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Volcano-tectonic earthquakes: A new tool for estimating intrusive volumes and forecasting eruptions

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ABSTRACT

We present data on 136 high-frequency earthquakes and swarms, termed volcano-tectonic (VT) seismicity, which preceded 111 eruptions at 83 volcanoes, plus data on VT swarms that preceded intrusions at 21 other volcanoes. We find that VT seismicity is usually the earliest reported seismic precursor for eruptions at volcanoes that have been dormant for decades or more, and precedes eruptions of all magma types from basaltic to rhyolitic and all explosivities from VEI 0 to ultraplinian VEI 6 at such previously long-dormant volcanoes. Because large eruptions occur most commonly during resumption of activity at long-dormant volcanoes, VT seismicity is an important precursor for the Earth's most dangerous eruptions. VT seismicity precedes all explosive eruptions of VEI ≥5 and most if not all VEI 4 eruptions in our data set. Surprisingly we find that the VT seismicity originates at distal locations on tectonic fault structures at distances of one or two to tens of kilometers laterally from the site of the eventual eruption, and rarely if ever starts beneath the eruption site itself. The distal VT swarms generally occur at depths almost equal to the horizontal distance of the swarm from the summit out to about 15 km distance, beyond which hypocenter depths level out. We summarize several important characteristics of this distal VT seismicity including: swarm-like nature, onset days to years prior to the beginning of magmatic eruptions, peaking of activity at the time of the initial eruption whether phreatic or magmatic, and large non-double couple component to focal mechanisms. Most importantly we show that the intruded magma volume can be simply estimated from the cumulative seismic moment of the VT seismicity from:
$\mathrm{Log10}\ V = 0.77\ \mathrm{Log}\ \Sigma\mathrm{Moment} - 5.32$, with volume, V, in cubic meters and seismic moment in Newton meters. Because the cumulative seismic moment can be approximated from the size of just the few largest events, and is quite insensitive to precise locations, the intruded magma volume can be quickly and easily estimated with few short-period seismic stations.
Notable cases in which distal VT events preceded eruptions at long-dormant volcanoes include: Nevado del Ruiz (1984–1985), Pinatubo (1991), Unzen (1989–1995), Soufriere Hills (1995), Shishaldin (1989–1999), Tacana' (1985–1986), Pacaya (1980–1984), Rabaul (1994), and Cotopaxi (2001). Additional cases are recognized at frequently active volcanoes including Popocateptl (2001–2003) and Mauna Loa (1984). We present four case studies (Pinatubo, Soufriere Hills, Unzen, and Tacana') in which we demonstrate the above mentioned VT characteristics prior to eruptions. Using regional data recorded by NEIC, we recognized in near-real time that a huge distal VT swarm was occurring, deduced that a proportionately huge magmatic intrusion was taking place beneath the long dormant Sulu Range, New Britain Island, Papua New Guinea, that it was likely to lead to eruptive activity, and warned Rabaul Volcano Observatory days before a phreatic eruption occurred. This confirms the value of this technique for eruption forecasting. We also present a counter-example where we deduced that a VT swarm at Volcan Cosiguina, Nicaragua, indicated a small intrusion, insufficient to reach the surface and erupt. Finally, we discuss limitations of the method and propose a mechanism by which this distal VT seismicity is triggered by magmatic intrusion.

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1. Introduction

The Volcano Disaster Assistance Program (VDAP) was formed by the US Geological Survey and the Office of Foreign Disaster Assistance following the disastrous eruption of Nevado del Ruiz, Colombia, in 1985. Since its inception, the VDAP team has helped build monitoring infrastructure in fourteen countries, responded to more than 25 volcanic crises worldwide, and had the opportunity to review tens of thousands of seismic records from those plus scores of additional eruptions and volcanic crises. One of the first phenomena the VDAP team noticed was that explosive eruptions are preceded by high-frequency volcano

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Table 1
Eruptions with known precursory distal volcano-tectonic (VT) earthquake swarms.

Volcano name	Date of 1st known dVT events	Date of 1st Phreatic (P) or Phreato-magmatic (PM) activity	Date of magmatic eruption onset	VEI	Years since prior eruption	Maximum VT magnitude	Log10 cumulative Moment nm	Depth km	Dist. km	Azimuth	References
Anatahan	≤20030506	20030510 PM	20030510	3	>400	M4.1	15.4	3	2.5	N	This study, Pozgay et al. (2005)
								3	3	SW	
Augustine	200504	20051220 P	20060111	3	20	M3.7	15.0	14	25	E	AVO Fisher et al. (2010);
								1	1	E	Power (1988)
Augustine	19850705	19860111 P	19860228	4?	10	M4.3	15.7	2	1	E?	AVO Power and Lalla (2010)
Augustine	19750502	19760122 P	19760123	4	5	M3.5	??	2	1	SE?	AVO Power and Lalla (2010)
Cerro Hudson	20111025	20111026 P	20111027	3	20	M5.0	16.6	9	9	W	Hermosilla Pineda (2012) SERNAGEOMIN
Cerro Negro	19950524	19950529 P	19951119	2	4	M3.4	15.0	Z?	8	E	This study, INETER
(Nicaragua)								Z?	5–10	W	
Cerro Negro	19990223	19990508 P	19990805	2	4	M5.0	17.2	10	12	E	This study, INETER La Femina et al. (2004)
(Nicaragua)								8	8	W	
Chaiten	≤20080501	20080502 PM	20080506	5	~400	M5.3	17.2	6	5	NE	This study, Basualto et al. (2008); Wicks et al. (2011) SERNAGEOMIN
								6	5	NW	
Chokai	197312	19740301 P	None	1	140	M3.0?		Z?	0–10	W	Nakamura and Ui (1975), Ui et al. (1977)
Colima	19910214	10010216 P	19910301	1	3	M3.5	14.5	2	6	NNW	This study, UCO Nunez Cornu et al. (1994),
Colima	19940704	19940721 P	19940721	1	2	M3.4	14.5	15	10–15	W?	This study, UCO Jimenez et al. (1995); Zamora-Camacho et al. (2007)
Colima	19970620	19980706 P	19981120	3	4	M4.0	15.1	3	2	W	This study., UCO Zamora-Camacho et al. (2007)
Cotopaxi	20010601	20020122 P	None	1	60	M3.9	15.9	7	10	N	This study, IGEP
								15	30	W	
El Chichon	198003	19820329 PM	19820403	5	132	M4.2	15.7	5	8	SE	This study, Espindola et al. (2006); Jiménez et al. (1999); Havskov et al. (1983)
Fuego, Guate.	19820217	19820223 P	None	1	1	M3.6	M3.7	7–10	8	S	This study, INSIVUMEH
Galeras	19930401	19930404 P	19930607	2	0.5	M4.5	16.4?	6	3	N	This study, INGEOMINAS Gomez M. et al. (1997); Jimenez et al., 2009
Galeras	20051020	None?	20060113	2	1	M4.7	16.5	6	4	NW	This study, INGEOMINAS
											Jimenez et al. (2009)
Galeras	20090509	20090509 P	20090607	2	0.1	M4.0	15.1	10	6	NE	This study, INGEOMINAS
								3	6	SSE	
								4	5	SW	
G. Pichincha	19810812	~19810820 P	None	1	100	M<4	<15.1	4–5	5–7	SE	This study, IGEP
G. Pichincha	198806	~19881007 P	None	1	5	M3.5	14.7	5	5–7	SE	This study, IGEP
G. Pichincha	~19980701	19980807 P	19990728	3	5	M4.0	16	14	15	NE	This study, IGEP Villagomez et al. (2003)
Irazu	199410	19941208 P	None	2	17	M3.4	14.2	4	3	NNW	This study, OVSICORI
Izu-Tobu	19890630	19890711? P	19890713	1	Infinite	M5.5	17.5	Z?	<40	ESE	Kasahara et al. (1991); Okada and Yamamoto (1991); Murase et al. (2010)
								4	3	N	
Kanlaon	20020205	20021128 P	None	1	6	M<4?				N	This study, PHIVOLCS
Karymsky	199505	????	19960102	3	26	M6.6	19.0	10?	5	S?	Pavlov et al. (2003)
Kasatochi	<20080720	2008080714 P	2008080720	4	109+	M5.8	18.0	10	10	W	AVO Ruppert et al. (2011)
Kick'em Jenny	200110	???	20011204	1?	10?	M3	13.6	Z?	3–5	NW	Lindsay et al. (2005)
Kizimen	200904	20101016 P	20101213	3	82	M5.2	17.0	5	5	E	Ji et al. (2013)
Krafla	19770120	???	19770427	1	1	M4.5		Z?	10–40	N	Brandsdottir and Einarsson (1979) GVP
Kuju	??	19951011 P	None	1	257	M3.0		0–6	5	NW	Sudo et al. (1998)
Loihi	19960716	???	19960522	1?	???	M5.1	17.5	Z?	4.5	SW	Caplan-Auerbach and Duennebier (2001) HVO
Mauna Loa	18680321	???	18680327	2	2	M7.75	~20.8	"Deep"	20	S	Wood (1914) HVO
Mauna Loa	197401	None	19750705	1	25	M5.5	17.5	6	6	WNW	Lockwood et al. (1987) HVO
								6	6	NNW	
								4	4	SW	
Mauna Loa	198104	19840318 P	19840325	1	9	M6.5v	19.1	6	6	WNW	Koyanagi (1987), Lockwood et al. (1987, 1987), Baher et al. (2003) HVO
								6	6	NNW	