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1 **An analysis of the seismic activity of Popocatepetl volcano, Mexico, associated with**
2 **the eruptive period of December 2002 to February 2003: looking for precursors.**

3
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10

11 **ABSTRACT**

12 Since it reactivated in 1994, Popocatépetl volcano has undergone cycles of formation and
13 destruction of several lava domes. This surface activity is generally associated with
14 increasing seismic activity before the explosions that destroy the domes. A comprehensive
15 analysis of seismic records from November 2002 to February 2003 is carried out in order to
16 identify precursors of a series of explosive events. Daily numbers of volcano-tectonic
17 earthquakes and long-period events, as well as daily tremor duration, are obtained. Spectral
18 features of the LP events and tremor are also calculated and high-frequency precursory
19 signals of the LPs are studied. No clear variations of these characteristics of the seismicity
20 can be detected before the eruptions. RSAM calculations show that, besides small
21 fluctuations related to the explosions, the rate of seismic energy released is quite stable
22 during the studied period. Minor short-lived variations of RSAM levels are observed before
23 only five of eighteen eruptions, with no accelerating release of energy. It is thus quite
24 difficult to identify reliable seismic precursors during the eruptive sequence. This situation
25 is probably related to the open state of the system and has important implications on future
26 risk assessment regarding this volcano.

27 Keywords: Popocatépetl volcano, volcano seismology, volcanic tremor, long period event,
28 explosion quake, precursor

29

30 **1. INTRODUCTION**

31

32 Popocatépetl is a Quaternary andesitic stratovolcano located 65 km from Mexico City in
33 the Trans-Mexican Volcanic Belt. A large volcanic eruption originating from this volcano
34 could potentially affect more than 40 million people living in the states of Mexico, Puebla
35 and Morelos and could greatly affect the country's economy. Popocatépetl volcano has
36 undergone several eruptive phases, seven of which comprise Plinian eruptions that
37 produced extensive deposits from pyroclastic flows, pumice falls and lahars (C. Siebe et al.,
38 1995). The most recent Plinian phase occurred ~30,000 – 50,000 years ago. Minor
39 magnitude explosive activity has been documented in pre-Hispanic Colonial chronicles and
40 Mexican codices (Aztec manuscript paintings), such as Vatican A and Telleriano-Remensis
41 (De la Cruz-Reyna, et al., 1995). From 1720 to 1919 the volcano had a period of relative

42 quiescence. During the first half of the 1920's a new explosive phase (1919 - 1927),
43 characterized by ash-rich columns (Macías and Siebe, 2005), modified the morphology of
44 the inner crater. This explosive activity was observed by Murillo (1939) and reported by
45 Waitz, (1921) and (Camacho, 1925). Since it re-awoke on December 21, 1994,
46 Popocatepetl's activity has consisted mainly of cycles of extrusion and destruction of lava
47 domes. On June 30, 1997, an 8 km high eruption cloud produced ash fall on Mexico City
48 and forced the airport to close for several hours (Valdés et al., 2002). Large eruptions were
49 recorded on April 23, 1999 and from December 11 to January 23, 2000 with a Volcanic
50 Explosive Index (VEI) of 2 - 3, and 2, respectively (Novelo-Casanova and Valdés-
51 González, 2008). On January 22, 2001 a VEI 3-4 eruption generated a 1-km-high cloud,
52 mud flows on the northern flank of the volcano and pyroclastic flows that reached up to 6
53 km from the crater (Martin-Del Pozzo et al., 2003). Small to moderate explosions have also
54 been reported by the Centro Nacional de Prevención de Desastres (CENAPRED) in 2002,
55 2003, 2005 and in late 2006 (Glob. Volcan. Netw. Bull, 2002a; 2002b; 2003a; 2003b; 2005;
56 2006).

57

58 Since its reactivation in 1994, Popocatépetl volcano has produced several tens of daily
59 long-period (LP) events that have been classified into different families based on distinctive
60 waveform features and frequency range (De la Rosa et al., 2003; Arciniega-Ceballos et al.,
61 2008). Volcano-tectonic events (VT), although scarce, have been associated with magma
62 intrusion during dome-growth phases and to local and regional stresses (Lermo et al.,
63 1996; 2006; Martínez-Bringas, 2006; Arámbula-Mendoza, 2007; Arámbula-Mendoza et al.,
64 2010; De la Cruz-Reyna et al., 2008). Sustained tremor, as well as intermittent tremor
65 episodes, have been observed during several eruptive phases over the past eighteen years
66 (Arámbula-Mendoza, 2002; Arciniega-Ceballos et al., 2003).

67

68 Nearly every eruption is preceded by an increase in earthquake activity along with other
69 precursory phenomena such as tilt, fault development and high concentrations of several
70 chemical species. This has been observed to be the case with several active volcanoes such
71 as Mt. St. Helens (Swanson et al., 1985), Redoubt (USA) (Brantley, 1990), Kelut
72 (Indonesia) (Lesage and Surono, 1995), Merapi (Indonesia) (Voight et al., 2000), Colima
73 Volcano (De la Cruz-Reyna and Reyes-Dávila, 2001) and many others. A significant rise of
74 seismic and fumarolic activity was registered on Popocatépetl in 1993 but did not lead to an
75 eruption (Glob. Volcan. Netw. Bull., 2002a, 2002b, 2003a, 2003b, 2005, 2006). Another
76 period of increased activity started on October 1994 and culminated two months later with
77 a series of explosions on December 21, 1994 (De la Cruz-Reyna, et al., 2008). The eruption
78 of June 30, 1997 was also preceded by a series of VT events with magnitudes of 2.0 to 2.7
79 and volcanic tremor marked the onset of the explosive activity. On November 22, 1998 a
80 rise in number of LP events and tremor episodes per day was recorded. Seismicity
81 increased again on November 23 and harmonic tremor was recorded the next day. An
82 intense eruptive episode that generated up to 4-km high clouds occurred from November 25
83 to 30, 1998 (Valdés et al., 2002). On September 2000 a series of VT events below the crater
84 were recorded. Degassing lasted up to 30 minutes and harmonic tremor was observed in the
85 coda (Valdés et al., 2002).

86

87 In contrast with these well-documented eruptive episodes that were preceded by increased
88 seismic activity, little attention has been paid to explosive phases with no clear precursory
89 seismicity. In this work we present a detailed analysis of the seismicity related to a series of
90 18 explosions observed in December 2002 and February 2003. In this period, a temporary
91 seismic network including several small-aperture arrays complemented the Popocatépetl's
92 permanent network. We identify tenuous precursory phenomena for some of the largest
93 explosions while most of them occurred without any precursor. The lack or the weakness of
94 precursory seismicity prior to the 18 explosive events during this period represents an
95 uncommon situation at Popocatépetl volcano and could be associated with an open-conduit
96 stage during a recharge phase that involves the formation of a dome and its subsequent
97 destruction. The 2002-2003 explosive phase is anomalous at Popocatépetl and of great
98 importance as it provides new insight on the diverse activity of this volcano. These
99 observations should be considered in Popocatépetl's future eruptive behavior.

102 2. SEISMIC NETWORKS

103
104 Popocatépetl volcano's permanent seismic network comprises seven stations with three-
105 component short-period (1 Hz) seismometers (Fig.1). This network is continuously
106 recording at 100 sps and all signals are transmitted by telemetry to the central recording
107 facility at CENAPRED (National Disaster Prevention Center) in Mexico City. Two of these
108 stations, Canario (PPP) and Chipiquixtle (PPX), located at 2 and 3.7 km from the crater
109 respectively also have a Guralp CMG 40T-30 s broadband seismometer.

110
111 In October 2002, a temporary network was deployed at Popocatépetl volcano. The study
112 was carried out in the framework of a cooperative project including the Université de
113 Savoie, France, the Institute de Recherche pour le Developpement (IRD), France, and the
114 Institute of Geophysics at UNAM, Mexico. The equipment consisted of nine Guralp CMG
115 40T (seven 30 s and two 60 s) broadband seismometers. They covered a distance range of 2
116 – 14 km from the vent and were located at elevations between 2500 and 4300 m asl (Fig.
117 1). Signals were recorded at 100 sps in continuous mode until February 2003 by Reftek 72-
118 02 Digital Acquisition Systems (DAS). Each station operated autonomously with solar
119 panels and batteries. The sensors were placed on a tile in a 1-m-deep hole, covered with
120 plastic bags, leveled and buried in sand to reduce temperature variations. In several places,
121 small arrays of 3 short-period vertical seismometers with aperture of about 100 m were also
122 set up (FPP, FPX, FCO) in order to measure slowness and back-azimuth and locate the
123 source of emergent signals (Fig.1).

124
125 The technique used to determine the slowness vector, i.e. back-azimuth and apparent
126 velocity, is based on the similarity of waveforms when the distances between sensors are
127 small enough (e.g. Métaxian et al., 2002). The time delays between each pair of sensors are
128 estimated using the cross-spectral method (Poupinet et al., 1984; Fréchet, 1985; Got et al.,
129 1994) for successive time windows sliding along the seismograms. The time delay, which
130 depends on the relative position of sensors, can be expressed as a function of the slowness
131 vector. Consequently, the slowness vector can be calculated by linear inversion assuming
132 that (1) the wave field is composed by non-dispersive plane waves, (2) only one wave

133 propagates across the array or one is dominant at a given time and (3) the medium beneath
134 the array is laterally homogenous. The direction of propagation of the wave field, for a
135 given time window, can be estimated by calculating the probability density function (PDF)
136 of the back-azimuth (Métaxian et al., 2002). If several seismic antennas are available, the
137 different back-azimuth PDFs can be combined to compute the PDF of the position of the
138 source (Métaxian et al., 2002). The maximum likelihood gives the source position of the
139 seismic signal. Métaxian et al. (2002) showed that the greater the number of seismic arrays
140 and the more evenly distributed around the volcano they are, the better the source position
141 is constrained. Results from the data recorded at both seismic networks as well as source
142 locations from explosive events are presented in section 3.3.

143 144 **3. SEISMIC ACTIVITY AT POPOCATÉPETL VOLCANO**

145
146 The reawakening of Popocatepetl volcano in December 1994 and subsequent eruptive
147 episodes have been preceded by an energetic rise in seismicity characterized by: VT events,
148 related to magmatic activity that generates stress changes and, as a consequence, brittle
149 failure; LP events and tremor, associated to pressure transients in the fluid that induce the
150 resonance of conduits or fluid-filled cracks (e.g. Chouet 1988). In this section, we present
151 the evolution of the seismicity from January 2002 to March 2003, and October 2002 to
152 February 2003. However, during this eruptive phase, no anomalous behavior in the
153 seismicity prior to the eruptions of December 2002 and February 2003 was observed.

154 155 **3.1 Overview of the seismicity from January 2002 to March 2003**

156
157 From January 2002 to March 2003, seismicity at Popocatepetl volcano consisted mostly of
158 LP, VT events, explosions and tremor episodes. The seismic activity in early and mid-2002
159 corresponds to the extrusion of the dome reported by CENAPRED in December 2001 and
160 its partial destruction. The extrusion of recent material that formed a new dome and its
161 destruction was observed from mid-2002 to early 2003.

162 A total of 8243 LP, 270 VT events and 36,050 minutes of volcanic tremor were recorded by
163 the permanent seismic network during this 15-month period. Seven explosions occurred in
164 February, April and May 2002 (all explosions are indicated with a vertical dashed line (Fig.
165 2). High occurrence of LP seismicity was observed from April 8 to May 30 with the highest
166 peak of the year, 124 events, on May 13. Two days later, on May 15, 18 VTs were
167 recorded. One VT event from this swarm reached a magnitude of M 3.7. LP activity
168 remained high and two explosions occurred on May 18 and 22. The current dome reduced
169 in size, suggesting it was partially destroyed by the activity reported on previous days. On
170 May 29 (Fig. 2b), VT occurrence increased from 2 to 4 events per day and reached another
171 peak on June 1, with a swarm of 14 events. VT activity averaged 4 events per day on June
172 11, 12, 17 and 27. LPs increased again on July 22: a total of 80 events were recorded and
173 ash emission was also observed. High rates in LP seismicity, from August 11 to September
174 2, coincided with high VT activity on August 18 and September 1 and 4. This behavior
175 may be related to a new dome reported by CENAPRED in early September. In addition,
176 from August 29 to September 30, tremor episodes lasted between 480 to 1200 minutes per
177 day (Fig. 2c). Moreover, on November 6, a strong degassing event occurred, followed by
178 ash emission from November 22 to November 25. On November 24, an increment in LP

179 events (78) was observed (Fig. 2a). Finally, LP activity decreased notably on December 14,
180 four days prior to the first of 18 explosions that occurred between December 2002 and
181 February 2003 and will be discussed later.

182

183 **3.2 Analysis of seismic events from October 2002 to February 2003**

184

185 In the present section, we provide a description of the waveform, energy, frequency content
186 and occurrence of explosions, LP events, VT events and volcanic tremor. We also look for
187 correlations between these characteristics and variations of these features that could be
188 related with forthcoming eruptions

189

190 ***Explosions***

191 Eighteen explosive events occurred from December 2002 to February 2003. All the
192 explosions were related to an open system that allowed continuous magma ascent and a
193 dome formation. This dome extruded in September 2002 and reached a height of 40 m. The
194 first explosion was registered on December 18, 2003 at 08:09 (hereafter we use GMT time)
195 and generated a 6-km-high ash column. This event was followed by another explosion on
196 December 23 at 07:10. According to CENAPRED, the total volume ejected from both
197 explosions was estimated in 500,000 m³. In January 2003, dome growth was reported by
198 CENAPRED (CENAPRED, Volcano Monitoring Reports). Explosive activity resumed in
199 February 2003 with a more intense eruptive phase comprising a series of 16 explosions that
200 partially destroyed the lava dome. Table 1 summarizes the main features of the explosions.
201 E/e refers to a classification by CENAPRED in large explosion (E) and strong degassing
202 event (e). VLP indicates the existence of signal in the period range from 5 to 30 s. A proxy
203 of the energy (E_k) released is calculated as

$$204 \quad E = \int_D v^2(t) dt \quad (1)$$

205 where $v(t)$ is the vertical ground velocity recorded at station PPP and it is related to the
206 wave amplitude and the energy released. D is the duration of the corresponding seismic
207 event. The impulse magnitude M_k was calculated using the equation determined for
208 Popocatepetl volcano by Cruz-Atienza et al (2001). In most cases, the explosions classified
209 as E are the most energetic and produced VLP signals. Conversely, many low energy
210 explosions produced long duration signals.

211

212 ***VT events***

213 All the 50 VT earthquakes that occurred during this period had magnitudes of $m_c = 1.9$ to
214 2.9 (Martinez-Bringas, 2006) and depths +2 to -2 km below sea level (González, 2003).
215 Thirty of these earthquakes were located below the summit crater, while the other 20 were
216 located southeast of the volcanic edifice. This hypocenter distribution is similar to that
217 usually observed on this volcano (Arámbula-Mendoza et al., 2010). The seismic rate for VT
218 events typically averaged one event per day. Besides, a maximum of 3 VTs was observed
219 on January 2. No increase of this kind of seismicity is detected before the explosions. This
220 is consistent with the persistent low level of VT activity at Popocatepetl since its
221 reactivation. The local stress pattern for these events indicate reverse focal mechanism

222 solutions for 14 VTs that occurred in November 2002, within a depth range of -1 to 1 km
223 asl (González, 2003). In December, VT events occurred at greater depths (-2 to 1.5 km asl).
224 Events were located at depths ranging from 0.5 to 1 km from late January to April 2003. A
225 predominance of normal fault solutions was observed in February and March (Arámbula-
226 Mendoza, 2007; Arámbula Mendoza et al., 2010).

227

228 ***LP events***

229 LP activity averaged 20 events per day with a maximum of 101 events on February 7, 2003.
230 In order to produce an overview of their features and temporal evolution, about 10 LP
231 events per day of various amplitudes and waveforms were analyzed, giving a total of 908
232 LPs from November 2002 to February 2003. Several types of LP signatures were identified
233 at Popocatepetl, most of which were characterized by dominant frequencies in the 1 – 6 Hz
234 range (Fig. 3). About two thirds of these events exhibited a high-frequency (HF) signal (4 –
235 8 Hz) occurring generally between 2 to 4 s before the main LP phase (Fig. 4). These HF
236 precursory signals were characterized by an emergent onset and almost constant amplitude
237 which was about 1/20th of that of the LP event. The HF signal was never observed without
238 the LP event, although some LPs were not associated with any HF signal (Fig. 3b). Figure 4
239 displays the delay between HF and low-frequency (LF) phase arrivals from November 2002
240 to February 2003. The average duration is 4.4 s in this period (Fig. 4), with a standard
241 deviation of 1.3 s. Although fluctuations of delay are observed, it is difficult to clearly
242 relate them to the eruptive activity. The amplitude and duration of the LP events in this
243 study are small compared with those of LP events during other periods of activity. For
244 example: in 2000, many events displayed duration of one minute or more (Arciniega-
245 Ceballos et al. 2008)

246

247 Spectral analysis performed on the 908 LPs showed, for most of them, a dominant peak
248 around 1.8-2.2 Hz (Fig. 5). This feature has been observed at Popocatepetl volcano since
249 1994, suggesting that the physical conditions at the sources of LP events are stable. No
250 clear variations in the peak frequency can be observed either at long term or at short term in
251 relation with the occurrence of the explosions (Fig. 7d).

252

253 ***Volcanic Tremor***

254 Two main types of tremor lasting from few minutes up to several hours were observed at
255 Popocatepetl Volcano: harmonic and spasmodic tremor (Fig. 6). Harmonic tremor was the
256 most common type observed during this period. It was characterized by a series of up to 20
257 narrow spectral peaks, with fundamental frequency usually in the range 0.6 to 1.5 Hz, and
258 regularly spaced overtones at integer multiples of the lowest frequency. Spasmodic tremor
259 had broad spectra with energy at frequencies of up to 12 Hz, maximum values around 2 Hz
260 and no marked spectral peaks. Some tremor episodes exhibited rapid transitions from
261 harmonic tremor to spasmodic tremor and back to harmonic tremor again. Pulsating tremor,
262 which consists of successive small amplitude pulses every 10 s approximately, was
263 detected, briefly, in November (Fig. 6c).

264 Harmonic tremor frequency was not stable through time and presented both short-term
265 glidings (Fig. 6a) and long-term variations. Again, no clear relationship between
266 fundamental frequency of harmonic tremor and surface activity of the volcano could be
267 observed (Fig. 7e). The tremor activity in 2002 peaked in August and September, with

268 durations of up to 1200 mins per day, and then decreased. Tremor activity reached 360
269 mins per day in November and early December. It became more sporadic from December
270 13 to January 20 and slightly renewed afterwards with durations of up to 180 mins per day.

271

272 *Correlation between types of events*

273 We looked for relationships and correlations between the different types of seismic activity
274 comparing the occurrences, features, and inter-event times of the VT, LP events, tremor
275 and explosions. All appeared to be highly uncorrelated to each other (Fig. 7). Thus, no type
276 of event can be considered as a precursor of any other type including explosions. Moreover,
277 the different kinds of seismic activity have probable different origins.

278

279 **3.3 RSAM and source location**

280

281 In order to have an overview of the level of seismic activity during the period of study, we
282 first calculated the Real-time Seismic Amplitude Measurement (RSAM, Endo and Murray,
283 1991) from October to February. For all the RSAM calculations, we used the vertical
284 component of the short-period seismometer of PPP, which was the closest station to the
285 crater, with a moving computing window of 60 s long without overlap. Figure 8 displays
286 the results together with the cumulative values of energy. It appears that the slope of the
287 cumulative curve is almost constant during the last 4 months of the period with an average
288 rate of energy of 730 Arbitrary Unit per hour (AU/h). This mean value includes the short
289 bursts of energy (some of which are associated with explosions) and elevates the mean
290 value. However, most of the time, such as in October, the rate was lower. Apart from some
291 small fluctuations, the seismic energy released was quite stable during the pre-eruptive and
292 eruptive sequences when examined at this scale.

293

294 To investigate the explosions more closely, we focused on shorter intervals preceding the
295 explosions, described the behavior of RSAM, and made use of the seismic arrays to locate
296 the origin of eventual seismic activity. The details of five such events vary widely, with
297 some explosions clearly preceded by marked increases in the RSAM for tens of minutes to
298 tens of hours and others apparently preceded by slight RSAM increases several days before
299 with only one case where coherent energy was clearly coming from the volcano. In
300 summary, an acceleration of RSAM could be detected before the eruptions. However, for
301 most of them, no variation could be observed.

302

303 *3.3.1. December 18, 2002 eruption.*

304 Twenty minutes before the eruption, the RSAM sharply increased (Fig. 9a). This activity
305 corresponded to the occurrence of relatively high-frequency (1-10 Hz) emergent signals,
306 which was probably spasmodic tremor and rock falls. In that period, only array FPX was
307 recording. No preferential back-azimuth was obtained during this 20 minute-long interval,
308 although seismic waves of a small event at 07:48:49 appeared to propagate from the crater.

309

310 *3.3.2. December 23, 2002 eruption.*

311 About 6 hours before the explosion, the RSAM increased from 356 to 1145 AU/h, and
312 again 40 minutes before the event (Fig. 9b). This was mainly due to an increasing level of
313 spasmodic tremor with energy distributed up to 12 Hz (Fig. 10). The back-azimuths

314 estimated at arrays FPX and FCO were random, except at FCO during 40 minutes
315 preceding the explosion, where they pointed towards the volcano.

316

317 **3.3.3. February 14, 2003 eruption.**

318 A small increment of the rate of energy (870 AU/h) was observed 80 minutes previous to
319 the eruption in association with a swarm of LP (1 – 10 Hz) events (Fig. 9c). While back-
320 azimuths estimated at array FPP mainly indicated the direction of the crater during several
321 hours before the event, the values obtained at FCO and FPX corresponded to the summit
322 direction only for short periods of tremor or discrete events.

323

324 **3.3.4. February 21, 2003 eruption.**

325 Similarly, the seismicity level progressively rose within the 7-hour interval prior to this
326 small explosion (Fig. 9d). Again, the signals contained low amplitude spasmodic tremor,
327 mainly recorded at the closest stations, with some bursts of energy or LP events, all in the
328 frequency range 1 – 12 Hz. Strangely, array processing at FPP gave a greater proportion of
329 back-azimuths pointing towards the crater before this period of increasing signal level than
330 during it. This indicates that the signals during this pre-eruptive period contained higher
331 proportion of incoherent noise.

332

333 **3.3.5. February 28, 2003 explosion.**

334 Finally, this event was preceded by a slight increment of the seismic energy rate (810
335 AU/h) during about 50 hours (Fig. 9c,e). The period began with a swarm of LP events and
336 spasmodic tremor on February 12 between 10:00 and 23:00 (Fig. 9c). The back-azimuths
337 estimated at FPP were relatively stable and pointed to the crater, especially in the last 12
338 hours (Fig. 11b). Similar results, with a lower proportion of good quality estimations, were
339 obtained for the other arrays. Furthermore, as observations from 3 arrays were available for
340 this period, many LP events, including the explosion itself, could be located by combining
341 the estimations of back-azimuths (Métaxian et al., 2002). The source locations obtained
342 were close to each other and were at less than 1 km south-westward of the crater (Fig. 12).
343 This shift could result from topographical and structural effects (Almendros et al., 2001;
344 Métaxian et al., 2009).

345

346 **3.3.6. Other eruptions.**

347 On the other hand, no increase of energy release was observed before the explosions of
348 February 3, 5, 6, 7, 19, 20, 22, 23, and 28 (Fig. 9e). A small decrease even occurred 2 hours
349 before the February 3 eruption.

350

351 **4. DISCUSSION**

352

353 As at most active volcanoes, the seismic activity of Popocatépetl is characterized by a wide
354 variety of phenomena. A crucial question is to determine the relationships between the
355 seismicity and the physical processes associated with dome extrusion and its subsequent
356 destruction. This is especially the case for the period from October 2002 to February 2003
357 which the present study is focused on.

358

359 The volcano-tectonic activity is of low level at Popocatépetl compared with other similar
360 volcanoes. It is mainly located in two areas, one below the crater and the other at the
361 southeast of the edifice. Most of the fault plane solutions indicate normal faulting although
362 the number of reverse fault mechanisms increases in some periods (Arámbula-Mendoza et
363 al., 2010). During the period of study, this type of event was even scarcer with less than one
364 event per day in average. However, no clear variations of the pattern of this seismicity,
365 including hypocenter distributions and fault plane mechanisms, could be observed.
366 Furthermore, no anomalous behavior of the VT activity occurred before the explosions.
367 These observations suggest that the solid structure of the volcano did not experience
368 marked stress variations in relation with the explosive events and dome extrusions. These
369 results are consistent with the deformation data from 2002 and early 2003 provided by
370 CENAPRED. Deformation of the volcanic edifice showed no significant changes from
371 October 2002 to February 2003, a behavior indicative of an open-conduit system.

372

373 Long-period events are the most common signals recorded at Popocatépetl during the
374 period of time studied here. Their spectra exhibit one or several peaks with varying
375 frequencies although they are generally close to 2 Hz. Part of them, especially before
376 explosions, have energy up to 12 Hz. Only a small proportion of LP events are
377 characterized by strong spectral peaks that could be associated to resonance effects at the
378 source. The diversity of features of the LP seismicity suggests that sources of different
379 kinds and/or locations are active in this volcano. Neither the number of events per day nor
380 their characteristic frequency present anomalous variations related with the explosions.
381 Only mild increases of this seismicity have been observed during a few minutes or hours
382 prior some events. Arciniega-Ceballos et al. (2008) described the seismicity of
383 Popocatepetl from December 1999 to March 2000. They identify three types of LP events,
384 two of which are associated with VLP events and strong degassing bursts. These authors
385 interpret the former events as the expulsion of pockets of gas through pre-existing cracks.
386 Although the LP events observed three years later are much smaller, the same mechanism
387 related to gas transfer could also be involved at the source.

388

389 Most of LP events are preceded by a relatively high-frequency and low-amplitude phase.
390 This striking feature has been observed since the unrest of Popocatépetl in 1994 (Arciniega-
391 Ceballos et al., 2008). This kind of signal is also common at Galeras, Colombia (Gil Cruz
392 and Chouet 1997), Koryakski, Russia (Gordeev and Senyukov 2003), Deception Island
393 (Ibañez et al., 2003), and Shishaldin volcano, Alaska (Caplan-Auerbach and Petersen
394 2005). Several processes have been proposed to explain these HF phases and could provide
395 an explanation for the observation at Popocatepetl. Gil Cruz and Chouet (1997) suggested
396 that at Galeras they are originated by a conduit segment that connects a system of
397 preexisting cracks, where LPs are generated, to the underlying magma reservoir. The
398 conduit segment is excited by the frothy liquid that results from a foam layer located at the
399 top of the magma column and that collapses episodically when pressurized gas escapes to
400 the surface. Ibañez et al. (2003) propose different locations for the LP and HF sources, the
401 latter resulting from the fracturing of small fluid-lubricated faults. In a study of Shishaldin
402 volcano, Caplan-Auerbach and Petersen (2005) described a model in which the HF signals
403 result from pressure perturbations in a fluid flow which generate transient waves. These
404 waves propagate in the fluid until producing bubble coalescence and LP event. At

405 Shishaldin volcano, they observed periods of relatively stable delays between the HF and
406 LF phases. Changes in those delays are related to variations of the acoustic velocity in the
407 fluid due to changes in gas content. From November 2002 to February 2003 at Popocatepetl
408 volcano, the average HF-LF delay remained around 4 s and no clear variations of this
409 duration appeared before the explosions (Fig. 4). Further detailed studies and observations
410 are required to evaluate the ability of the former models to explain this HF precursory
411 signal.

412

413 The occurrence of volcanic tremor remained sporadic during the five-month-long period of
414 study and no correlation has been found between the eruptive events and the duration or
415 frequency of tremor. Tremor is thought to be mainly related to degassing (Konstantinou and
416 Schlindwein, 2002). Among the numerous mechanisms proposed to explain this
417 phenomenon (see e.g. Ferrazzini and Aki, 1987; Chouet, 1988; Johnson and Lees, 2000;
418 Julian, 1994; 2000; Schlindwein et al., 1995; Hellweg, 2000; Powell and Neuberger, 2003),
419 the clarinet model (Lesage et al., 2006) appears to be one of the most plausible to produce
420 the observed signals (Rust et al., 2008). Following this model, intermittent gas flow through
421 fractures in the plug produces repetitive pressure pulses that can be stabilized, or not, by a
422 feedback mechanism associated with resonance in the magmatic conduit. This mechanism
423 could explain the evenly spaced spectral peaks of the tremor of Popocatepetl volcano.

424

425 The calculation of RSAM showed that the rate of seismic energy release is remarkably
426 stable over the 5 months. Except for a few cases, the rate varied by less than a factor of 2.
427 This suggests that the volcanic system did not suffer large modifications during the eruptive
428 sequence. At a shorter time scale, no variation of the RSAM rate was observed prior to
429 most of the 18 explosions. Only for five of them, among the largest ones, low level and
430 short-lived (tens of minutes to tens of hours) precursory seismic activity occurred and
431 generated an increase in the RSAM values. This activity generally consisted of relatively
432 high-frequency (< 12 Hz) spasmodic tremor, LP events and background noise. The
433 processing of array data, for such events, confirms that the corresponding sources are close
434 to the crater, probably at shallow depth.

435

436 The most important point with respect to the pre-eruptive activity is that acceleration of the
437 energy release did not generally occur before the explosions, even for the largest ones. This
438 behavior is in clear contrast with that of the seismic activity reported on many volcanoes,
439 such as Pinatubo (Cornelius and Voight, 1996), Bezymyanny (Voight, 1988), Mt. St.
440 Helens and Redoubt (Voight and Cornelius, 1991), Villarrica (Ortiz et al., 2003), Soufrière
441 Hills (Kilburn and Voight, 1998), or Tungurahua (Tárraga et al., 2007). In many cases, the
442 eruption time could be successfully estimated by using the Material Failure Forecast
443 Method (FFM) which is based on the concept of material damaging before a rupture
444 (Voight, 1988; Cornelius and Voight, 1994). In these examples, the acceleration of the
445 observable, such as deformation or seismic activity level, is proportional to a power of its
446 rate of change. A variant of the FFM model, which uses a linear visco-elastic model of
447 Kelvin-Voigt, has been applied to eruptions of the Colima volcano (De la Cruz-Reyna and
448 Reyes-Dávila, 2001; Reyes-Dávila and De la Cruz-Reyna, 2002). Following this
449 interpretation, tertiary creep of material, involving progressive loss of cohesion, is
450 identified by the accompanying phenomena that can be used as precursors of the eruption.

451 However, this process requires the medium to be closed, as an open or semi-open system
452 may have different behavior (De la Cruz-Reyna and Reyes-Dávila, 2001). This approach
453 can thus provide a possible explanation of either the lack or weakness of seismic precursors
454 before the Popocatépetl explosions. Indeed, as dome emplacement occurred a few days or
455 weeks before the eruptions, the magma system was probably still open.

456
457 From another point of view, complex processes strongly modify the physical properties of
458 the magma in the uppermost part of the feeding conduit, including the dome if any.
459 Degassing and microlites growth produce dramatic viscosity increase and large excess fluid
460 pressures at the top of the conduit and in the dome. This pressurization may lead to
461 instabilities and unexpected explosions (Sparks, 1997). These phenomena are not
462 necessarily accompanied by seismic activity and could thus give another interpretation of
463 our observations.

464
465 All the preceding analysis and discussion, together with the fact that some seismic bursts
466 were not followed by explosions, demonstrate that it would have been very difficult, if not
467 impossible, to predict the eruptions of December 2002 and February 2003. However, in
468 such situations, the high level of hazard of the volcano could be identified, with the
469 corresponding implications in terms of civil protection. The results we have presented in
470 this paper highlight the variability of precursory signals or lack thereof in a volcano with an
471 open-conduit system. It also stresses the importance of the use and interpretation of
472 different monitoring techniques to determine the current state of the volcano. Yet, further
473 analysis of future eruptive stages without precursory signals is required for a better
474 understanding of volcanic activity at Popocatépetl.

475

476 **5. CONCLUSIONS**

477

478 Many papers in the volcanological literature present observations of more or less clear
479 precursors of eruptions and attempts to predict these events, mostly, in an a posteriori
480 approach. There are much fewer papers that analyze the lack or faintness of precursory
481 phenomena that characterize some eruptions, although these observations are quite
482 important for risk assessment. Hence several relevant questions must be addressed such as:
483 in which cases a forthcoming eruption is preceded by precursors? How is the existence or
484 lack of precursors related to the state of the system, the physical properties of the magma
485 and the recent surface activity? To answer these questions a better understanding of the
486 physical processes that lead to eruptions is required.

487

488 The present work is focused on a short period of dome building and explosive destruction
489 at Popocatépetl volcano. Many features of the seismic activity have been studied in detail in
490 order to detect possible precursory phenomena: rate of occurrence of VT, LP and tremor,
491 characteristic frequency, fault mechanism and source location, and duration of the
492 precursory HF phase of LP events. The main result of this study is that the December 2002
493 and February 2003 explosions are characterized by a lack or a weakness of the seismic
494 precursors. Only in a few cases, moderate increase of the level of seismicity has been
495 observed in short period (minutes to hours) before the explosion. Conversely some bursts
496 of seismic activity were not followed by an eruption. In this situation, it is thus difficult to

497 identify reliable precursors. This is a consequence of the open state of the system, although
498 precursory activity can be observed in some open systems. It is therefore of paramount
499 importance to detect this kind of situation and to take it into account for risk assessment and
500 protection of the population and, in particular, of the volcanologists that work on the
501 volcano.

502

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518

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720 35.

721

722 **TABLE AND FIGURE CAPTIONS**

723

724 Figure 1. Permanent monitoring seismic network and temporal arrays used in this study at
725 Popocatépetl volcano, Mexico. The black solid triangles indicate the permanent network
726 and the lighter solid triangles the temporary small-aperture arrays. The squares indicate
727 nearby towns.

728

729 Figure 2. Seismicity at Popocatépetl volcano from January 2002 to March 2003 reported by
730 CENAPRED: a) Number of LPs recorded daily, b) Number of VTs recorded daily and c)
731 Total tremor duration per day in minutes. Dashed vertical lines indicate the days the
732 explosive events occurred. The shaded area corresponds to the period analyzed in this
733 paper.

734

735 Figure 3. LP events observed at Popocatépetl volcano. For each example, seismogram,
736 spectrogram (short-term Fourier Transform) and spectrum of section between vertical
737 dotted lines are displayed. a) Common LP event recorded on February 13, 2003 at 15:51. b)
738 LP event recorded on December 13, 2002 at 04:13. It is preceded by a high-frequency (1-13
739 Hz) precursory signal with duration of 6 s, the spectrum of which is plotted in bottom
740 panel. c) Relatively high-frequency event recorded on February 4, 2003 at 10:12, 47
741 minutes before explosion.

742

743 Figure 4. Delay between the high-frequency (HF) phase and the low-frequency signal of
744 LP events. Dashed lines indicate the days the explosive events occurred. No significant
745 changes were observed prior to the explosions.

746

747 Figure 5. Histogram of the frequency of the maximal spectral amplitude of LP events from
748 November 2002 to February 2003. All the events were recorded with a broad-band
749 seismometer at Canario station (PPP). Note that the energy for most LP events is
750 concentrated around 2 Hz.

751

752 Figure 6. Examples of different types of volcanic tremor observed at Popocatépetl volcano.
753 a) Spasmodic tremor (from 1000 to 2300 s) followed by harmonic tremor, recorded on
754 December 10, 2002 at 10:21. Averaged periodograms of sections of spasmodic (green
755 dotted lines) and harmonic (red dotted lines) tremors are displayed in two bottom panels
756 with logarithmic vertical scale. Spectrum of harmonic tremor contains 12 clear regularly
757 spaced peaks. b) Spasmodic tremor recorded on December 18, 2002, at 07:54 before

758 explosion of 08:07. c) Tremor composed of series of short pulses recorded on November
759 11, 2002. This kind of tremor was observed only sporadically.

760

761 Figure 7. Main features of the seismicity observed from November 2002 to February 2003:
762 a) Number of LP events per day; b) Number of VT events per day; c) Tremor duration; d)
763 Frequency of the maximum spectral amplitude of LP events (The black vertical lines
764 indicate the frequency range observed on each LP event), and e) Frequency of the
765 fundamental spectral peak of harmonic tremor.

766

767 Figure 8. Real-time Seismic Amplitude Measurement (RSAM) of the vertical short-period
768 component of stations PPP from October 1, 2002 to February 28, 2003. A moving window
769 of 60 s with no overlap is used for the calculation. The cumulative value of RSAM is also
770 plotted. Vertical dashed lines indicate the occurrence of explosions.

771

772 Figure 9. RSAM and cumulative value of RSAM for several periods enclosing the eruptive
773 events of: a) December 18; b) December 23; c) February 21; d) February 14; e) February
774 28. Vertical dashed lines indicate the occurrence of the explosions. Arrows mark increases
775 in RSAM rate.

776

777 Figure 10. Seismic record obtained with the vertical short-period component of station PPP
778 and corresponding spectrogram before the December 23 explosion. The explosion onset is
779 close to second 4000.

780

781 Figure 11. Time series of back-azimuth estimated at: a) array FCO on December 23, 2002;
782 b) array FPP on February 14, 2003. The vertical line indicates the beginning of the
783 explosion. On the right panels, the probability density function of the back-azimuth is
784 represented for the shadowed 40-minutes long window before the December explosion and
785 for the whole 2-hours window in February. Note the rapid azimuth variation around second
786 2000 at array FCO, probably due a moving vehicle travelling on a road close to the array
787 (Almendros et al., 2002).

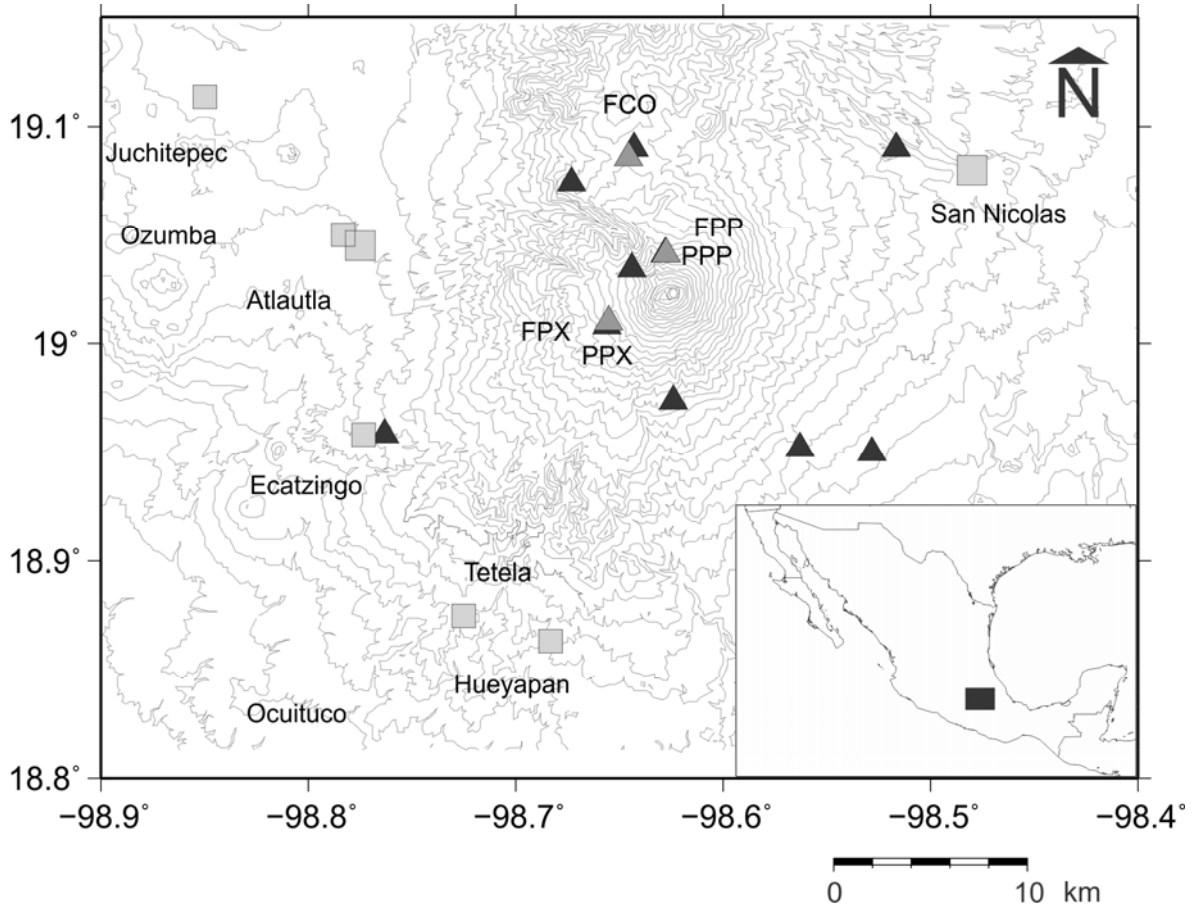
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789 Figure 12. Probability density functions of source position computed for the explosion of
790 February 14, 2003 at 11:34:26 and five LP events that occurred during the preceding three
791 days. For each event, calculations are performed on a 10 s time window of signal recorded
792 by three seismic arrays (FPP, FPX and FCO). The position of the source is given by the
793 maximum of likelihood indicated as a white star. The day and the beginning of time
794 windows are indicated above each panel.

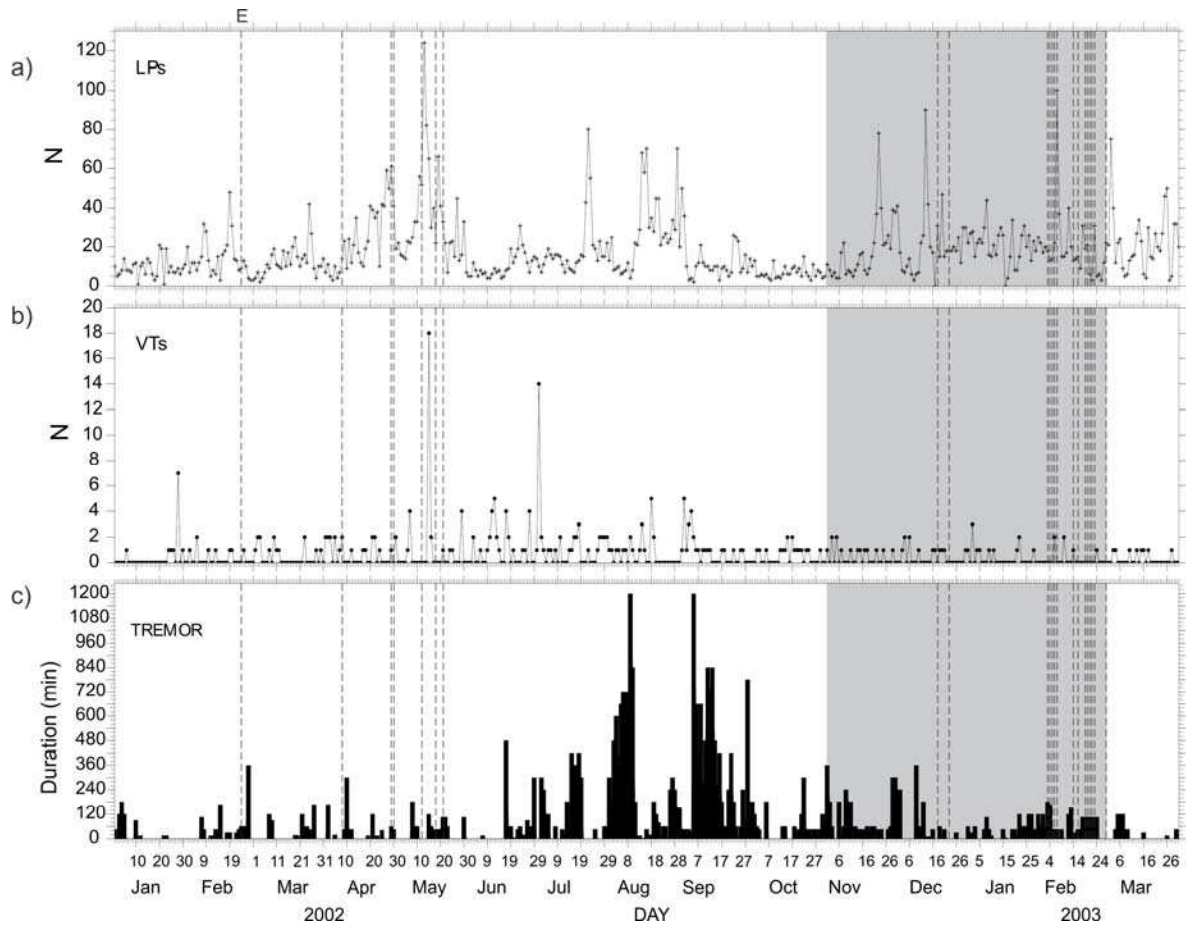
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796 Table 1. Main features of the explosions of Popocatépetl volcano in December 2002 and
797 February 2003. E and e indicate large explosion and strong degassing event, respectively.
798 ‘Precursors’ and ‘VLP’ columns indicate events preceded by precursors and containing

799 very long period signals. M_k is the impulse magnitude (Cruz-Atienza et al., 2001). E_k is a
800 proxy of the energy of the explosion quakes. The last column gives their duration (in s.).
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802
803 Quezada-Reyes_etal_Figure1.cdr



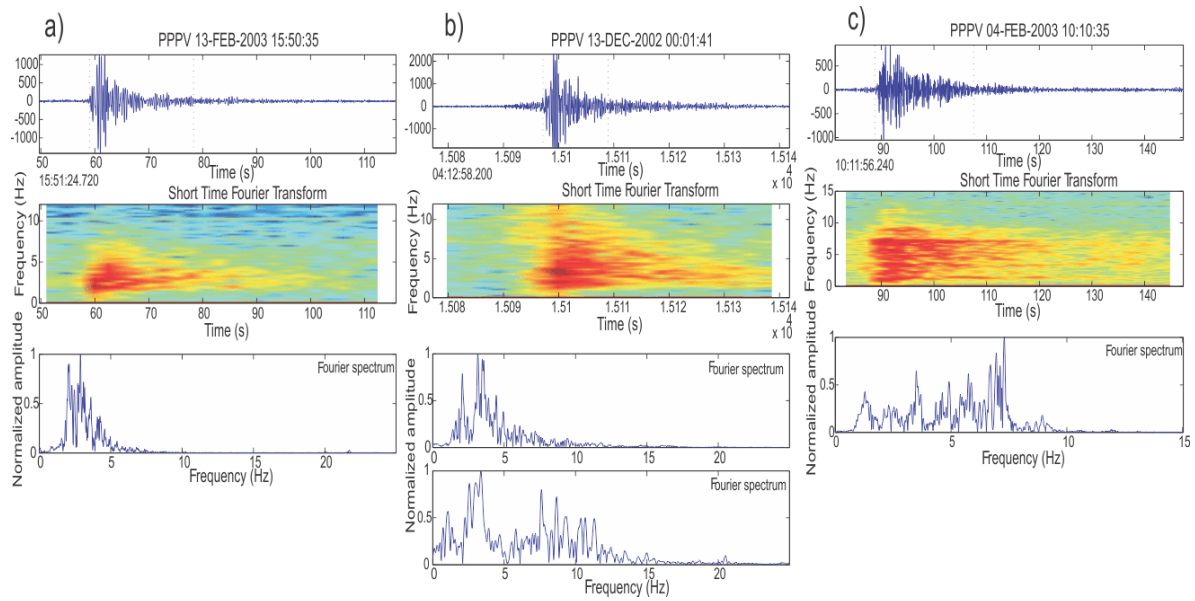
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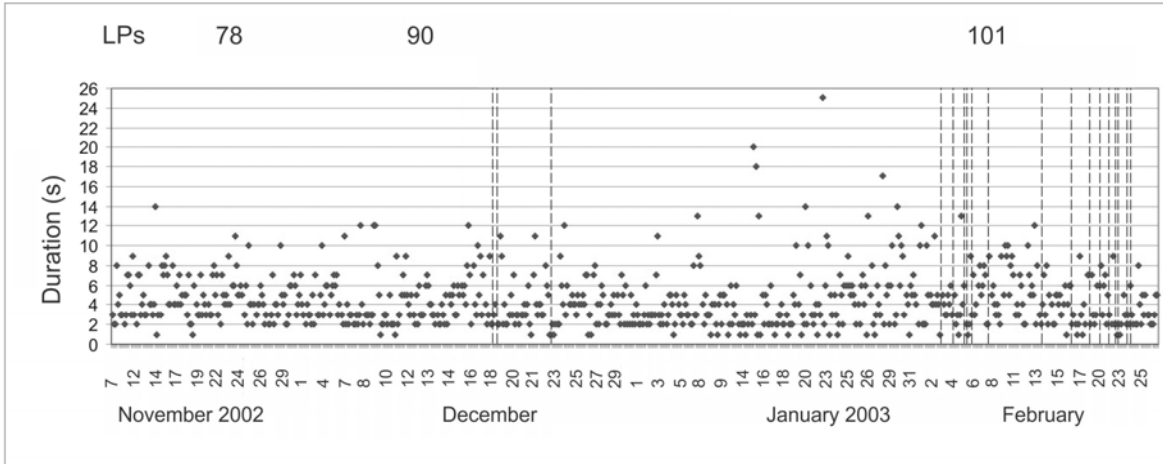
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810 Quezada-Reyes_etal_Figure3.cdr



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812 Quezada-Reyes_etal_Figure4.cdr

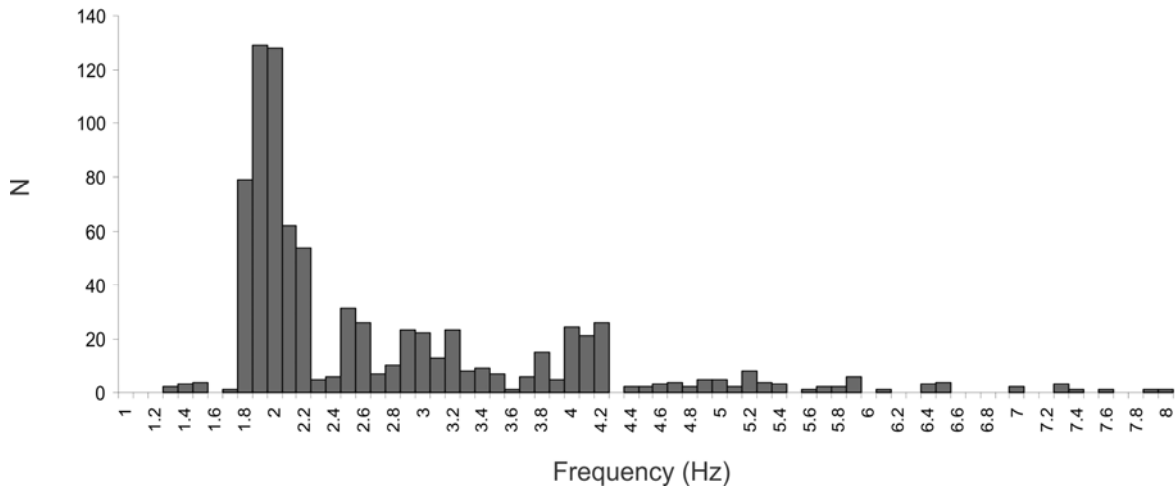


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816 Quezada-Reyes_etal_Figure5.cdr

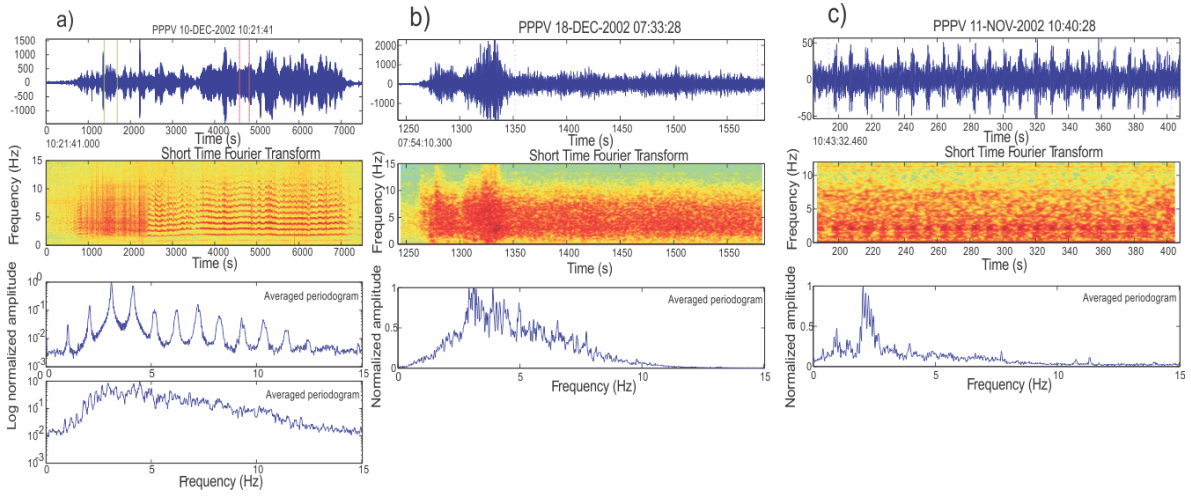


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819 Quezada-Reyes_etal_Figure6.cdr

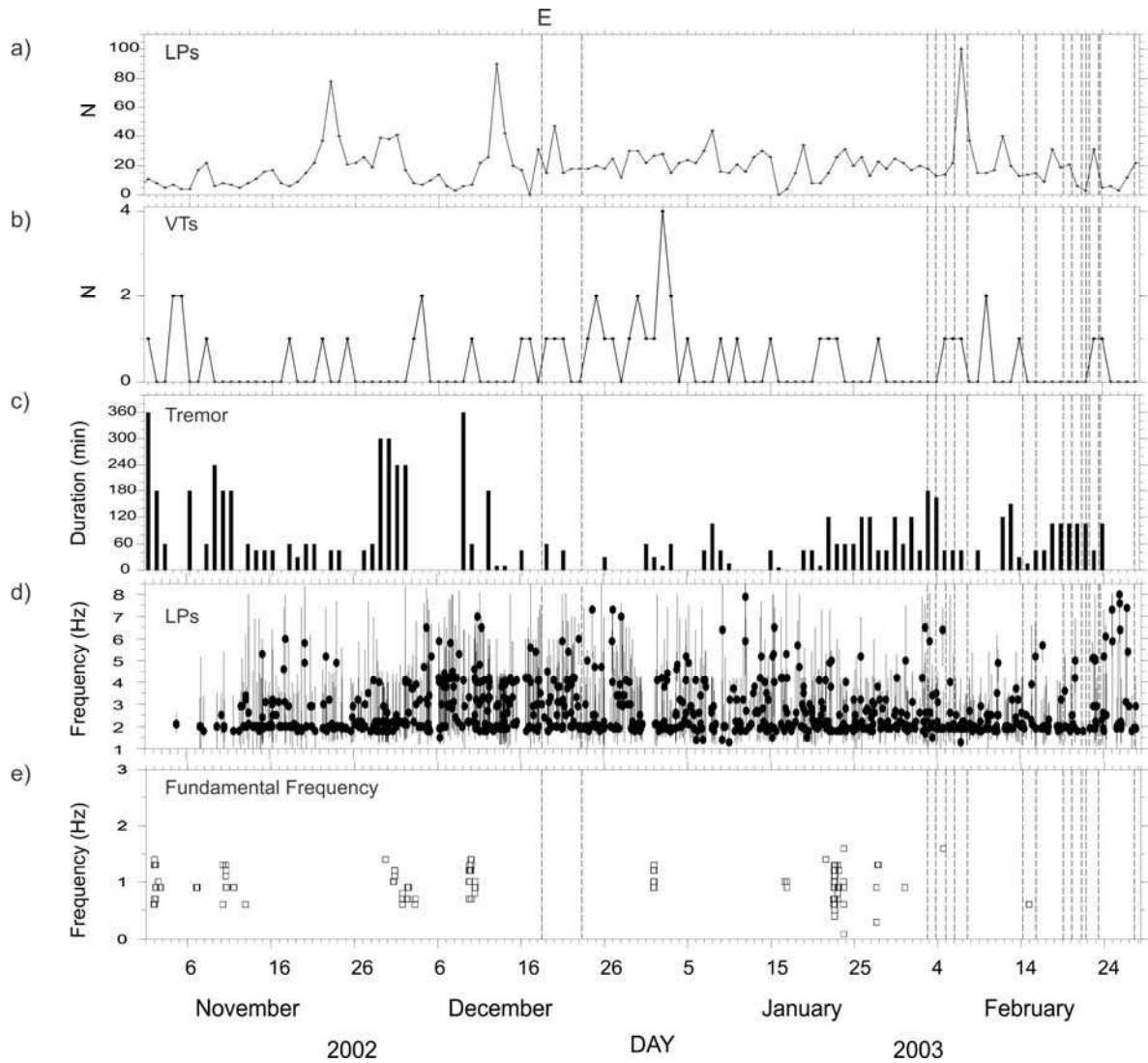
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823 Quezada-Reyes_etal_Figure7.cdr

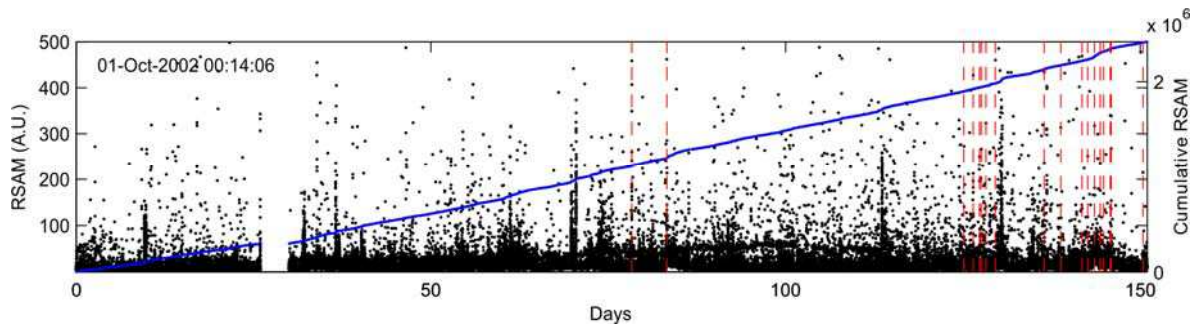


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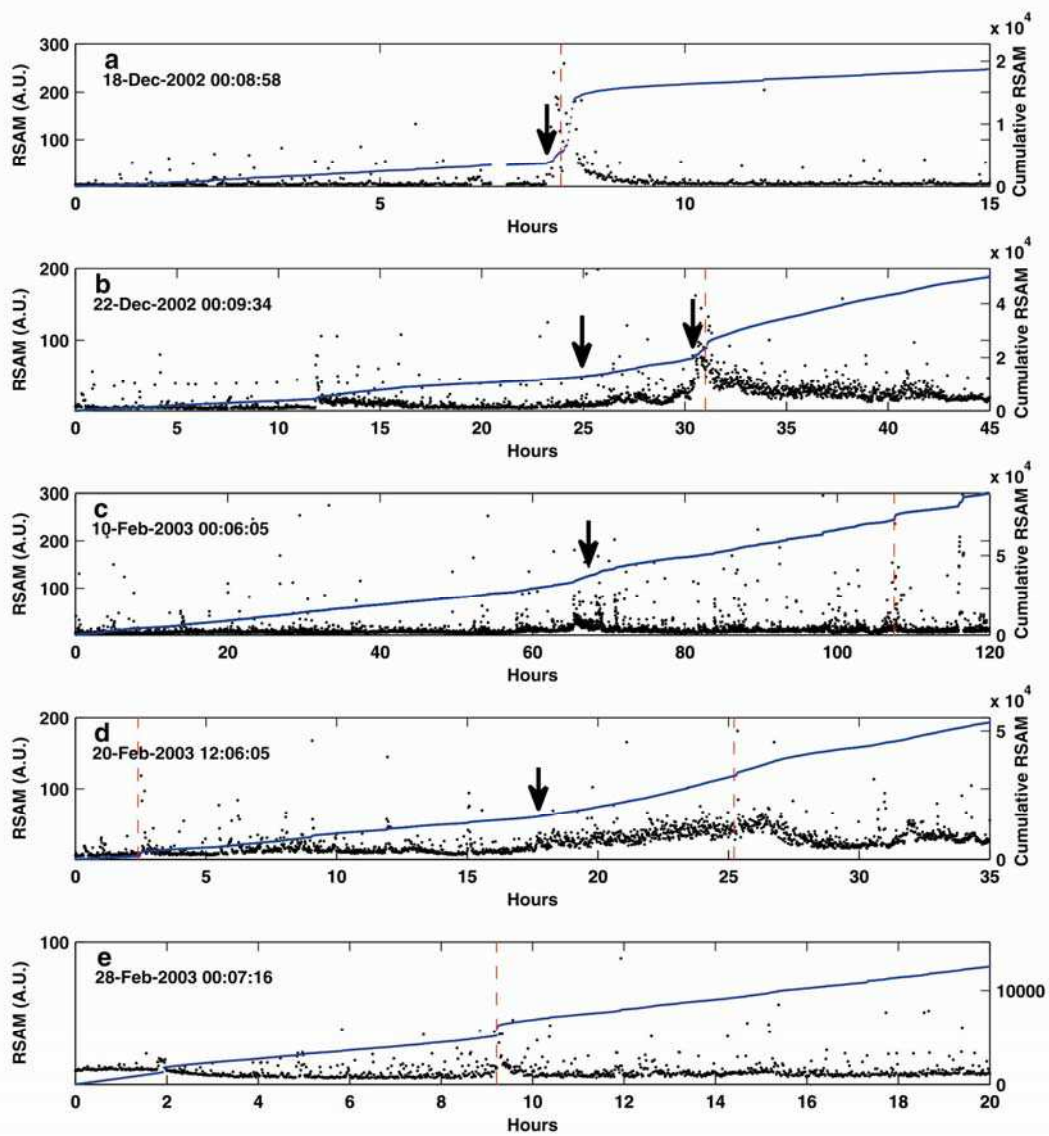
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826 Quezada-Reyes_etal_Figure8.cdr

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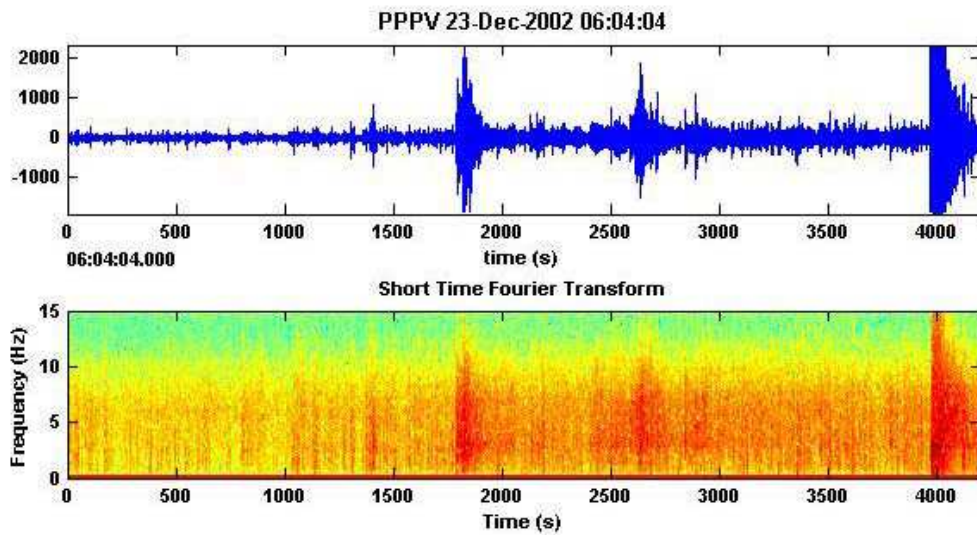


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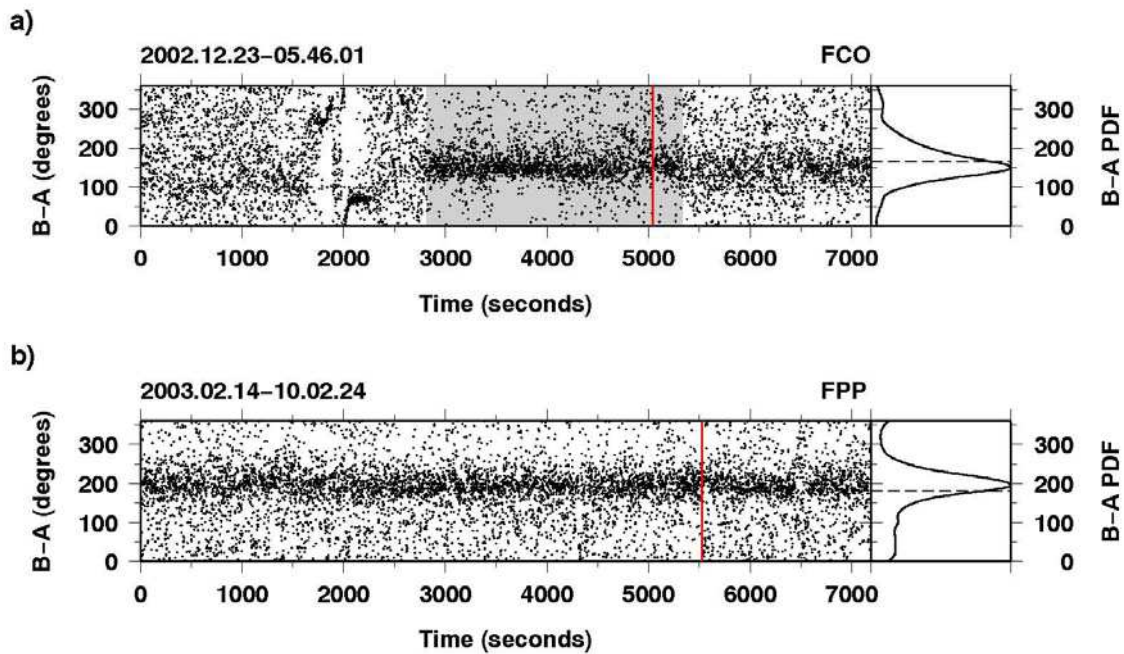
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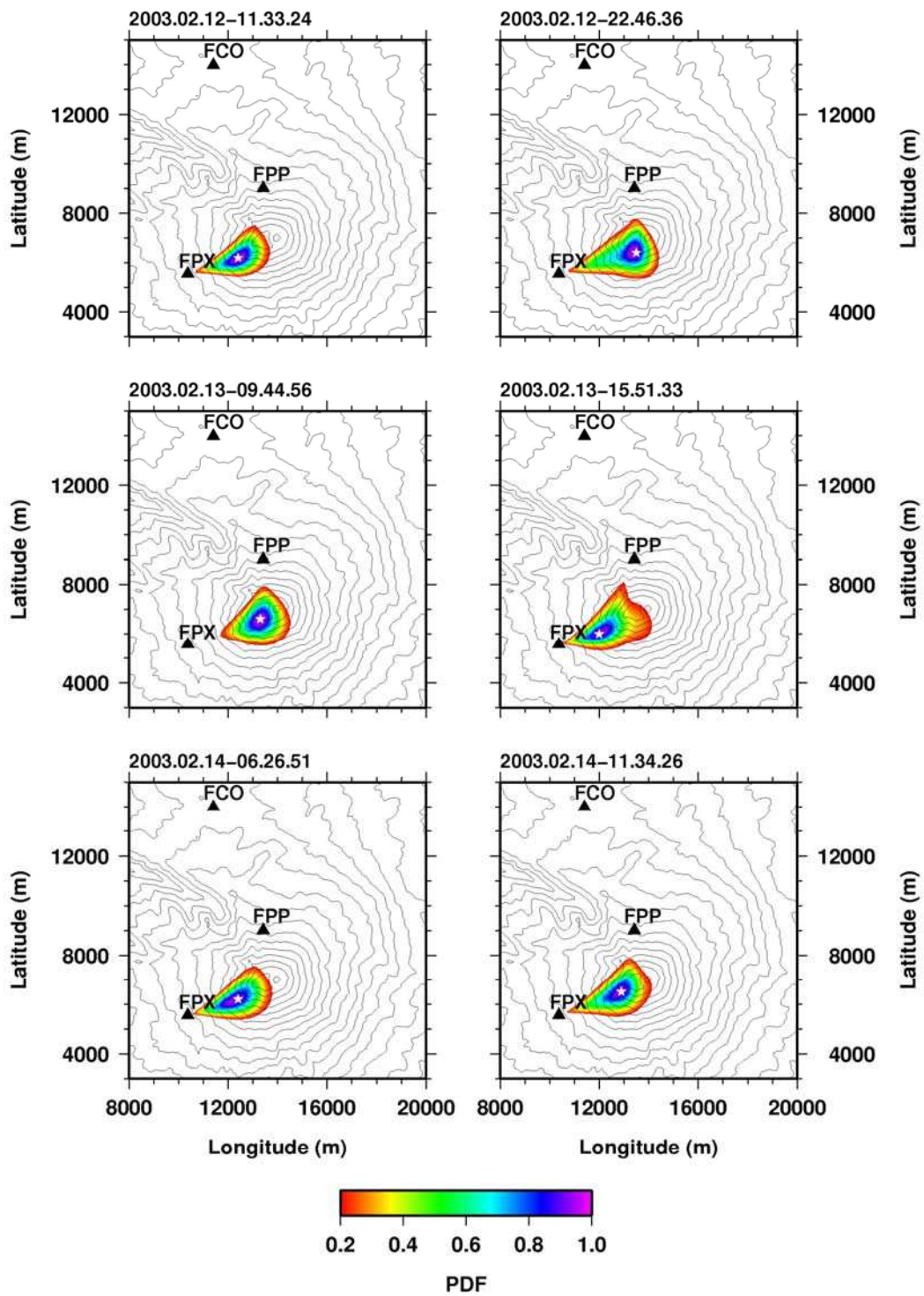
835 Quezada-Reyes_etal_Figure11.cdr



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838 Quezada-Reyes_etal_Figure12.cdr



839

840

841 Table 1

842

Date	Time	E/e	Precursors	VLP	Mk	Ek	Duration
Dec. 18, 2002	08:07	E	Yes	Yes		9,50E+07	540
Dec. 23, 2002	07:10	E	Yes	Yes	2,4	6,70E+08	40
Feb. 3, 2003	03:07	e	No	No		1,30E+06	210
4	10:59	E	Yes	Yes	2,9	1,20E+09	65
5	08:35	e	No	No		3,50E+05	180
5	14:53	e	No	No		3,00E+05	600
6	05:56	E	No	No		2,70E+05	150
7	14:00	e	No	Yes	1,4	9,40E+05	210
14	11:34	E	Yes	Yes	2,8	4,80E+08	80
16	19:02	e	No	No		1,20E+06	240
19	19:20	e	No	Yes		6,80E+05	430
20	14:30	e	No	Yes		6,30E+06	130
21	13:19	e	Yes	No		2,00E+06	190
22	08:39	e	No	Yes	2,8	6,60E+08	100
22	20:36	e	No	Yes	2,9	3,40E+08	135
23	19:01	e	No	Yes	2,8	5,40E+08	80
23	22:14	e	No	No		7,50E+05	390
28	09:15	E	No	Yes		1,60E+07	110

843

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