Inflation therefore encouraged this earthquake. (b) Model simulation of the 1 Jan 1996 earthquake. Fault dislocation causes a "butterfly" distribution of the mean stress (red = extension, green = compression), where the volcanoes KV and ANC are located exactly in one of the lobes subject to maximum extension. The sigma 1 trajectories indicate the expected direction of a dike intrusion. Normal stress calculation at the 170° dike trend (red = unclamping, green = clamping) shows that a stress concentration occurs just between KV and ANC, i.e. a dike would be unclamped and intrusions would be facilitated. On 2 Jan 1996, a dike intrusion occurred with orientation N170°. Background is SRTM slope map, blue area is the Akademia Nauk Caldera lake.

due to magma inflation and showed that the Coulomb failure stress increased at the tectonic fracture system. Other models were set up to simulate the 1/1/1996 earthquake and showed that the most likely dike orientation between Karymsky and Akademia Nauk Caldera was N170°E. The 1996 eruption centers and the output of thermal springs follow this trend (Eichelberger and Izbekov, 2000). These findings also correlate with the location of surface fractures mapped in this area (Leonov, 1998), surface deformation (Maguskin et al., 1998), earthquakes and their aftershocks (Gordeev et al., 1998a,b; Zobin and Levina, 1998; Zobin et al., 2003). Moreover, these findings are supported by the similar petrology of some products at the two eruptive centers conjoint with extended dike injection (Izbekov et al., 2004a,b). This paper shows that earthquake–eruption coupling can be explained by the transfer of the static stress field.

The models presented here are based on geologic, geodetic and geophysical information. However, several assumptions and simplifications were made in order to simulate the processes involved. The models assume a homogeneous and linearly elastic material. Material heterogeneities may be present locally under the volcanoes as well as horizontally (layering) and vertically (fracture zones), and affect the distribution and magnitude of the stress and strain (Cailleau et al., 2007; Manconi et al., 2007). The calculations neglect a pre-existing long-term tectonic stress field and only show the short-term effect. The earthquake may have further encouraged opening of an already existing pre-conditioned fracture zone.

As was stated above, the dimension of the large magma chamber is not well known. Since several authors suggested the presence of a "large" magma chamber in between Karymsky Volcano and Akademia Nauk Caldera, the stress field models are based on this information. The amount of inflation was somewhat greater than the mean eruption volume during eruptive episodes at Karymsky Stratovolcano (i.e. generally less than 0.1 km^3, Ivanov et al., 1991), and translated to a magma overpressure of about 7 MPa for a chamber 4 km in radius at a depth of 18 km. 7 MPa is on the same order as needed to cause existing dikes to propagate (Rubin, 1995), but is almost one order of magnitude below the critical magma chamber overpressure for evolved dikes (Jellinek and DePaolo, 2003). Concerning the earthquake models, here I used a simple dislocation model of a complicated shallow event that caused no apparent co-seismic surface fractures. Variations of the model assumptions (strike, dip, rake of the earthquake) may produce a slightly different result. However, since the model setup is based on a detailed study of the earthquake and aftershock distribution as well as geologic constraints and the known regional fracture zone orientation (Fedotov, 1998; Maguskin et al., 1998; Gordeev et al., 1998a,b; Leonov, 1998; Zobin and Levina, 1998; Zobin et al., 2003), the presented results appear sound. The effects of the stress redistribution on the magmatic system remain to be discussed in some greater detail.

Changes of the static stress field may have affected the volcano system in various ways, as suggested by studies at other volcanoes (Nostro et al., 1998; Walter and Amelung, 2006). A direct mechanical effect may result from the unclamping of the fissure system. A pre-existing network of cracks may be connected, nucleate and thereby facilitate preferred paths for magma ascent. Moreover, several indirect effects may have occurred. For instance, due to unclamping and magma rise, the magma may have further expanded so that gas phases exsolved and ascended, further increasing the eruption possibility by increasing the governing parameters such as the buoyancy, mobility and overpressure. Such a change of the

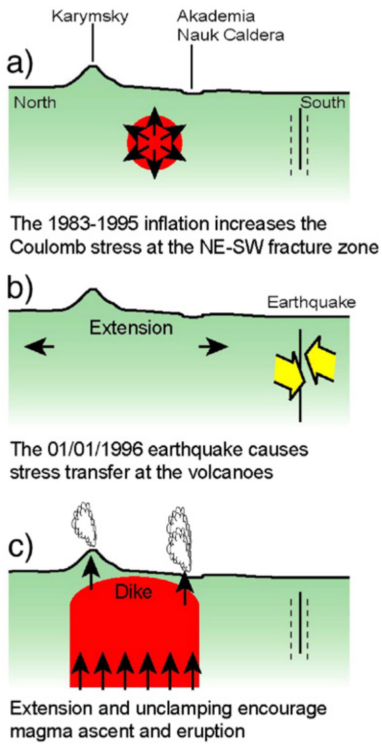


Fig. 7. Synthesis and proposed mechanisms of the events that led to the 1996 eruption. A period of sustained inflation increased the Coulomb stress at the regional fault zone south of the volcanoes. An earthquake at the regional fault zone caused expansion at the volcanoes and unclamped a north–south oriented fracture into which a dike could propagate. The dike passed through solidified shallower reservoirs and triggered eruptions at Karymsky Volcano and Akademia Nauk Caldera.

physical properties of the magma could affect its ability to mix with another magma type (Izbekov et al., 2004a,b). Also, the shaking effect during the passage of the seismic waves (Manga and Brodsky, 2006) may have encouraged the eruption by the release and ascent of gas bubbles. The dynamic stress changes are transient and act only during the passing of the seismic waves, whereas static stress changes as discussed in this work act permanently. The magnitude of stress changes, however, is larger in the dynamic case, especially at a distance (Hill et al., 2002). Dynamic triggering may therefore be eminent even at large distances, and may affect volcanic and hydrological reservoirs (Linde and Sacks, 1998). In this context, it was recently suggested that the Jan 1996 earthquake triggered a sudden change in the ion and gas content at a water well in Petropavlovsk, located about 100 km to the south of the earthquake (Biagi et al., 2004). As already noted before, the Kamchatka events were slightly preceded or even overlapping with recordings of a larger earthquake Mw = 7.9 near Indonesia. One may hypothesize that dynamic triggering of this event may also have slightly contributed, since recent studies suggest pressure gradients by teleseismic waves operate even at distances exceeding 10,000 km (Cornet and Doan, 2007); however, no further supporting data were found for such a far-field effect in this case.

The composition of the magmas erupted at Karymsky Stratovolcano and Akademia Nauk Caldera is of Andesite type. (The last basaltic eruption occurred at Karymsky Stratovolcano about 2800 yr BP; see (Ivanov, 1996).) In the case of the 1996 earthquake–eruption sequence, new petrological evidence suggests that a crustally stored Andesite magma chamber was replenished, heated and partly bypassed by new basaltic magma from a deeper reservoir, so that for about 2 months the eruptive products were contaminated (Belousov et al., 2000; Izbekov et al., 2004a,b). The eruption is therefore triggered not directly by the earthquake, but more likely by an intermediate step such as fracture unclamping, magma expansion and degassing and basaltic dike injection into or through an evolved magma chamber (Fig. 7). Although the final mechanism of eruption triggering is still unclear, the scenario that took place at Karymsky Stratovolcano and Akademia Nauk Caldera in 1996 implies that a tectonic earthquake may initiate processes leading within hours to unusual volcanic and explosive activity in regions where historically no major eruptions have occurred. Carried forward to other volcanic centers in comparable conditions, such as Long Valley, Santorini, Vesuvius or Campi Flegrei, this means that assessment of the eruption hazard potential requires that a potential stress triggering effect be taken into account.

5. Conclusion

Located at distance of only a few tens of km from the epicenter, two Kamchatkan volcanoes erupted simultaneously in 1996: Karymsky Stratovolcano and Akademia Nauk Caldera. In this paper, I presented three-dimensional boundary element models that show: (a) that the pre-eruption period of inflation increased the Coulomb failure stress at the tectonic fracture system and therefore encouraged the earthquake; and (b) that the 1 Jan 1996 earthquake caused a major stress change in the region of Karymsky Stratovolcano and Akademia Nauk Caldera, unclamped the north–south trending fissure, and facilitated dike propagation and eruption.

Acknowledgements

I thank Alexander Belousov and Marina Belousova for numerous discussions and continuous (food and drink) support during the field trip at Karymsky. This work benefited from very detailed comments of three reviewers. Financial support for the field visit came from the Deutsche Forschungsgemeinschaft (WA 1642/1-4).

References

Alam, M., Kimura, M., 2004. Statistical analysis of time-distance relationship between volcanic eruptions and great earthquakes in Japan. Earth Planets and Space 56 (2), 179–192.

Bautista B.C., Bautista M.L.P., Stein R.S., Barcelona E.S., Punongbayan R.S., Laguerta E.P., Rasdas A.R., Ambubuyog G., Amin E.Q. Relationship of regional and local structures to Mount Pinatubo activity, in: Fire and mud; eruptions and lahars of Mount Pinatubo, Philippines, Philippine Institute of Volcanology and Seismology, Quezon City, Philippines, University of Washington Press United States, 1996.

Beeler, N.M., Simpson, R.W., Hickman, S.H., Lockner, D.A., 2000. Pore fluid pressure, apparent friction, and Coulomb failure. Journal of Geophysical Research B: Solid Earth 105 (11), 25533–25542.

Belousov, A., Belousova, M., 2001. Eruptive process, effects and deposits of the 1996 and ancient basaltic phreatomagmatic eruptions in Karymskoye lake, Kamchatka, Russia. Special Publication of the International Association of Sedimentologists 30, 35–60.

Belousov, A.B., Belousova, M.G., Muravyev, Y., 1997. Holocene eruptions in the Akademiya Nauk Caldera and the age of the Karymsky Stratovolcano, Kamchatka, Transactions (Doklady) of the Russian Academy of Sciences. Earth Science Sections 355 (5), 653–657.

Belousov, A., Voight, B., Belousova, M., Muravyev, Y., 2000. Tsunamis generated by subaquatic volcanic explosions: unique data from 1996 Eruption in Karymskoye Lake, Kamchatka, Russia. Pure and Applied Geophysics 157 (6–8), 1135–1143.

Belousov, A., Walter, T.R., Troll, V.R., 2005. Large-scale failures on domes and stratocones situated on caldera ring faults: sand-box modeling of natural examples from Kamchatka, Russia. Bulletin of Volcanology 67 (5), 457–468.

Biagi, P.F., Castellana, L., Piccolo, R., Minafra, A., Maggipinto, G., Ermini, A., Capozzi, V., Perna, G., Khatkevich, Y.M., Gordeev, E.I.,

2004. Disturbances in groundwater chemical parameters related to seismic and volcanic activity in Kamchatka (Russia). Natural Hazards and Earth System Science 4 (4), 535–539.

Braitseva, O.A., Melekestsev, I.V., 1991. Eruptive history of Karymsky Volcano, Kamchatka, USSR, based on tephra stratigraphy and 14C dating. Bulletin of Volcanology 53 (3), 195–206.

Braitseva, O.A., Melekestsev, I.V., Ponomareva, V.V., Sulerzhitsky, L.D., 1994. Age of active volcanoes of the Kurile-Kamchatka region. Volcanology and Seismology 4–5, 5–32.

Braitseva, O.A., Melekestsev, I.V., Ponomareva, V.V., Sulerzhitsky, L.D., 1995. Ages of calderas, large explosive craters and active volcanoes in the Kuril-Kamchatka region, Russia. Bulletin of Volcanology 57 (6), 383–402.

Brodsky, E.E., Prejean, S.G., 2005. New constraints on mechanisms of remotely triggered seismicity at Long Valley Caldera. Journal of Geophysical Research B: Solid Earth 110 (4), 1–14.

Bursik, M., Renshaw, C., McCalpin, J., Berry, M., 2003. A volcanotectonic cascade: activation of range front faulting and eruptions by dike intrusion, Mono Basin-Long Valley Caldera, California. Journal of Geophysical Research, B, Solid Earth and Planets 108 (B8), 2393. doi:10.1029/2002JB002032.

Cailleau, B., LeFemina, P.C., Dixon, T.H., 2007. Stress accumulation between volcanoes: an explanation for intra-arc earthquakes in Nicaragua? Geophysical Journal International 169 (3), 1132–1138. doi:10.1111/j.1365-246X.2007.03353.

Comninou, M., Dundurs, J., 1975. Angular dislocation in a half space. Journal of Elasticity 5, 203–216.

Cornet, F.H., Doan, M.L., 2007. Small pressure drop triggered near a fault by small teleseismic waves. Earth and Planetary Science Letters 258 (1–2), 207–218.

Darwin, C., 1840. On the connexion of certain volcanic phenomena in South America; and on the formation of mountain chains and volcanoes, as the effect of the same power by which continents are elevated. Transactions of the of the Geological Society of London 2 (1840).

Eichelberger J.C., Izbekov P.E. Eruption of andesite triggered by dyke injection; contrasting cases at Karymsky Volcano, Kamchatka and Mt Katmai, Alaska, in: The causes and consequences of eruptions of andesite volcanoes; papers of a discussion meeting Mathematical, Physical and Engineering Sciences. 358; 1770, pp. 1465–1485, Royal Society of London, London, United Kingdom, 2000.

Fedotov, S.A., 1998. Study and mechanism of the simultaneous 1996 Karymsky Volcano and Akademii Nauk caldera eruptions in Kamchatka. Volcanology and Seismology 19 (5), 525–566.

Gordeev, E.I., Droznin, D.V., Kasahara, M., Levina, V.I., Leonov, V.L., Miyamachi, H., Okayama, M., Saltykov, V.A., Sinitsyn, V.I., Chebrov, V.N., 1998a. Seismic events associated with the 1996 volcanic eruptions in the Karymsky volcanic center. Volcanology and Seismology 19 (5), 713–735.

Gordeev, E., Lees, J.M., Ripepe, M., 1998b. No resonating conduit at Karymsky Volcano. AGU 1998 fall meeting, 79. American Geophysical Union, Washington, DC, United States, p. 595. 45, Suppl.

Harris, R.A., 1998. Introduction to special section: stress triggers, stress shadows, and implications for seismic hazard. Journal of Geophysical Research B: Solid Earth 103 (B10), 24347–24358.

Hill, D.P., Johnston, M.J.S., Langbein, J.O., Behr, J., 1994. The role of crustal fluids in the triggered response of Long Valley Caldera to the M = 7.3 Landers, California, earthquake. Proceedings of Workshop LXIII; USGS Red-Book Conference on the Mechanical Involvement of Fluids in Faulting. S. Geological Survey. U S, Geological Survey, pp. 87–91.

Hill, D.P., Pollitz, F., Newhall, C., 2002. Earthquake-volcano interactions. Physics Today 55 (11), 41–47.

Ivanov, B.V., 1996. Petrologic and geochemical peculiarities of the Karymsky volcano andesites: indicators of eruption types. Volcanology and Seismology 17, 461–470.

Ivanov, B.V., Braitseva, O.A., Zubin, M.I., 1991. Karymsky volcano. In: Fedotov, S.A., Masurenkov, Y.P. (Eds.), Active Volcanoes of Kamchatka, 2. Nauka, Moscow, pp. 181–203.

Izbekov, P.E., Eichelberger, J.C., Ivanov, B.V., 2004a. The 1996 eruption of Karymsky Volcano, Kamchatka; historical record of basaltic replenishment of an andesite reservoir. Journal of Petrology 45 (11), 2325–2345.

Izbekov, P., Gardner, J.E., Eichelberger, J.C., 2004b. Comagmatic granophyre and dacite from Karymsky volcanic center, Kamchatka: experimental constraints for magma storage conditions. Journal of Volcanology and Geothermal Research 131 (1–2), 1–18.

Jellinek, A.M., DePaolo, D.J., 2003. A model for the origin of large silicic magma chambers: precursors of caldera-forming eruptions. Bulletin of Volcanology 65 (5), 363–381.

Leonov, V.L., 1998. Ground surface breaks produced by an earthquake and volcanic eruptions in the Karymsky Volcanic center on January 1–2, 1996. Volcanology and Seismology 19 (5), 655–674.

Lipman, P.W., Lockwood, J.P., Okamura, R.T., Swanson, D.A., Yamashita, K.M., 1985. Ground deformation associated with the 1975 magnitude-7.2 earthquake and resulting changes in activity of Kilauea Volcano, Hawaii. U. S. Geological Survey, Reston, VA, United States, p. 45.

Linde, A.T., Sacks, I.S., 1998. Triggering of volcanic eruptions. Nature 395 (6705), 888–890.

Maguskin, M.A., Enman, V.B., Seleznev, B.V., Shkred, V.I., 1982. Surface displacements at Karymsky volcano in 1970–1981 according to geodetic and photogrammetric data. Volcanol Seismol 4, 49–63.

Maguskin, M.A., Sharoglazova, G.A., 1993. Ground surface deformation in Karymskiy volcanic area. Volcanology and Seismology 14 (4), 450–470.

Maguskin, M.A., Fedotov, S.A., Levin, V.E., Bakhtiarov, V.F., 1998. Ground surface deformation caused by seismic and volcanic activity in the Karymsky volcanic center during January 1996. Volcanology and Seismology 19 (5), 637–654.

Manconi, A., Walter, T.R., Amelung, F., 2007. Effects of mechanical layering on volcano deformation. Geophysical Journal International 170 (2), 952–958. doi:10.1111/j.1365-246X.2007.03449.x.

Manga, M., Brodsky, E.E., 2006. Seismic triggering of eruptions in the far field: volcanoes and geysers. Annual Reviews of Earth and Planetary Sciences 34, 263–291.

Masurenkov, Y.P., 1980. Karymsky volcanic center: structure, dynamics, and composition. Nauka 111–116.

Masurenkov, Y.P., 1991a. Geodinamika i rudoobrazovanie v kupolno-koltsevoi strukture vulkanicheskogo poyasa. Nauka 1987.

Masurenkov, Y.P., 1991b. Tectonic position and general history and evolution of eastern Kamchatka volcanoes. In: Fedotov, S., Masurenkov, Y.P. (Eds.), Active Volcanoes of Kamchatka, 2. Nauka, Moscow, pp. 8–15.

Marzocchi, W., Casarotti, E., Piersanti, A., 2002. Modeling the stress variations induced by great earthquakes on the largest volcanic eruptions of the 20th century. Journal of Geophysical Research B: Solid Earth 107 (11) ESE 13–1–13–8.

Miklius, A., Cervelli, P., 2003. Interaction between Kilauea and Mauna Loa. Nature (London) 421 (6920), 229.

Muraviev, Y.D., Fedotov, S.A., Budnikov, V.A., Ozerov, A.Y., Maguskin, M.A., Dvigalo, V.N., Andreev, V.I., Ivanov, V.V., Kartasheva, L.A.,

Markov, I.A., 1998. Volcanic activity in the Karymsky center in 1996: summit eruption at Karymsky and Phreatomagmatic eruption in the Akademii Nauk caldera. Volcanology and Seismology 19 (5), 567–604.
Nakamura, K., 1975. Volcanic eruption caused by squeeze up of magma due to compressive tectonic stress. Kasan = Bulletin of the Volcanological Society of Japan 20, Second Series(2), p. 116.
Nostro, C., Stein, R.S., Cocco, M., Belardinelli, M.E., Marzocchi, W., 1998. Two-way coupling between Vesuvius eruptions and southern Apennine earthquakes, Italy, by elastic stress transfer. Journal of Geophysical Research B: Solid Earth 103 (B10), 24487–24504.
Pavlov, V., Levin, V., Maguskin, M., Kasahara, M., 2003. Volcano-seismic crisis of January 1–2, 1996. Karymsky Volcanic Center (Kamchatka): Elastic Modeling of Geodetic Observations, in: XXIII General Assembly of IUGG A P, Sapporo, Japan.
Pritchard, M.E., Simons, M., 2004. An InSAR-based survey of volcanic deformation in the central Andes. Geochemistry, Geophysics, Geosystems- G3, 5, Q02002.
Rubin, A.M., 1995. Propagation of magma-filled cracks. Annual Review of Earth and Planetary Sciences 23, 287–336.
Shirokov, V.A., Ivanov, V.V., Stepanov, V.V., 1988. Deep structure of the Karymsky Volcano and characteristics of its seismicity based on data from a local network. Volcanology and Seismology 3, 71–80.
Siebert, L., Simkin, T., 2002. Volcanoes of the World: An Illustrated Catalog of Holocene Volcanoes and their Eruptions, Global Volcanism Program Digital Information Series GVP-3, Smithsonian Institution.
Stein, R.S., 1999. The role of stress transfer in earthquake occurrence. Nature 402 (6762), 605–609.
Thatcher, W., Savage, J.C., 1982. Triggering of large earthquakes by magma-chamber inflation, Izu Peninsula. Japan, Geology (Boulder) 10 (12), 637–640.
Thomas A.L., Poly3D: a three-dimensional, polygonal element, displacement discontinuity boundary element computer program with applications to fractures, faults, and cavities in the earth's crust, M.S. Thesis, Stanford University, Stanford, California, 221, 1993.
Walter, T.R., Amelung, F., 2006. Volcano-earthquake interaction at Mauna Loa volcano, Hawaii. Journal of Geophyiscal Research 111 (B05204).
Walter, T.R., Amelung, F., 2007. Volcanic eruptions following $M \geq 9$ megathrust earthquakes: Implications for the Sumatra-Andaman volcanoes. Geology 35 (6), 539–542.
Walter, T.R., Acocella, V., Neri, M., Amelung, F., 2005. Feedback processes between magmatic events and flank movement at Mount Etna (Italy) during the 2002–2003 eruption. Journal of Geophysical Research 110 (B10205).
Walter, T.R., Wang, R., Zimmer, M., Grosser, H., Lühr, B.-G., Ratdomopurbo, A., 2007. Volcanic activity influenced by tectonic earthquakes: static versus dynamic stress triggering at Mt. Merapi, Indonesia. Geophysical Research Letters 34, L05304.
Zobin, V.M., Levina, V.I., 1998. Rupture history of the January 1, 1996, Ms 6.6 volcanic earthquake preceding the simultaneous eruption of Karymsky and Akademia Nauk volcanoes in Kamchatka, Russia. Journal of Geophysical Research, B, Solid Earth and Planets 103 (8), 18315–18324.
Zobin, V.M., Firstov, P.P., Ivanova, E.I., 1983. Earthquake swarm in the region of Karymsky volcano in Jan.–Feb. 1978. Volcanology and Seismology 5, 64–73.
Zobin, V.M., Levina, V.I., Maguskin, M.A., 2003. Seismicity and crustal deformation preceding the January 1996 eruptions at Karymsky Volcanic Center, Kamchatka. Bulletin of Volcanology 65 (7), 477–485.