



Correlations between earthquakes and large mud volcano eruptions

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[1] We examine the potential triggering relationship between large earthquakes and methane mud volcano eruptions. Our data set consists of a 191-year catalog (1810–2001) of eruptions from 77 volcanoes in Azerbaijan, central Asia, supplemented with reports from mud volcano eruptions in Japan, Romania, Pakistan, and the Andaman Islands. We compare the occurrence of historical regional earthquakes ($M > 5$) with the occurrence of Azerbaijan mud volcano eruptions and find that the number of same-day earthquake/eruption pairs is significantly higher than expected if the eruptions and earthquakes are independent Poisson processes. The temporal correlation between earthquakes and eruptions is most pronounced for nearby earthquakes (within ~ 100 km) that produce seismic intensities of Mercalli 6 or greater at the location of the mud volcano. This assumed magnitude/distance relationship for triggering observed in the Azerbaijan data is consistent with documented earthquake-induced mud volcano eruptions elsewhere. We also find a weak correlation that heightened numbers of mud volcano eruptions occur within 1 year after large earthquakes. The distribution of yearly eruptions roughly approximates a Poisson process, although the repose times somewhat favor a nonhomogenous failure rate, which implies that the volcanoes require some time after eruption to recharge. The volcanic triggering likely results from some aspect of the seismic wave's passage, but the precise mechanism remains unclear.

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1. Introduction

[2] Strain and stress perturbations from large earthquakes are capable of affecting systems as diverse as groundwater aquifers, hydrocarbon systems, geothermal systems, and magmatic volcanoes at long distances [e.g., Beresnev and Johnson, 1994; Gomberg and Davis, 1996; Linde and Sacks, 1998; Gomberg et al., 2001; Roeloffs et al., 2003]. A variety of mechanisms have been proposed to explain how earthquakes can alter these systems but considerable uncertainties remain [e.g., Brodsky et al., 1988; Brodsky, 2003; Hill et al., 2002; Pankow et al., 2004; Prejean et al., 2004]. It has been suggested that earthquakes can also trigger large methane mud volcano eruptions (*Abikh* [1863], as cited by Aliyev et al. [2002, 2001] and Aliyev [2004]). One recent example of earthquake/mud volcano triggering occurred when a mud volcano on the island of Baratang, in the Middle Andaman islands, erupted throwing mud above the height of surrounding trees just several

minutes after the 2004 great Sumatra-Andaman Islands M 9 earthquake [*Geological Survey of India*, 2005]. Previous instances of mud volcano activity associated with seismic activity have been documented elsewhere, notably in Pakistan [*Delisle et al.*, 2002], Romania [*Baciu and Etiopo*, 2005], Italy [*Martinelli and Dadomo*, 2005], Turkmenistan [*Guliyev and Feizullayev*, 1995], and Japan [*Chigira and Tanaka*, 1997; *Nakamukae et al.*, 2004] (Table 1). While reports of correlations between large earthquakes and mud volcano eruptions are widespread, little is known about the robustness of the correlation, the exact triggering mechanisms, magnitude thresholds and triggering distances, and whether delayed triggering is possible. The purpose of this study is to quantitatively investigate the link between earthquakes and mud volcanoes eruptions in order to help constrain required triggering thresholds. Auxiliary material¹.

[3] We examine the effects of large earthquakes on mud volcano activity in Azerbaijan, using techniques applied previously on magmatic volcanoes, and we then compare the results with eruption/earthquake pairs documented in other regions. We investigate two possibilities: first, whether mud volcano eruptions can be immediately triggered by earthquakes and second, whether mud volcano activity increases for a period of time after nearby earthquakes. For the first possibility, we define “triggering” as any earthquake/mud volcano eruption pair that appears to be

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Table 1. Earthquakes and Closely Related Mud Volcano Eruptions as Compiled From Various Sources^a

Region	Earthquakes				Mud Volcano Eruptions				References
	Latitude	Longitude	<i>M</i>	Date	Name	Latitude	Longitude	Distance, km	
Azerbaijan	40.6	48.6	4.6	09/24/1848	Marazy	40.56	48.97	<50	A
Azerbaijan	40.6	48.7	5.7	01/28/1872	Kalamaddyn	40.27	48.85	<50	A
Azerbaijan	-	-	-	-	Shikhzairli	40.49	49.05	<50	A
Azerbaijan	40.7	48.6	6.9	02/13/1902	Shikhlairli	-	-	<50	A
Azerbaijan	-	-	-	-	Bozakhtarma	40.51	49.14	<50	A
S. Caspian	39.5	53.7	8.2	07/08/1895	Livanova Bank	39.8	52.1	140	G&F
Andaman	3.3	95.8	9.0	12/26/2004	Baratang	12.2	92.7	~90 ^b	GSI
Romania	45.77	26.76 (d = 90)	7.2	03/04/1977	Baciu	45.3	26.7	100	B&E
Makran	24.5	63.0	8.0	11/28/1945	Ormara	25.2	64.2	<50 ^b	D
Japan	41.77	143.90	8.3	09/26/2003	Niikappu	42.3	142.4	~100 ^b	C&T
Japan	40.45	143.49	7.7	12/28/1994	Niikappu	-	-	~150 ^b	C&T
Japan	42.16	142.36	6.5	03/21/1982	Niikappu	-	-	34	C&T
Japan	41.8	144.1	8.1	03/04/1952	Niikappu	-	-	<100 ^b	C&T

^aA is *Aliyev et al.* [2002], G&F is *Guliyev and Feizullayev* [1995], GSI is Geological Survey of Indian (2005, available at <http://www.gsi.gov.in/mudvol.htm>), B&E is *Baciu and Etiope* [2005], D is *Delisle et al.* [2002], and C&T is *Chigira and Tanaka* [1997]. Earthquake locations are from *Kondorskaya and Shebalin* [1982] when available; otherwise, they are from the NEIC. Historical earthquakes without locations (indicated by a dash) were not found in the available catalogs. Depths of earthquakes are shallow or assumed shallow except for the 1977 Romania event (90 km).

^bDistance was calculated to the nearest rupture rather than the epicenter.

closely related, both temporally (minutes to hours) and spatially (within approximately hundred kilometers of the earthquake). For the second possibility, we investigate whether increased numbers of eruptions, within ~100 km of the earthquake of interest, occur in the months or years after large earthquakes ($M > 5.5$).

[4] We use as our primary data set a catalog of mud volcano eruptions in Azerbaijan. For a more comprehensive list of events we also rely on independent global seismic catalogs of moderate earthquakes (above magnitude 5.5), which can be readily distinguished from smaller events that might be associated with the eruptive process itself [*Panahi*, 2005; *Aliyev et al.*, 2002]. We supplement the Azerbaijan data set with other global earthquake/mud volcano pairs that appear to be causatively related. Our goal is to help establish the degree of correlation between large earthquakes and mud volcano eruptions and to establish triggering thresholds with respect to distance and earthquake intensity. Our aim is to provide constraints on eruption mechanisms and triggering thresholds.

[5] “Mud volcano” is a generic term commonly used to describe any structure that emits water, mud, or hydrocarbons. Geothermal areas often have small structures called mud volcanoes which are created by hot water and steam. Small structures (<5 m) created during liquefaction events are also called mud volcanoes. In this study we use the term mud volcano to refer to the large (tens to hundreds of meters) nongeothermal structures which emit water and mud (or hydrocarbons) and are driven by methane or carbon dioxide [e.g., *Milkov*, 2000; *Kopf*, 2002] (Figure 1). Although this type of mud volcano occurs most commonly offshore, onshore mud volcanoes also exist in selected localities, generally in compressional tectonic settings [*Milkov*, 2000; *Kopf*, 2002]. Mud volcanoes emitting methane are usually also associated with substantial hydrocarbon deposits (such as in the Caspian Sea and the Gulf of Mexico). The Absheron Peninsula in Azerbaijan has more onshore mud volcanoes than any other known locality [*Jakubov et al.*, 1971; *Aliyev*, 2004]. Other significant onshore localities include Trinidad, Romania, and the Makran coast of Pakistan [*Dia et al.*, 1999; *Delisle et al.*, 2002].

In recent years interest in mud volcanoes has increased, in part because of petroleum exploration but also due to the role mud volcanoes play in the global methane budget, a potent greenhouse gas [*Hovland et al.*, 1997; *Milkov et al.*, 2003; *Milkov and Etiope*, 2005]. The hazard from mud volcanoes is low, although isolated casualties have been reported [*Aliyev et al.*, 2002]. The primary risk from mud volcano eruptions is to infrastructure, both onshore and offshore.

[6] Recently, high-quality three-dimensional seismic reflection data has increased our understanding of the deep structure and origins of the offshore Caspian mud volcanoes near Azerbaijan [*Fowler et al.*, 2000; *Kopf et al.*, 2003; *Yusifov*, 2004; *Davies and Stewart*, 2005]. It appears that most of the volcanoes originate in a deep thick shale formation (Oligocene-Miocene Maykop shale) and extend upward in a near-vertical column. The volcanoes tend to be associated with faults, and a conduit is often observed extending up from the Maykop at a depth of roughly 10–12 km, although the fine details tend to be obscured by gas charge.

[7] As a result of the flames, violent behavior, and close association with hydrocarbons, the mud volcanoes in Azerbaijan have long been the object of study, both for scientific and religious purposes. Eruptions of mud volcanoes in Azerbaijan vary greatly, ranging from quiet continuous emissions to large explosive eruptions and expulsion of thousands (or even millions) of cubic meters of mud. The mud is clayey with clasts of country rock and is referred to as “mud breccia.” Expelled fluids include water and oil, as well as large amounts of gas [*Aliyev et al.*, 2002; *Etiope et al.*, 2004]. The driving force of the eruptions is enhanced fluid pressures and expansion of dissolved methane [*Kopf*, 2002]. As the gas (mostly methane) blows out, a considerable volume of mud and fluid is also driven out, which can cause collapse of the top of the volcano. Eyewitnesses often report a subterranean “noise” or “drone” immediately before the eruption. Small to moderate-size earthquakes also have been reported to occur near mud volcanoes in conjunction with eruptions. Unless spontaneous ignition of the methane occurs, in general the temperature of the fluids

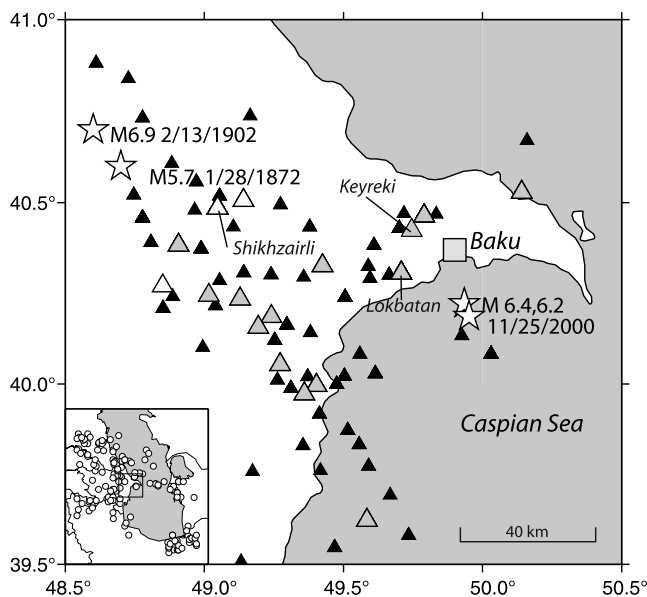


Figure 1. Map of the Absheron Peninsula and surrounding area with approximate locations of known mud volcanoes (solid triangles) and epicenters of large earthquakes that appear to have triggered mud volcano activity (stars). Open triangles indicate volcanoes that erupted on the same day as the 1872 and 1902 earthquakes, and gray triangles show volcanoes that erupted in the year after the 25 November 2000 earthquakes. Labeled mud volcanoes are highly active and used to construct a repose diagram. Inset shows a more regional view of our study area (open square) that includes the locations of all earthquakes (circles) used in this study. Mud volcano locations are based primarily on *Jakubov et al.* [1971] with additional refinement using remote sensing and locations provided by *Planke et al.* [2003] and *Scholte* [2005].

is only slightly elevated over the surrounding strata [*Kopf*, 2002] although higher temperatures have been reported [*MacDonald et al.*, 2000].

[8] Mud volcanoes also produce localized permanent deformation, such as summit elevation changes and collapse features. In general, these features are 10 s to 100 s of meters in spatial extent [e.g., *Planke et al.*, 2003]. The subsidence is almost certainly from the sudden withdrawal of thousands of cubic meters (perhaps from a shallow chamber), which occurs within hours to days during an eruption. In recent years GPS surveys have been conducted on the Absheron Peninsula [*Guliyev et al.*, 2002] although no sites (as far as we know) are near mud volcanoes. Attempts have also been made to monitor mud volcanoes using InSAR to identify deformation signals, but no clear success has currently been reported [*Mellors et al.*, 2005; *Scholte*, 2005].

[9] Two lines of evidence are commonly cited to demonstrate links between earthquakes and mud volcano eruptions. First, several examples exist of eruptions occurring within minutes of strong shaking caused by the passage of seismic waves from earthquakes. The Baratang Island eruption after the 2004 Sumatra earthquake is an example of the apparent same-day triggering and *Aliyev et al.* [2002]

cites several cases of close succession (\sim days to weeks) of eruptions after large earthquakes in Azerbaijan. Second, mud volcanic activity may be more pronounced in the months and years after large earthquakes. Perhaps the best example of heightened activity occurred in 2001 when a record number of mud volcano eruptions were recorded in Azerbaijan, which may have been activated by a two nearby (distances <100 km) earthquakes (M_w 6.0 and 6.3) in November 2000.

[10] Previous studies have investigated the relationship between earthquakes and mud volcanoes. On the basis of time correlations between eruptions and numbers of earthquakes in Azerbaijan, *Bagirov et al.* [1996b] suggested that the time lag between an earthquake and a triggered mud volcano eruption has a phase delay of 1 to 3 years. Both *Bagirov et al.* [1996b] and *Aliyev et al.* [2002] suggest that triggering is dependent on earthquake intensity, but they do not present a quantitative analysis and they restrict their study to only Azerbaijan eruptions and earthquakes. In this work, we focus on the relationship between large earthquakes (rather than numbers of earthquakes) and eruptions, and compare the results we compute using Azerbaijan data to similar earthquake/volcano pairs worldwide.

2. Data and Procedure

2.1. Earthquakes

[11] The Caspian is an area of active tectonics and considerable seismic activity. In general, most of the seismic activity is to the north (mid-Caspian Absheron sill) and west (Caucasus Mountains) of the primary concentration of mud volcanoes (Figure 1). The seismicity is mostly crustal (depths typically <30 km), although events as deep as 80 km have been reported and may represent incipient subduction [*Jackson et al.*, 2002] across the mid-Caspian. The first seismic station in the region was installed in Tashkent in the early 1900s and the Azerbaijan Institute of Seismology has operated analog seismic stations in the region since the 1950s. In 2003, a 14-station broadband network was installed, which increased the detection threshold in the Azerbaijan region.

2.2. Azerbaijan Mud Volcano Eruption Catalog

[12] The first scientific studies of mud volcano eruptions were conducted in the late 1800s. In 1966 an institute devoted to the study of the mud volcanoes of Azerbaijan was created, which focused on conducting a systematic study and data archival of mud volcanoes including detailed geology and structure, geochemistry, and geophysics over the last 40 years. The first catalog created by the institute was issued in 1971 and an updated catalog was issued in 2002 [*Jakubov et al.*, 1971; *Guliyev and Feizullayev*, 1995; *Aliyev et al.*, 2002].

[13] A total of 299 eruptions have been recorded on 77 different volcanoes in the last two centuries. The eruption catalog includes the volcano name, date, time, and a brief description of the eruption (if available). The precision of the date and time varies; 152 of the eruptions (especially before 1900) are listed only by year, or by year and month. The remaining events include the date and about 20% report the hour and sometimes minute of the eruption. The description usually consists of comments about the eruption

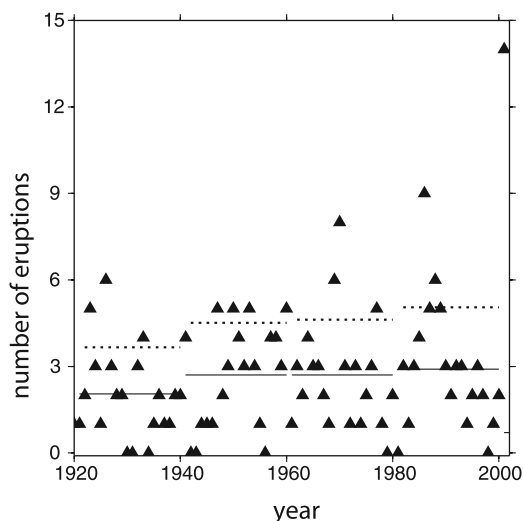


Figure 2. Eruptions (triangles) per year according to the catalog of *Aliyev et al* [2002]. Horizontal lines show the mean number of eruptions over a 20-year period. The mean has remained close to 3.0 since 1940. Dashed lines indicate 2 standard deviations from the mean. The increase in the reported number of eruptions over time is likely due to the increasing completeness of the catalog.

(i.e., noise heard beforehand, height of eruption, etc.) and an estimate of the volume of breccia expelled (in thousands of m^3). One problem with this eruption catalog is apparent typographical errors, usually identified by duplications or inconsistencies with other tables. The 2002 catalog produced by the institute is estimated to be the most complete for the last 40 years as most of the organized studies have been conducted in this time [*Bagirov et al.*, 1996a] but “it is undoubted that some have been missed” [*Aliyev et al.*, 2002]. However, for the volcanoes that lie in or near highly populated areas (such as Lokbatan and Keyreki) it is likely that the record is reasonably comprehensive. The volcano Lokbatan lies a few hundred meters from an active oil field, which has been producing oil since the 1940s, and therefore Lokbatan eruptions are likely well documented. Even if the usually relatively brief (less than an hour) explosive phase is not observed, the mudflows are unmistakable, even to nonspecialists, for months or years afterward and can often be observed on satellite images as well [*Scholte*, 2005].

[14] The most active volcano in the Azerbaijan region is Lokbatan, which has erupted 22 times since 1810. The time between eruptions is erratic, ranging between two and 27 years. Similarly, another active volcano, Dashgil, has been active every 6 to 37 years in historic time [*Aliyev et al.*, 2002]. In recent years, quantitative records of mud volcano emissions have been cataloged [*Hovland et al.*, 1997; *Delisle et al.*, 2002; *Albarelo et al.*, 2003].

[15] For comparison, we have also compiled a sampling of other known mud volcano/earthquake pairs from locations around the world (Table 1). These include the 2004 Sumatra earthquake and Baratang island eruption (Geological Survey of India, 2005, available at <http://www.gsi.gov.in/mudvol.htm>), an eruption observed in Romania associated with the 1977 M 7.2 Vrancea earthquake [*Baciu and Etiope*, 2005], spectacular mud volcanism observed on the Makran

coast associated with a 1944 M 8.0 earthquake [*Delisle et al.*, 2002], and a series of eruptions at the mud volcano Niikappu in Japan that occurred after large (M 6.5–8.3) offshore earthquakes [*Chigira and Tanaka*, 1997; *Nakamukae et al.*, 2004]. For most of these events we have fairly reliable locations for both the earthquake and mud volcano, although for some pairs the exact earthquake/volcano distance is difficult to define due to the large size of the earthquake rupture zone. In these cases (M_w 7.5 and greater) our distance measurements represent the distance to the nearest edge of the rupture zone [*Byrne et al.*, 1992; *Yamanaka and Kikuchi*, 2003]. For the Makran earthquake/eruptions, although we have inferred from the reports that the eruptions were directly associated with the earthquake, precise data on the time delay between the earthquake and the eruption is lacking.

2.3. Catalog Completeness and Statistics

[16] The average number of eruptions per year (3.2) in the Azerbaijan catalog has remained fairly constant since 1950, which suggests no gross changes in detection level during that time (Figure 2). *Bagirov et al.* [1996a], who used a slightly different and earlier version of the catalog, conducted an analysis of the data which attempted to estimate the number of missing eruptions. It was assumed that very strong eruptions were not missed and that the ratio of very strong eruptions to total number of eruptions was constant. This resulted in an average of 3.5 “strong” eruptions per year in Azerbaijan and surrounding areas (up to the year 1995). Intensities were based on a cluster analysis of eruption parameters. Eruptions do not occur with equal frequency at all volcanoes, rather, roughly 70% of the eruptions occur at 30% of the volcanoes [*Bagirov et al.*, 1996a].

[17] For an alternate estimate of catalog completeness, we use the eruption time-of-occurrence information. We find 25 (out of 116) eruptions since 1965 have the time of eruption recorded. The number of recorded events (3) is much lower from 2300 LT to 0700 LT than in the remaining hours (22). If we assume that the time of eruption is uniformly distributed (this may not be true) and that the change in the reported number is due solely to missed eruptions at night, then this would suggest that the catalog contains about 75% of the total eruptions since 1965. This corresponds to an increased average rate of 4.2 eruptions per year. This is likely an overestimate, as some of the “missing” overnight eruptions would be quickly noticed due to fresh breccia flows and thus would be included in the catalog but without a precise time. We conclude that 4.2 eruptions per year is an upper bound on the average number of eruptions per year. Given the uncertainties, an average of 3.2 ± 1 eruptions per year seems reasonable. We do not make an attempt to distinguish between strong and weak eruptions and note that our average is less than the 3.5 average of *Bagirov et al.* [1996a] because our data set covers a smaller region. Assuming our estimates are correct, then the completeness of our catalog is between 37% and 71% for the entire 191-year time span (1810 to 2001).

[18] Before we make an estimate of the likelihood of same-day earthquakes and eruptions, we need to establish the temporal distribution of the eruptions. *Bagirov et al.* [1996a] assumed that the distribution of eruptions follows a

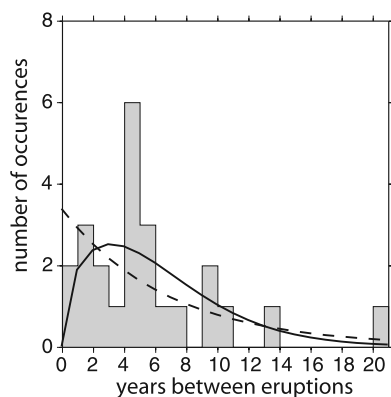


Figure 3. Histogram (gray) of repose times (bin size of 1 year) for eruptions recorded at the volcanoes Lokbatan, Keyreki, and Shikhzairli (combined). The dashed line shows the expected shape (exponential) if the eruption process was Poisson, and the solid line shows the expected shape if the eruption process was a nonhomogenous (Weibull) Poisson process. Although the data are sparse, the observed data appear to match a nonhomogenous process more closely than a homogenous process.

Poisson process, as is commonly assumed for magmatic eruptions and large earthquakes. Recognizing that our data is incompletely sampled, temporally aliased, and censored (in a statistical sense), our goal is to examine the distribution of eruptions using the most accurate subset of data (1960–2001).

[19] First, we note that the variance (6.9) of the number of eruptions since 1960 (thought to be the most accurate data) exceeds the mean (3.1) for that time period, which is not consistent with a Poisson process. We next examine the repose times between eruptions [Ho, 1996; Connor et al., 2003]. If we assume that the eruptions follow a Poisson process, then the repose times should be exponentially distributed with a peak value at 0. If the eruption process possesses an expected failure time, then the distribution of repose times will not be exponential but will possess a peak (such as a Weibull distribution) [Kalbfleisch and Prentice, 1980]. Figure 3 shows a histogram of repose times since 1960 for the three volcanoes. In general, the shorter repose times occur more frequently, as expected for an exponential distribution, but a peak occurs at a repose time of 5 years, which implies a tendency toward a nonhomogenous Poisson process, such as Weibull or log-logistic rather than a pure homogenous Poisson process. A Weibull plot shows a reasonably linear fit with a B value of 1.48 (maximum likelihood fit with a 95% confidence interval from 0.98 to 1.97). However, as a Poisson distribution ($B = 1$) falls within the 95% confidence bounds of the B value, we cannot reject the hypothesis that the eruptions follow a homogenous Poisson process. Given the sparseness of the data, we are hesitant to conduct more extensive analyses. We conclude that a Poisson distribution is a reasonable first-order approximation of the existing eruption catalog, but that a nonhomogenous distribution is capable of fitting the available data better. From a physical viewpoint, a nonhomogenous Poisson distribution would imply that the volcanoes require some time after eruption to recharge as

opposed to a Poisson process, which indicates that any given volcano can erupt at any time.

2.4. Assessing the Correlation Between Earthquakes and Mud Volcano Eruptions

[20] As a first test, we note that most reports of immediate (same-day) mud volcano activation seem to include earthquakes that produce fairly violent shaking at the triggered volcano location such as on Baratang Island following the 2004 great Sumatra earthquake. We do not have independent estimates of intensities at the Baratang mud volcano caused by the 2004 earthquake, but based on damage reports from nearby areas and the proximity to the M 9.0 earthquake rupture zone, it is clear that the intensity of shaking was significant and likely at least 6. We examine the relationship between the distances between earthquake/volcano pairs as a function of earthquake magnitude (>5.0) and highlight known triggering pairs such as the 2004 M 9 Andaman/Sumatra earthquake and mud volcano eruption in Romania (Figure 4). From these observations it appears that only the nearby (<100 km) large earthquakes seem capable of provoking eruptions.

[21] To estimate the approximate intensity of shaking of the earthquake at the locations of the mud volcanoes, we first compile a list of major earthquakes in the Azerbaijan region (Table 2) between 35° and 45° N latitude and 45° and 55° E longitude. We use the regional catalog of Kondorskaya and Shebalin [1982] (hereinafter referred to as KS) and the global catalog of the International Seismological Centre (ISC) (on-line bulletin, rectangular selection, 2004, <http://www.isc.ac.uk/Bull>) as primary sources. The KS catalog is a compendium of events in the former USSR and includes historical as well as instrumentally recorded events. We note that the locations of preinstrumental events are based on reports of shaking and therefore the epicentral locations may be in error by tens of kilometers. We have also consulted other global catalogs (National Earthquake Information Center (NEIC) and Harvard centroid moment tensor) to ensure we obtain a comprehensive list.

[22] To obtain consistency among earthquake intensity estimates, we use an intensity relationship based on magnitude, distance, and depth previously derived for Azerbaijan [Kondorskaya and Shebalin, 1982]. As the mud volcanoes are spatially clustered (see Figure 1), we calculate the expected intensity of shaking at the location of the mud volcano at the location of two representative volcanoes: Lokbatan (near Baku) that roughly represents the Baku region and Shikhzairli, which lies further west in the foothills of the Caucasus (Figure 1). We calculate intensities for all earthquakes greater than magnitude 5.5. To check our calculated intensity estimates, we compare our values with observed intensities reported in Baku during the November 2000 earthquakes. We estimate intensities of Mercalli 6 and 7 for the two closely spaced shocks, which is a close match to the observed intensity of 6 in Baku (ISC, 2004). Confirming these estimates, reports of structural damage in Baku indicate that the shaking was definitely in the 6–7 intensity range. Intensities derived from different mathematical relationships can change the absolute values of the estimates, but these differences have little effect on the relative intensity between events.

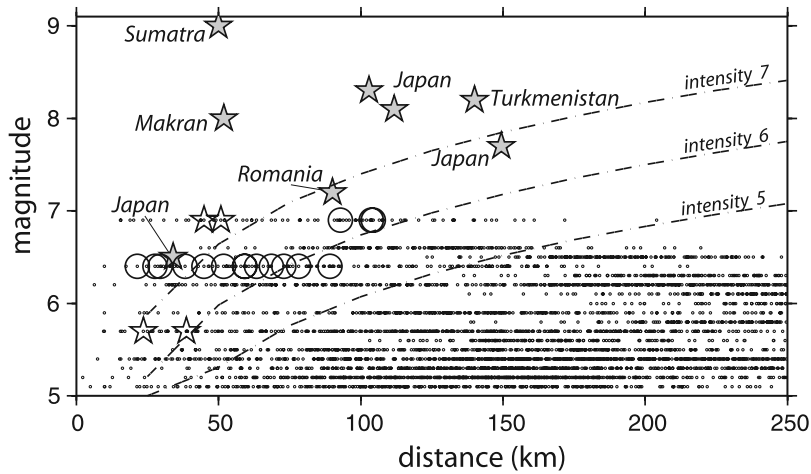


Figure 4. Plot of distance versus magnitude for earthquakes and mud volcanoes. The small dots show nontriggering distance/magnitude pairs in our catalog (from each earthquake epicenter to a known mud volcano location that did not erupt). Open stars show Azerbaijan mud volcano locations that were reported to have eruptions on the same day as a large earthquake. Open circles were reported to show increased activity after the earthquakes in November/December 2000. Gray stars show magnitude/distance for other reported earthquake/eruption triggering pairs listed in Table 1. Approximate Mercalli earthquake intensity bounds (dashed lines) are also shown. Note that seismic shaking of approximately Mercalli intensity ~ 6 represents an approximate lower limit for triggering and that open stars juxtapose with small dots indicating that the assumed distance/magnitude triggering thresholds are sufficient but not always imperative, suggesting mud volcanos require a recharging time to reaccumulate pressure.

[23] We next compare a list of earthquakes and estimated seismic intensities with the dates of Azerbaijan mud volcano eruptions (Table 2). For volcanoes within 100 km of the earthquake, we find that almost all large earthquakes with intensity values that exceed a mean value (between the two mud volcano locations) of Mercalli 5.5 were associated with reports of anomalous mud volcano activity in the Azerbaijan catalog. Significantly, two of the top five earthquakes in

terms of intensity (the M 5.7 1872 and M 6.9 1902 earthquakes) coincided with same-day mud volcano eruptions. The 1895 magnitude 8.2 earthquake is not reported to have caused an eruption in Azerbaijan although it apparently did likely trigger an eruption at the offshore mud volcano Livanova Bank across the Caspian Sea in Turkmenistan [Guliyev and Feizullayev 1995; Bagirov et al., 1996b]. This eruption is not in the catalog of Aliyev et al. [2002], and

Table 2. Intensity of Shaking and Distance at Two Selected Mud Volcanoes for the Strongest Recorded Earthquakes Since 1810 Ranked in Order of Intensity^a

Date	Longitude	Latitude	M	Lokbatan		Shikhzairli		Mean	
				Intensity	Distance, km	Intensity	Distance, km	Intensity	Distance, km
11/19/1981	49.0	40.5	5.0	3.8	77	4.7	45	4.3	61
12/06/2000	54.8	39.5	7.4	4.6	435	4.4	493	4.5	464
03/22/1879	47.6	39.2	6.5	4.4	214	4.6	187	4.5	200
09/16/1989	51.6	40.4	6.5	4.9	161	4.4	215	4.6	188
11/04/1946	54.5	39.8	7.5	4.8	405	4.6	462	4.7	433
08/03/1832	48.6	40.6	5.4	4.0	99	5.3	44	4.7	72
08/09/1828	48.4	40.7	5.7	4.2	117	5.3	59	4.7	88
06/20/1990	49.3	37.0	7.4	4.8	369	4.8	389	4.8	379
08/07/1875	48.7	40.7	5.4	4.1	95	5.6	38	4.8	66
01/27/1963	49.8	41.1	6.2	5.2	102	5.1	108	5.1	105
02/19/1924	48.6	39.4	6.6	5.1	155	5.2	146	5.1	151
06/07/1911	50.5	41.0	6.4	5.3	111	4.9	141	5.1	126
06/11/1859	48.5	40.7	5.9	4.6	110	5.8	52	5.2	81
01/28/1872 ^b	48.7	40.6	5.7	4.6	90	6.3	32	5.5	61
09/18/1961	50.2	41.1	6.6	5.6	114	5.3	133	5.5	123
07/08/1895	53.7	39.5	8.2	6.1	349	5.9	406	6.0	378
11/25/2000	50.0	40.2	6.2	7.0	32	5.5	85	6.3	59
	49.9	40.2	6.4	6.5	55	5.6	94	6.0	74
02/13/1902 ^b	48.6	40.7	6.9	6.2	103	7.5	46	6.9	75

^aThese two volcanoes represent the two major mud volcano districts (Lokbatan in the Baku/Absheron area and Shikhzairli in Shemakli, see Figure 1). The 1895 event, although it did not appear to trigger any eruptions in Azerbaijan was reported to have triggered a mud volcano eruption in Turkmenistan.
^bSame-day earthquake/eruption pairs.

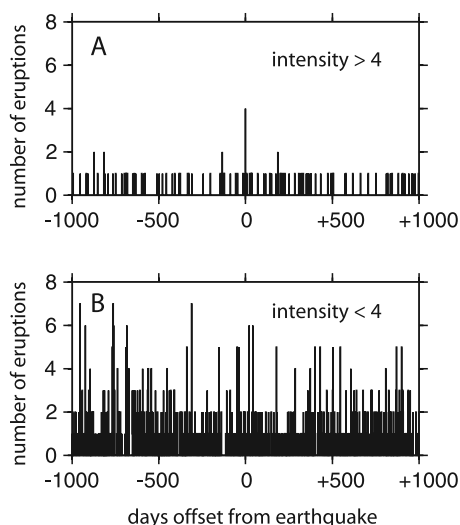


Figure 5. Histogram of the number of mud volcano eruptions with respect to the day of a large earthquake for all earthquakes in our catalog. Only eruptions with known dates are included (49% of the data). (a) Eruptions with respect to earthquakes that generated intensities of 4 and greater at the location of the volcano. (b) As in Figure 5a but for intensity below 4. Unlike the lower intensities (<4), the number of eruptions on the day of the earthquake is substantially greater than average for intensities above 4.

consequently, we do not include it in Table 2. Strong shaking was also reported in 2000 from a pair of earthquakes (M 6.5 and M 6.4) offshore Azerbaijan and an M 7 in Turkmenistan. Although we know of no eruptions on the same day as the earthquakes in 2000, 14 eruptions were reported in the following year (more than 3 standard deviations above average).

[24] The eruption of Kalamaddyn in January 1872 is listed on page 35 in the mud volcano catalog as occurring on 26 January 1872, but it is also listed again, on pages 68 and 69 of that same catalog, as occurring on 28 January 1872, simultaneous with a large earthquake (together with the eruption of the volcano Shikhzairli). In the *Kondorskaya and Shebalin* [1982] earthquake catalog this 1872 earthquake is listed as occurring on 28 January. The 26 January date in the catalog is a typographical error, and 28 January is the correct date for the eruptions.

[25] We next address what the probability is that earthquake/eruption pairs occur on the same day. Conservatively assuming a mean of four mud volcano eruptions per year, the probability of two eruptions occurring independently on the same day is less than 2% (1.64%) and expected on average only about 3 times over 190 years if the observations are complete. In the current incomplete catalog (172 eruptions with dates, out of a theoretical total of 611 events assuming 3.2 events per year for 191 years), four observations of same-day eruptions are cited (26 January 1872, 13 February 1902, 27 July 1915, and 25 November 1948). More strikingly, two of these dates (in 1872 and 1902) also coincide with some of the highest seismic intensities recorded in Azerbaijan. If we assume strong earthquakes also occur randomly at a rate of 1 per year (greater than

observed), we would expect multiple mud volcano eruptions on the same day as a strong earthquake (intensity >5) to occur by chance over 191 years at less than 1% (25 times in 10,000 simulations). Even if the 1872 eruptions are omitted, this still strongly suggests a causative link between the seismic shaking and eruptions, as has been reported previously.

[26] As a secondary test, we apply the procedure similar to that used by *Linde and Sacks* [1998], who evaluated the likelihood that large earthquakes trigger magmatic volcanoes. Using the 158 eruptions with known dates, we calculate the number of mud volcano eruptions as a function of days offset from the date of large ($M > 5$) earthquakes in our catalog (Figure 5). We test two subsets of the earthquake list: earthquakes with mean intensities at the mud volcanoes greater than four and those with intensities less than four. We find a clear peak associated with the large earthquakes at a zero offset (i.e., same day) but do not see any strong correlation for earthquakes that generate intensities less than four at the mud volcano sites. To assess the validity of these results, we fix the locations and dates of the mud volcano eruptions and then randomize the day of the earthquakes (keeping the locations fixed) within a 2000-day window centered on the actual date of the earthquake. We repeat this 10,000 times. On the basis of these randomized catalogs we find that multiple eruptions on the same day as an strong earthquake happens in less than 1% of the simulated 191-year catalogs. We conclude that the recorded observations of same-day earthquake and eruption pairs are highly suggestive of a seismic influence on mud volcanic eruptions.

[27] It is clear that triggering of mud volcanoes by earthquakes, although present, is still not consistently observed for all earthquake/volcano pairs. Even when the earthquake generates intensities greater than Mercalli 6 at the location of a mud volcano only a small fraction of the known volcanoes are triggered. For the M 5.7 1872 and M 6.9 1902 earthquakes there are approximately 30 known volcanoes at distances where we expected triggering, yet for these earthquakes only two volcanoes have documented same-day eruptions. Lack of detection cannot explain this lack of apparent triggering. The November 2000 earthquakes, although generating considerable intensities (>5) at nearby volcanoes did not, as far as we know, trigger any same-day eruptions. There is only one documented report of eruptions triggered by the 1977 Romania M 7.2 earthquake even though numerous mud volcanoes exist in the region.

2.5. Delayed Activity

[28] The next question we address is whether mud volcano triggering is enhanced within weeks to a year after a large earthquake. Delayed triggering (days to weeks) of other phenomena by earthquakes has been observed previously in other regions [e.g., *Pankow et al.*, 2004; *Prejean et al.*, 2004], and we therefore expect it might exist in Azerbaijan as well. In particular, the large number (14) of reported eruptions in the year 2001, which is more than 3 times the standard deviation from the mean, occurred within a year of some of the largest earthquakes in this region.

[29] Using the same data as before, we attempt to quantify how often “heightened mud volcano activity” occurs after an earthquake. We measure an increase in

activity by counting the number of eruptions in the calendar year following an earthquake as compared with the number of eruptions in the calendar year before the earthquake. For example, to assess the effect of the earthquakes in year 2000, we count the number of eruptions in 2001 and subtract the number of eruptions in 1999. A calendar year is used because many of the events in the mud volcano catalog are not precisely dated and eruptions in the same year as the earthquake are omitted to avoid simultaneous “same-day” events. The use of a difference reduces the bias due to time-variable catalog thresholds.

[30] We calculate the difference in number of eruptions in both the entire Azerbaijan mud volcano and earthquake data set and a subset from 1960 to 2001. This subset is believed to contain the most complete record of both eruptions and earthquakes. If no triggering occurs, the expected average difference is zero. Our results show an average of 0.07 with a standard deviation of 2.55 for the entire catalog. However, for years containing an earthquake with intensity greater than 4 the average difference is 1.23 with a standard error of 0.31. These results are strongly affected by the large number of eruptions in the year 2000. Subsets of the catalog that do not include the year 2000 show no significant change in eruption frequency with respect to large earthquakes.

[31] Given the hazards inherent in statistics of small samples, we also assess the expected range of the mean using simulations. We allow the year of the large earthquakes to vary randomly within the entire time window from 1810 to 2000, but keep the mud volcano catalog unchanged. We compute 10,000 random simulations to help test how often theoretically predicted heightened volcanic activity occurs after large earthquakes in comparison with the correlation for the observed data catalog. We find that the mean average difference in eruptions before and after a large earthquake in the simulations exceeded the value in the observed data only 3% of the time. While these results are not conclusive, they suggest a weak correlation between large earthquakes and mud volcano eruptions in the months to years after an earthquake.

3. Discussion

[32] In this study we have shown quantitatively that nearby earthquakes can trigger mud volcano eruptions. Earthquakes produce both static and dynamic stress changes and both have been cited as causes for aftershocks and volcanic triggering following large earthquakes [Harris, 1998; Steacy *et al.*, 2005]. Static stress changes, which refer to permanent changes in the absolute stress level of the crust after an earthquake, are strongest near the earthquake and decrease rapidly with distance. Earthquake-induced long-term stress changes may also be caused by viscoelastic or pore pressure effects [Freed, 2005]. Dynamic stress changes tend to be larger in amplitude but transitory as they occur during passage of seismic waves. Dynamic stress changes also decrease more slowly with distance making them a more effective triggering agent at long distances. Earthquake rupture directivity can cause an asymmetric pattern in dynamic stress changes, whereas the static stress change patterns are unchanged by directivity effects [Kilb *et al.*, 2000; Gomberg *et al.*, 2001; Kilb, 2003].

[33] A basic rule-of-thumb is that near-field triggering is defined to be primarily regions within ~ 1 main shock fault length of the earthquake rupture zone, whereas far-field triggering extends much farther, in some observed cases more than ~ 5 – 10 fault lengths away [i.e., Hill *et al.*, 1993; Prejean *et al.*, 2004]. It has been suggested that near-field triggering results primarily from a combination of static and dynamic stress/strain changes, which at close distances are difficult to definitively separate, and that far-field triggering results from dynamic stress/strain changes [Steacy *et al.*, 2005]. However, this idea is not fully adopted in the community [Ziv and Rubin, 2000].

[34] If we assume magnitude ~ 6 earthquakes have rupture lengths of ~ 20 km, then the observed triggering distances of ~ 25 – 40 km (see Figure 4) are approximately 1–2 fault lengths away. If we assume the magnitude ~ 7 earthquakes have rupture lengths of ~ 70 km, then the observed triggering distances of ~ 50 km are less than a fault length away. Yet, for the Romania earthquake ($M \sim 7$, which likely has a rupture length of ~ 70 km), the observed triggering distance of ~ 90 km is slightly more than a fault length away. For the larger events, ($M > 7$, rupture lengths of ~ 100 km) in Japan and Makran the triggered volcanoes are ~ 150 – 200 km away, which again falls in the category of ~ 1 – 2 fault lengths away. Although none of these earthquake/volcano triggering pairs are separated by distances that can be definitively labeled as the “far field,” we suggest that dynamic stress changes induced by the passage of the seismic waves might play a role in these triggering processes, because at these distances static stress changes are likely an order of magnitude smaller than the dynamic changes.

[35] Exactly how seismic waves from large earthquakes provoke volcanic eruptions is not clear, although a plethora of mechanisms have been suggested to explain the possible links between earthquakes and activation of magmatic volcanoes or geothermal systems [e.g., Hill *et al.*, 1993, 2002; Gomberg and Davis, 1996; Linde and Sacks, 1998; Roeloffs *et al.*, 2003; Power *et al.*, 2001; Feuillet *et al.*, 2004; Moran *et al.*, 2004; Prejean *et al.*, 2004]. These theories include large-scale seismic liquefaction, excitation of bubbles and resulting fluid overpressure, hydraulic surge, changes in groundwater levels, rupturing blockages in confined aquifers, a sinking crystal plume, dike openings and a relaxing magma body [Cayol *et al.*, 2000; Brodsky, 2003; Manga and Brodsky, 2005]. It is not clear how well these simple to complex mechanisms might apply to the mud/water/methane system of a mud volcano although groundwater related mechanisms seem more likely. Aliyev *et al.* [2001] suggested that triggering is enhanced when the mud volcanoes and earthquakes lie along the same fault structure. The intensities and distances required to trigger eruptions resemble empirical relations developed for liquefaction [e.g., Ambraseys, 1988; Manga and Brodsky, 2005]. An implication of liquefaction is that the triggering effect might be enhanced not only by the amplitude of shaking but also by the duration of shaking. This hypothesis is consistent with the eruption on Baratang Island, as the duration of shaking experienced at this location was likely greater than any of the other mud volcano locations in this study due to the large size of the 2004 Sumatra earthquake (Table 1). However, as mud volcanoes commonly erupt without the

aid of earthquake-induced liquefaction, liquefaction cannot be the sole driving force behind all eruptions.

[36] More speculative causes of triggering might be related to sonic effects on hydrocarbon systems, as documented by *Beresnev and Johnson* [1994]. Pronounced increases in oil production were observed in 1971 after an M 6.5 earthquake and aftershocks in Dagestan, just north of Azerbaijan, where ~ 50 km from the earthquake oil production increased an order of magnitude after the main shock. Similar effects were found in a study by *Steinbrugge and Moran* [1954] after the Kern County earthquake in California. In general, the duration of these triggering effects are on the order of months to a few years and typically the observed changes occur at ranges less than 100 km. Sonic stimulation of hydrocarbon systems has been tested in the laboratory [*Beresnev and Johnson*, 1994] and it appears that both pore pressure and the effect of multiple fluid phases may be important. High-frequency simulations appear to be the most effective at increasing productivity. This is counter to some studies of groundwater changes following remote large earthquakes that suggest low-frequency oscillations are more apt to promote triggering [*Brodsky*, 2003]. Theoretical and laboratory tests have also been used to provide insight into how large earthquakes trigger subsequent aftershocks and volcanic eruptions [e.g., *Beeler et al.*, 2000; *Boettcher and Marone*, 2004]. On the basis of these tests, there is currently no clear consensus in terms of the importance of amplitude and/or frequency required for triggering. However, one recent observational study indicates that large amplitude deformations might be a necessary, but not sufficient, condition for triggering, which suggests that triggering is not strongly frequency dependant [*Gomberg and Johnson*, 2005].

[37] Alternately, the cause of the heightened mud volcano activity may be linked to changes and variations in groundwater. Groundwater levels in wells near the M_L 7.3 1999 Chi-Chi earthquake rupture showed dramatic changes, both positive and negative, and showed a slow (weeks to months) return to preseismic groundwater levels [*Chia et al.*, 2001]. There are also observations that well water levels can be changed by large earthquakes thousands of kilometers away [e.g., *Roeloffs et al.*, 2003]. Such changes might potentially disturb the sensitive system of a mud volcano.

[38] Another approach in constraining the triggering process is by analysis of the statistical distribution of eruptions. We explore two end-member triggering processes: a homogenous Poisson process that implies that the mud volcano system is ready to fail at any time, and a non-homogenous process with a variable (presumed increasing) chance of failure over time. In a nonhomogenous process the further the volcanic system is from failure the larger the stress/strain fluctuation needed to cause an eruption. A homogenous process is consistent with theories that assume triggered volcanoes are almost always on the edge of eruption and small stress/strain perturbations are ultimately all that is needed to promote triggering [*Ziv and Rubin*, 2000; *Ogata*, 2005]. If all mud volcanoes were on the edge of eruption then we would expect a large number of them to erupt when sufficient seismic shaking occurs. This is not observed in Azerbaijan, at least not at the recorded intensities. Our work shows that the distribution of repose times

for most mud volcanoes in Azerbaijan require at least one or two years to recharge to a level that allows eruption. These observations are most consistent with a process in which the system needs to gradually recharge over time and at any given time, only a few volcanoes are susceptible to triggering.

[39] In a more complex scenario, some locations might be more susceptible to triggering than other regions [e.g., *Gomberg et al.*, 2001; *Moran et al.*, 2004; *Brodsky and Prejean*, 2005]. This type of complexity is supported by the observations that, for example, water well levels from closely located wells can have drastically different behaviors. This suggests there is a site-specific dependence to the triggering threshold, which might explain the apparent susceptibility of certain volcanoes to erupt and others to remain dormant following large shaking from earthquakes. It may also be that some volcanoes (such as Shikhzairli in Azerbaijan and Niikappu in Japan) are particularly susceptible to triggering. Further study of these volcanoes may be productive in helping to pinpoint specific triggering mechanisms.

[40] It is likely, as many studies suggest, that remote triggering results from a combination of multiple processes [e.g., *Prejean et al.*, 2004]. For example, the far-field large amplitude oscillatory dynamic stress changes might evoke processes that start to initiate a volcanic eruption, but after this process is in play it is localized processes that brings the rupture to fruition. For example, strain changes from a remote earthquake can cause changes in pore pressure, but it is the localized reequilibration of fluids within the system that ultimately are responsible for breaking the mud seal at the top of the conduit. So, although the triggering is initiated by dynamic strains from the remote earthquake, eruption of the system also requires specific localized conditions and effects. This domino effect of both remote and localized processes constitutes the finally triggering scenario. If this is the case, it is possible that remotely triggered mud volcano eruptions might have a signature that differs from a “normal” eruption.

[41] Future tests that better constrain the mud volcanoes structure and composition will hopefully narrow the prominent triggering processes. For example, it would be helpful, and relatively straightforward, to conduct liquefaction tests on samples of mud volcano breccia or to carefully monitor the daily emission of mud volcanoes for changes related to well-constrained nearby seismicity. These results could help pinpoint the importance of liquefaction in the triggering process and reduce the uncertainties in current studies where the catalog completeness is an issue.

4. Conclusions

[42] On the basis of observations of eruptions following large earthquakes, our results show that large earthquakes can trigger large mud volcano eruptions at a statistically significant confidence level, at a rate greater than that expected for independent Poisson processes. The effect appears to be strongest in areas where the triggering main shock produces shaking of roughly intensity 6 at the mud volcanoes, and may be more pronounced at distances less than 100 km. We suspect that the triggering is related to the passage of seismic waves that generate intensities of ap-

proximately Mercalli 6 and above. The effective distance/magnitude triggering range resembles the threshold for seismic liquefaction [e.g., *Ambraseys*, 1988; *Manga and Brodsky*, 2005], suggesting that the triggering may be a related phenomena.

[43] Even when intensities exceed the apparent threshold, only a fraction of active volcanoes erupt. This indicates that other factors also play an important role in the triggering process. Examination of repose times suggest that mud volcanism can be reasonably approximated by a Poisson process at the 95% level. The fit between observed repose times and assumed distribution could be further improved by assuming a nonhomogenous Poisson process that includes a time to failure term. This type of model, in which the mud volcanoes require a minimum time between eruptions to reaccumulate pressure, is consistent with the observations that only a fraction of the volcanoes are sufficiently near to eruption to be triggered by the seismic waves.

[44] We also find a weak correlation between large earthquakes and a delayed onset (up to a year) of mud volcano activity, especially for the November 2000 Baku earthquakes and 2001 mud volcano activity. If true, the underlying mechanism is not clear but might be related to changes resulting from near-field stress changes such as groundwater equilibration.

[45] Our results immediately provide ideas for future studies. It would be useful to conduct tests of mud volcano breccia for susceptibility to liquefaction and to compare with other intensity measures (especially intensity measures which include a duration component such as Arias intensity) commonly used to estimate liquefaction potential. Continuous monitoring of minor eruptions and seeps might provide better constraints on repose periods and other statistics, which in turn will hopefully help us understand more about how mud volcanoes might be triggered by earthquakes.

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