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Years to weeks of seismic unrest and magmatic intrusions precede monogenetic eruptions

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DETAILS OF THE SEISMICITY AND BRIEF PETROLOGICAL REVIEW

Canary Islands (Spain)

Mafic monogenetic volcanoes are common in the Canary Islands and the volcanic historical activity consists of mafic and monogenetic eruptions. In 1492, during his first trip to America, Christopher Columbus described the eruption of Boca Cangrejo in Tenerife which is considered the first historical eruption in the archipelago (Carracedo et al, 2007). We have considered here for comparison seven representative monogenetic eruptions occurred after the Boca Cangrejo eruption in the islands of Tenerife (Siete Fuentes, Fasnia and Arafo in 1704-05 and Chinyero in 1909), La Palma (San Juan in 1949 and Teneguía in 1971), and El Hierro (the 2011 submarine eruption) (Fig. 1a). Only the 2011 submarine eruption on El Hierro has been monitored.

According to the information recorded in historical documents about the unrest of the eruptions of Siete Fuentes, Fasnia and Arafo (1704-05) (Sánchez, 2014), the seismic activity started one week before the first eruption (Supplementary Table DR1). We can't establish the beginning of the unrest for the second and the third eruption separately. Then, we have considered in Fig. 1a the beginning of the Arafo eruption as time = 0. We have recently performed diffusion modelling in olivine crystals (Albert et al., 2015) that reveals the occurrence of three magma mixing processes around one year, two months and two weeks prior to the eruptions (Fig. 1b).

The San Juan eruption occurred in 1949 in La Palma involved three eruptive centres: Llano del Banco, Duraznero and Hoyo Negro (Bonelli Rubio, 1950; Klügel et al., 2000; Romero-Ortiz, 1951). Around two years before the eruption two earthquakes were felt by the population and during the three months prior to the eruption earthquakes became more frequent and stronger (Fig. 1a and Supplementary Table DR2). A previous mixing time scales study (Klügel et al., 2000) reveals the occurrence of three magma mixing events some years, few months and some days before the eruption (Fig. 1b). These data match with the factual accounts about the unrest activity (Fig. 1).

Weeks to months before the Teneguía eruption periodic earthquakes were felt by the population (Klügel et al., 1997), and from six days prior to the eruption earthquakes and their intensities were reported dayly (Sánchez, 2014) (Fig. 1a and Supplementary Table DR3). For Teneguía eruption petrological studies indicate the presence of rhyolitic and basaltic magmas that coexisting and thus indicate the presence of open system and subvolcanic reservoir (Araña and Ibarrola, 1973).

The eruption of Chinyero in 1909 was preceded by two years of seismic swarms (Sánchez, 2014) (Fig. 1a and Supplementary Table DR4). Our petrological study of this eruption reveals a virtually closed system origin for the magmas (equilibrium textures), but with some high Mg/Fe olivine xenocryst. Thus, this eruption also shows evidence of open system processes although are less well developed than in other eruptions from Tenerife.

The last monogenetic eruption in the Canaries occurred on October 10, 2011 in El Hierro Island. After a long period of quiescence in El Hierro the number of earthquakes started to increase in 2006. Nevertheless during the period 2006-2010 just one earthquake was recorded as felt by the population in 2007. A bigger increase of the seismic activity occurred during the previous three months before the eruption. During the previous month earthquakes were felt daily (Fig. 1a) (for a complete catalogue of the seismic activity see www.ign.es). Diffusion times calculated from olivine crystals reveal the existence of two mixing events before the eruption. There are data from two different studies. The first mixing event happened between 25 to 150 days (Longpré et al., 2014) or one month prior to the eruption (Martí et al., 2013), and the second event 2 to 90 days (Longpré et al., 2014) or three weeks (Martí et al., 2013) before the eruption (Fig. 1b).

Michoacan monogenetic volcanic field (Mexico)

During the previous two months before the eruption of the Paricutin (February 20, 1943) earthquakes with M≥3 were recorded by the Tacubaya seismic station (in Mexico City, 320 km away from Paricutin) (Yokoyama and De la Cruz-Reyna, 1990) (Fig. 1a). Traditionally this eruption was described as a classic example of fractional crystallization and crustal assimilation, and recent data have proved the existence of mixing processes between three compositionally distinct magmas at shallow depth (Rowe et al., 2011).

Information about Jorullo unrest previous to the September 29, 1759 eruption is vague. It seems that, from April some weak earthquakes were felt in the surrounding area and from the end of June every day were felt between 12 and 47 earthquakes (Yokoyama and De la Cruz-Reyna, 1990; Carreón, 2001; De la Cruz-Reyna and Yokoyama, 2011) (Fig. 1a). The presence of zoned olivine crystals have been related with the mixing between magmas previously stalled at different levels of the plumbing system (Johnson et al., 2008).

Higashi-Izu monogenetic volcanic field (Japan)

Based on previous works we can establish an unrest duration of two weeks with a change in the trend nine days before the eruption (Ukawa, 1993) for the Ito-oki submarine eruption (July 13, 1989). In the available dataset of the unrest at the Japan Meteorological Agency (JMA) the number of earthquakes is given in time intervals. Therefore, it is not possible for us to reconstruct a proper time series to compare the unrest data of this eruption before 13 days prior to the eruption in Fig. 1a. There are petrological studies that

also report the co-existence of mafic and silicic melts, but in this case the silicic melts were interpreted to be due to melting of shallow sediments (Yamamoto et al., 1991).

Goropu Mountains (Owen Stanley Range, Papua)

The eruption occurred in December 1943 in the Waiowa or Goropu area was preceded by two years of earthquakes, sometimes at the rate of two or three per day. Columns of steam and ash from other vents were observed since October (Baker, 1946). The information is too vague to be included in Fig. 1a. We did not find any petrological information.

Heimaey (Iceland)

In 1973, after two days of earthquakes (not felt by the population) and one day with shallower earthquakes (three felt by the population) a monogenetic volcano (Eldfell eruption) appeared in the island of Heimaey (Thorarinsson et al., 1973). Recent studies have shown evidences of mixing between magmas from the same source (Mattsson and Oskarsson, 2005; Higgins and Roberge, 2007).

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99 **SUPPLEMENTARY TABLES**

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Supplementary Table DR1. Factual accounts of the unrest activity preceding the eruptions of Siete Fuetnes (SF), Fasnia (F) and Arafo (A).

Chronological range		Days before and after the eruption			Event	Localities
		SF	F	A		
1704	December					
	24	-7	-12	-40	Low but continuous ground shaking. 29 earthquakes 3 h. Panic-stricken people. Houses shaken. The population leaves the houses.	LO, PC, LR
	25	-6	-11	-39	Increase of ground shaking. 23 earthquakes before the afternoon (some of them strong). Panic-stricken people. Houses shaken. The population leaves the houses.	G, C, A
	26	-5	-10	-38	Earthquakes every 2 or 3 h (some of them strong).	LO, PC, LR, G, C, A
	27	-4	-9	-37	Earthquakes every 2 or 3 h (some of them strong). Three in 1 h. Houses shaken, panic-stricken people. People realize that seismicity might be due to a volcano. Innumerable earthquakes during the night. The population sleeps outdoors.	LO, PC, LR, G, C, A
	28	-3	-8	-36	Some earthquakes, some of them strong. Some houses damaged. Panic-stricken people, especially in La Orotava.	LO, PC, LR
	29-30	-1	-6	-34	Some earthquakes, mainly small.	LO, PC, LR
	31	0	-5	-33	Some earthquakes. **SIETE FUENTES ERUPTION**.	LO, PC, LR
1705	January					
	2	2	-3	-31	Six strong earthquakes and some small ones.	LO, PC, LR
	3	3	-2	-30	Small earthquakes. Also the volcanic activity reduces.	LO, PC, LR
	4	4	-1	-29	Earthquakes every hour.	LO, PC, LR
	5	5	0	-28	Two very strong earthquakes in 5 h. Collapses in cliffs and mountains. Panic-stricken people. Houses strongly shaken and damaged (many collapsed). The population sleeps outdoors. **FASNIA ERUPTION.** (End SIETE FUENTES ERUPTION?).	LO
	8-10	10	5	-23	Many earthquakes, some of them strong. Continuous ground shaking.	LO, PC, LR
	11	11	6	-22	Many earthquakes. Four strong. Continuous ground shaking.	LO, PC, LR
	12	12	7	-21	Many earthquakes, one very strong. Continuous ground shaking.	LO, PC, LR
	13	13	8	-20	Four earthquakes in 1 h. Two earthquakes very strong in the afternoon. The population thinks another vent has opened. Continuous ground shaking. One earthquake at midnight very strong and long. Some earthquakes during the night.	LO, PC, LR
	14-15	15	10	-18	Many earthquakes. (End FASNIA ERUPTION?)	LO, PC, LR
	16	16	11	-17	(End FASNIA ERUPTION?)	
	17	17	12	-16	One earthquake very strong and long. Collapse of some houses. Panic-stricken people. Strongest effects in La Orotava.	LO
	19	19	14	-14	Many small earthquakes and some strong. One earthquake very strong.	LO, PC, LR
	20	20	15	-13	Many small earthquakes and some strong. One earthquake very strong and long.	LO, PC, LR
	21	21	16	-12	Many small earthquakes and some strong. One of the stronger earthquakes until this date. So many strong earthquakes during the night that they were not counted. The population sleeps in the churches.	LO, PC, LR
	22	22	17	-11	20 strong and smaller earthquakes. Two earthquakes very strong in 2 h. Continuous ground shaking during the night.	LO, PC, LR

	23	23	18	-10	Some small earthquakes.	LO, PC, LR
	24	24	19	-9	Many small earthquakes and some strong. Two earthquakes very strong in the morning. In the afternoon one earthquake very strong: collapse of many houses. Collapses in some cliffs and mountains.	LO, PC, LR
	25	25	20	-8	Some small earthquakes. Loud noise in the mountains and smoking areas. Some collapses in cliffs and mountains. People expect another eruption.	LO, PC, LR
	26-27	27	22	-6	Some small earthquakes.	LO, PC, LR
	28	28	23	-5	Many earthquakes. Two of the strongest and longest earthquakes in the morning. Other earthquakes very strong during the night.	LO, PC, LR
	29	29	24	-4	Many strong and long earthquakes (so many that they could not be counted). Continuous ground shaking.	LO, PC, LR
	30	30	25	-3	Many strong and long earthquakes (so many that they could not be counted). Continuous ground shaking. Large smoking cavity opened close to Güimar, loud noise from it. People expect a new volcano.	LO, PC, LR
	31	31	26	-2	Many strong earthquakes. Panic-stricken people. The population sleeps outdoors.	LO, PC, LR
1705	February					
	1	32	27	-1	Conflicting reports.	
	2	33	28	0	Many strong earthquakes. Houses shaken (collapse of some buildings). People fall down because of the ground shaking. Panic-stricken people. People expect a new volcano. Very strong earthquake felt in the upper valley between Güimar and Arafo. **ARAFO ERUPTION.**	LO, PC, LR
	3	34	29	1	Two strong earthquakes felt in the whole island. Collapse of some houses. People relate these earthquakes to the opening of a new vent in the volcano. People fall down because of the ground shaking. Panic-stricken people. Collapses in cliffs and mountains.	LO, PC, LR
	4-28	59	54	26	Seismic activity continues.	LO, PC, LR
1705	March					
	1-27	86	81	53	Seismic activity continues. End of ARAFO ERUPTION on March 27th.	

LO, La Orotava; PC, Puerto de la Cruz; LR, Los Realejos; A, Arafo; C, Candelaria; G, Güimar (Supplementary Figure DR2).

Supplementary Table DR2. Factual accounts of the unrest activity preceding the eruption of San Juan.

Chronological range		Days before eruption count down	Event	Localities
1947	January			
	22	-883	One earthquake.	EP
	May			
	6	-779	One earthquake.	EP
1949	March			
	24	-91	Cracks in the lighthouse of Fuencaliente. From this day earthquakes become more frequent and stronger.	EP
1949	June			
	20	-3	Two strong earthquakes.	EP
	22	-1	Frequent small earthquakes. People with restlessness.	EP
	23	0	Small earthquakes felt in the whole island, but stronger in Las Breñas, Mazo and the Valle de Aridane. No damages. **SAN JUAN ERUPTION**.	LB, M, VA, EP, LLN, LM, J, F
1949	July			
	29	36	End SAN JUAN ERUPTION.	

EP, El Paso; LB, Las Breñas; M, Mazo; VA, Valle de Aridane; LLN, Los Llanos; LM, Las Manchas; J, Jedey; F, Fuencaliente (Supplementary Figure DR2).

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Supplementary Table DR3. Factual accounts of the unrest activity preceding the eruption of Teneguía.

Chronological range		Days before eruption count down	Event	Localities	Maximum Intensity
1971	October				
	19	-6	One small earthquake. Vibration of furniture in the houses.	F	
	20	-5	Six or seven earthquakes (three stronger compared to the others) felt in the area between Fuencaliente and Valle de Aridane. No damages.	F, VA, M, EP	III (EMS-98)
	21	-4	13 earthquakes, four of them strong. Some people sleep outdoors in El Paso and Fuencaliente. According to the Newspaper "Diario de Avisos", almost 100 seismic movements with different intensities were recorded in Fuencaliente. 1000 seismic events recorded by the hydrophonic station of the Palisade Geophysical Institute in Puerto Naos (La Palma).	F, VA, M, LLN, EP	II (EMS-98)
	22	-3	15 earthquakes, at least four strong during the night. Population feel great fear and leave the houses. During the day one strong earthquake trigger collapses in cliffs and mountains and landslides blocking coast roads in the Fuencaliente area. Las Indias hermitage bells tolled alone.	F, VA, M, LLN, EP	III (EMS-98)
	23	-2	Four small earthquakes.	F	
	24	-1	One strong earthquake (the strongest until this day) of 12-16 s and five small earthquakes. Las Indias hermitage bells tolled alone. Collapses in cliffs and mountains and landslides. Damages in walls and roofs of some houses. Population feel great fear and leave the houses. The earthquake was felt even in the north of the island.	F, VA, SA, S, SC	IV (EMS-98)
	25	0	**TENEGUIA ERUPTION.**		
1971	November				
	17	23	End TENEGUIA ERUPTION.		

F, Fuencaliente; VA, Valle de Aridane; M, Mazo; EP, El Paso; LLN; Los Llanos; SA, San Andrés; S, Suaces; SC, Santa Cruz (Supplementary Figure DR2).

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Supplementary Table DR4. Factual accounts of the unrest activity preceding the eruption of Chinyero.

Chronological range		Days before eruption	Event	Localities	Maximum Intensity
1908	March				
	23	-605	One earthquake.	LO	II-III (FM)
	26	-602	Two earthquakes.	LO	V(M)
1908	July				
	23	-483	One small earthquake.	LO	
	25	-481	One small earthquake.	V	
	26	-480	One small earthquake.	PC	
	27	-479	Two earthquakes in La Orotava (IV and VII). One small earthquake felt in Puerto de la Cruz during 3 s.	LO, PC	VII (FM)
	28	-478	One medium-strong earthquake during 3 s. Repeated again 10 minutes later but smaller and shorter. Two small earthquakes 1 h later.	LO	
1908	August				
	4	-471	One strong earthquake.	IC	
1908	September				
	9	-435	One small earthquake.	LR	
1908	November				
	4	-379	Short earthquake with loud underground noise.	LR	
	17	-366	One strong earthquake and three smaller. Some people count 10 or 12 earthquakes during the night in Los Realejos. Many earthquakes felt in La Orotava: V, V, V, III, IV, IV (Forel-Mercalli).	LR, LO	V (FM)
	18	-365	Many earthquakes: V, V, V, III, IV, IV (Forel-Mercalli).	LO	V (FM)
	24	-359	One small earthquake.	LR	
	30	-353	One small earthquake.	LR	
1908	December				
	8	-345	Three earthquakes: small, medium and strong.	MAV	
	19	-334	One earthquake felt in Puerto de la Cruz (V) and Los Realejos (strong). One earthquake felt 20 m later in La Orotava (VI). One earthquake 40 m later in Puerto de la Cruz (V to VI).	PC, LR, LO	VI (FM)
1909	January				
	4	-318	Long and strong earthquake (12 s) felt in La Laguna, Icod and Santa Cruz. Strong movement of the furniture, doors and windows. Great fear among the population. VI (Rossi-Torel).	LL, IC, LR, SC	VI (RT)
	5	-317	One strong earthquake felt in Santa Cruz followed by another one smaller. One strong earthquake felt 1 h later in La Paz and La Orotava during 6 s (VI, Rossi-Foret). Strong movement of the furniture. Great fear among the population. Many people leave La Orotava.	SC, LP, LO	VI (RF)
	8	-314	One small earthquake.		
	9	-313	One small earthquake.		
1909	March				
	19	-244	One strong earthquake.	LR	
	21	-242	Two small earthquakes (3 s) with underground noise.	LO	
1909	April				
	4	-228	One small earthquake.	LR	
	7	-225	One small earthquake.	LR	
	18	-214	One small earthquake with loud underground noise.	LR	

	26	-206	One small earthquake.	LR	
1909	May				
	21	-181	Two small earthquakes of 3 s each (III-IV).	LO	IV (FM)
	24	-178	One or two earthquakes with loud underground noise.	LO	IV-V (FM)
	25	-177	Three strong earthquakes. The population left the houses. Small damages in some houses. Some collapses in cliffs.	LR	
	27	-175	One small earthquake.	LR	
	28	-174	One small earthquake.	LR	
1909	June				
	19	-152	One earthquake very long. Many cracks in the buildings. Stronger damages in the oldest buildings. One earthquake very small (1 s) felt 1 h later.	IC, LO	IV-V (FM)
1909	July				
	6	-135	One short earthquake.	LR	
1909	September				
	23	-56	Two earthquakes of 2 s. Buildings and trees shaken.	LP	VI (FM); VI-VII (MM)
1909	October				
	4	-45	One small earthquake.	LR	
	6	-43	Two earthquakes, the second one small.	LR	
	9	-40	One small earthquake.	LR	
	10	-39	One long earthquake.	LR	
	11	-38	One earthquake.	LR	
	13	-36	One small earthquake.	LR	
1909	November				
	13	-5	One small earthquake.	LR	
	14	-4	Two earthquakes, the first one strong, followed by three or five small earthquakes (felt in Los Realejos). Panic-stricken people. Two strong earthquakes followed by others smaller felt in Santiago del Teide (ground and walls shaken). Two earthquakes followed by more than 20 small shakes felt in Icod; great fear among the population.	LR, ST, IC, CA	V-VI (FM); VII (MM)
	15	-3	Two earthquakes, the second one small, felt in Los Realejos. Two small earthquakes followed by another one strong felt in Icod. Continuous shaking in Icod until the eruption.	LR, IC, CA	
	17	-1	One strong earthquake felt in Caraveo. Continuous shaking.	LR, CA	
	18	0	One strong earthquake felt in Los Realejos. Continuous underground noise and shaking. One strong earthquake (almost as the June 19th earthquake) felt in Icod immediately followed by the eruption. **CHINYERO ERUPTION**. Panic-stricken people because of the volcano; nearest village abandoned.	LR, IC	
1910	June				
	28	222	End CHINYERO ERUPTION.		

LO, La Orotava; V, Vilaflor; PC, Puerto de la Cruz; IC, Icod; LR, Los Realejos; MAV, Montaña Alta Vista; LL, La Laguna; SC, Santa Cruz; LP, La Paz; ST, Santiago del Teide; CA, Caraveo. M, Mercalli; MM, Modified Mercalli; FM, Forel-Mercalli; RT, Rossi-Torel; RF, Rossi-Foret (Supplementary Figure DR2).

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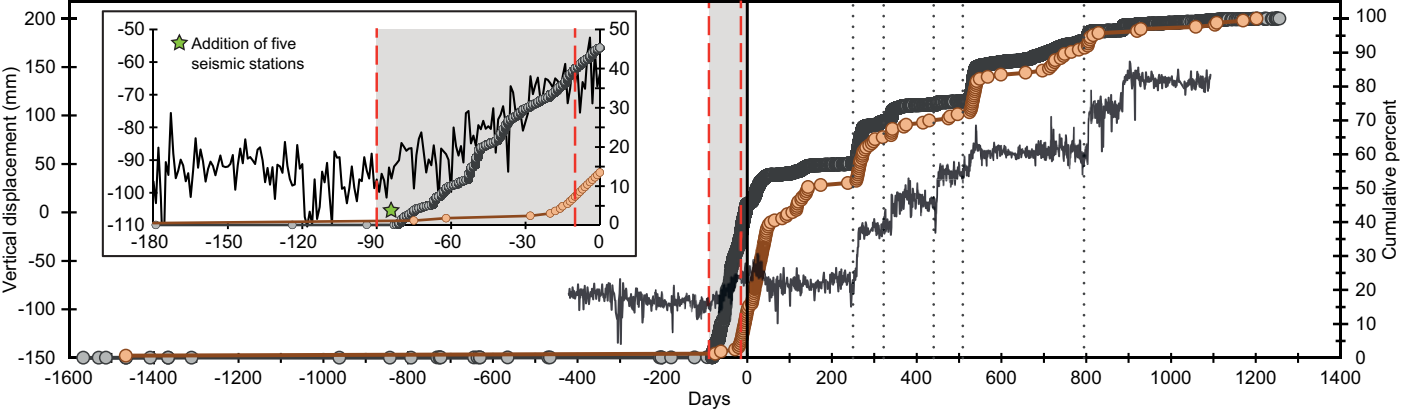

Figure DR1. Comparison between macroseismicity and monitored seismicity and deformation at the El Hierro (Canary Islands) 2011 eruptive vent. Cumulative percent of the days with felt earthquakes (orange dots) and total number of seismic events (gray dots) occurred before and after the El Hierro 2011 eruption. Gray line shows the vertical displacement recorded by one GPS station. Black dotted lines indicate the five post-eruptive episodes of unrest. Black line at time = 0 is the eruption time. Red dashed lines mark 90 and 15 days before the eruption. The general trend and the abrupt changes for the three curves are consistent. Note that the seismic unrest can be considered to start when deformation starts, and thus earlier earthquakes can be taken as background seismicity. Note also that in July 2011, the number of seismic stations at El Hierro increased from two to seven, shown by a star (Cerdeña et al., 2014). The sharper change in the trend of the instrumental seismicity occurs before the felt seismicity. This is an artifact of the increased in seismic monitoring, since this discrepancy is not present for the post-eruptive seismic crises. The trend of the cumulative percent of days with felt earthquakes is consistent with the trend of the cumulative percent of earthquakes and the geodetic data.

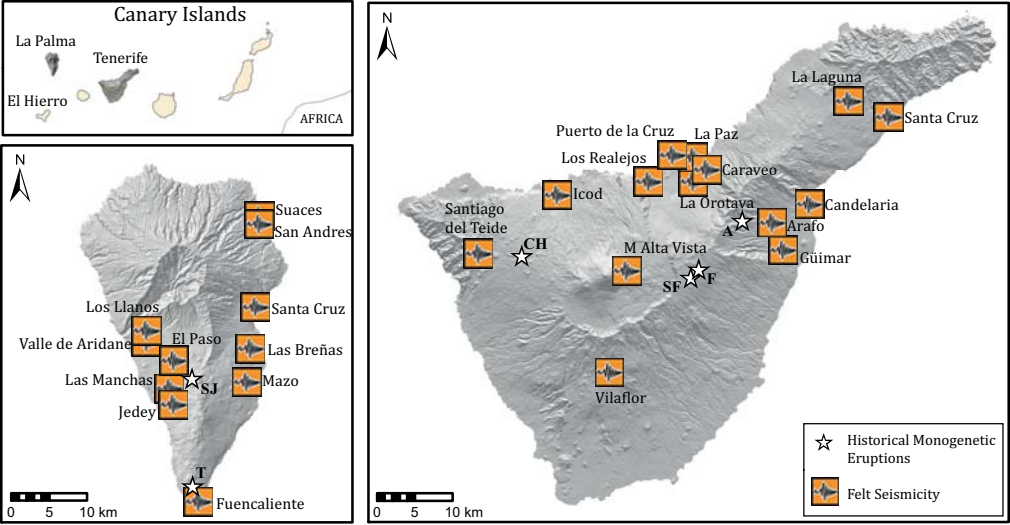

Figure DR2. Localities where the seismicity was felt by the population during the unrest of the eruptions of San Juan (SJ, 1949) and Teneguía (T, 1971), both in La Palma, and Siete Fuentes (SF, 1704), Fasnia (F, 1705), Arafo (A, 1705) and Chinyero (CH, 1909) in the island of Tenerife.

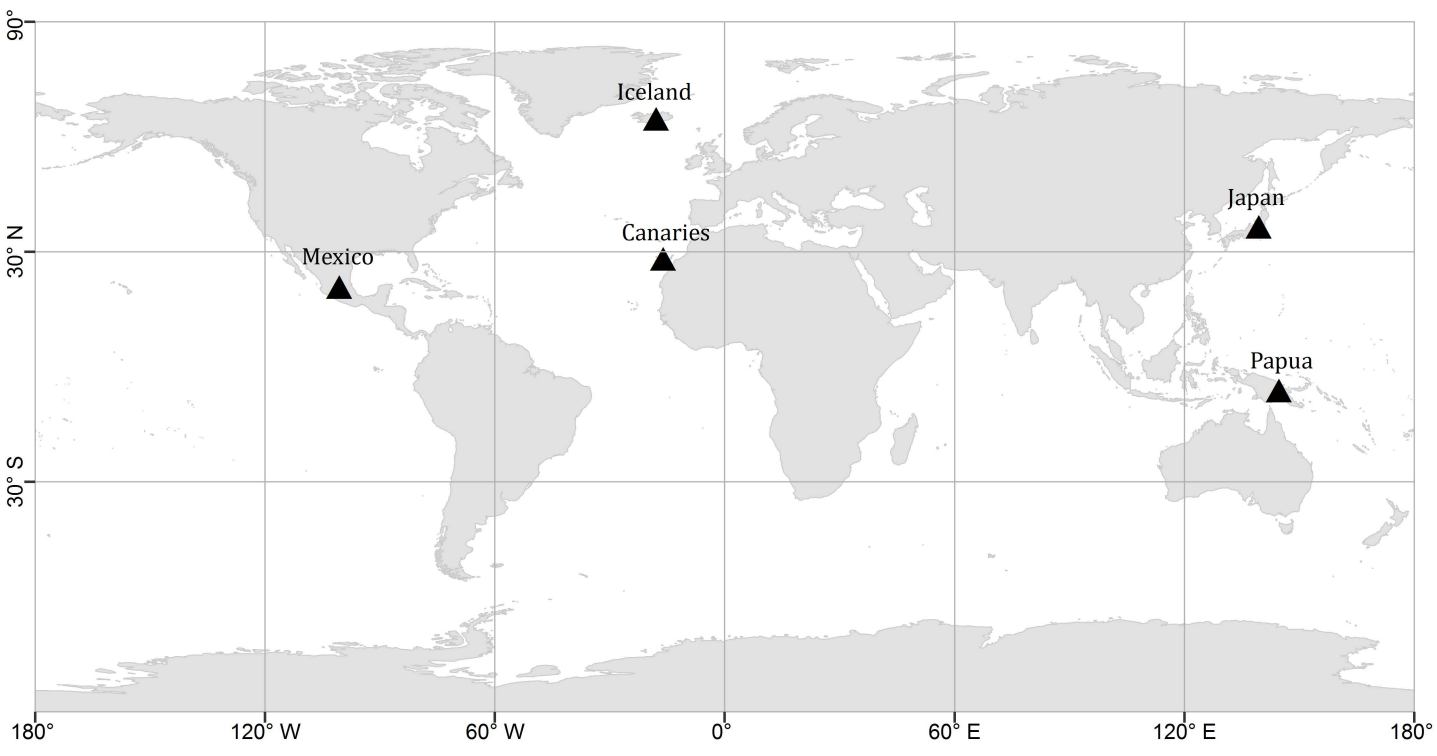
Iceland
Canaries
Mexico
Japan
Papua
90°
30° N
30° S
180°
120° W
60° W
0°
60° E
120° E
180°

Figure DR3. Global location map. Tenerife, Canaries (Latitude 28.271°N, Longitude 16.641°W). La Palma, Canaries (Latitude 28.57°N, Longitude 17.83°W). El Hierro, Canaries (Latitude 27.73°N, Longitude 18.03°W). Michoacan, Mexico (Latitude 19.85°N, Longitude 101.75°W). Goropu Mountains, Papua (Latitude 9.57°N, Longitude 149.075°W). Heimaey, Iceland (Latitude 63.43°N, Longitude 20.28°W). Higashi-Izu, Japan (Latitude 34.9°N, Longitude 139.098°W).