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Study of seismic activity at Ceboruco Volcano (Nayarit, Mexico) in the period 2012 to 2014

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ABSTRACT

Ceboruco volcano is a stratovolcano located in western central Mexico within the state of Nayarit. Ceboruco volcano is one of the active volcanoes of the Trans-Mexican Volcanic Belt and lies within the Tepic-Zacoalco Rift structure. Eruptions at Ceboruco volcano have been reported over the last 1000 years with eruptions every 126 years on average, with the most recent eruption occurring in 1870. Current activity at Ceboruco volcano is primarily fumarolic emissions. Continued population and socio-economic growth around the volcano over the last 20 years, make urgent the need to study Ceboruco volcano. Previous investigations of seismicity classified the recorded earthquakes into four families using waveform and spectral features. In this paper, we present a seismicity study from March 2012 to July 2014 using four portable seismic stations within the context of the regional stress and structures near Ceboruco volcano. Of the 489 volcanic earthquakes recorded during this time period, only 33 could be located using P- and S-wave arrivals registered at least three stations. The P- and S-phase arrival times were obtained using particle motion. The epicentral distribution of these earthquakes is around the volcanic edifice along three structural lineaments with preferred ENE-WSW orientations, roughly perpendicular to Tepic-Zacoalco Rift and, following the youngest deformation pattern. Hypocentral depths locate within first 10 km, indicating the earthquakes are a result of local tectonic stresses, intrusions into the magma chamber, or both.

1. Introduction

Ceboruco volcano (21° 07′ 30″ N and 104° 30′ 29″ W; 2280 mamsl) is located in central western Mexico, in the state of Nayarit, It is located at the northwestern edge of the Tepic-Zacoalco Rift (TZR), at the northwestern edge of the Trans Mexican Volcanic Belt (TMVB), close to the boundary between the Sierra Madre Occidental (SMO) (Fig. 1) (Allan, 1986; Michaud et al., 1993).

Two concentric horseshoe-shaped calderas form Ceboruco volcano, with one larger outer of and a second, smaller inner caldera (Rodríguez–Uribe et al., 2013; Browne and Gardner, 2004; Gardner and Tait, 2000). Within the inner caldera are several domes, and andesitic to basaltic lava flows and cinder cones comprise the edifice and have a generally NW-SE trend (Browne and Gardner, 2004; Gardner and Tait, 2000). Near the Ceboruco, there are small monogenetic volcanoes such as San Pedro Pochotero, El Comal, El Pinchancha, El Molcajete and El Pedregal. To the northwest, at 42 km, there is another volcano considered active in the area, the Sangangüey volcano (Fig. 1).

The activity of the Ceboruco volcano has been separated into four stages by Demant (1979), Nelson (1986) and Suárez-Plascencia (1998). The construction of the main edifice may have reached about 2700 mamsl, and is characterized by andesitic lavas without pyroclastic material between the flows, corresponding to the first stage. This cycle ended approximately 1000 years ago with a Plinian explosion of rhyodacite pumice (Jala eruption), which formed the first, outer caldera. The formation of the Dos Equis dacitic dome within the first caldera, which reached a size of 1.78 km in diameter and 280 m above the caldera floor, characterizes the second stage. Nelson (1986) proposed that the second, internal, caldera was formed by the collapse of the Dos Equis dome, but there is no agreement among researchers on the age or mechanism of this collapse (Thorpe and Francis, 1975; Luhr, 1978; Demant, 1979; Nelson, 1980).

The third eruptive stage began with the growth of an andesitic dome inside the inner caldera and included andesitic lavas eruptions, which are more acidic and rich in titanium and potassium oxides (Nelson, 1980). The fourth stage comprises the more recent eruptive processes originating in the inner caldera, including the extrusion of two dacitic domes and the lava flow of the 1870 eruption (Caravantes, 1870; Iglesias et al., 1877; Thorpe and Francis, 1975; Demant, 1979; Nelson, 1986).

Since the Jala eruption with a Volcano Explosion Index (VEI = 6) in the year 1065 ± 55 years (Sieron and Siebe, 2008), at least seven significant eruptive episodes took place (Nelson, 1980; Sieron and Siebe, 2008), including the formation of fifteen cinder cones. This number implies a mean of 126 years between eruptions; the most recent occurred in 1870–1872. Based on the types and frequency of eruptive

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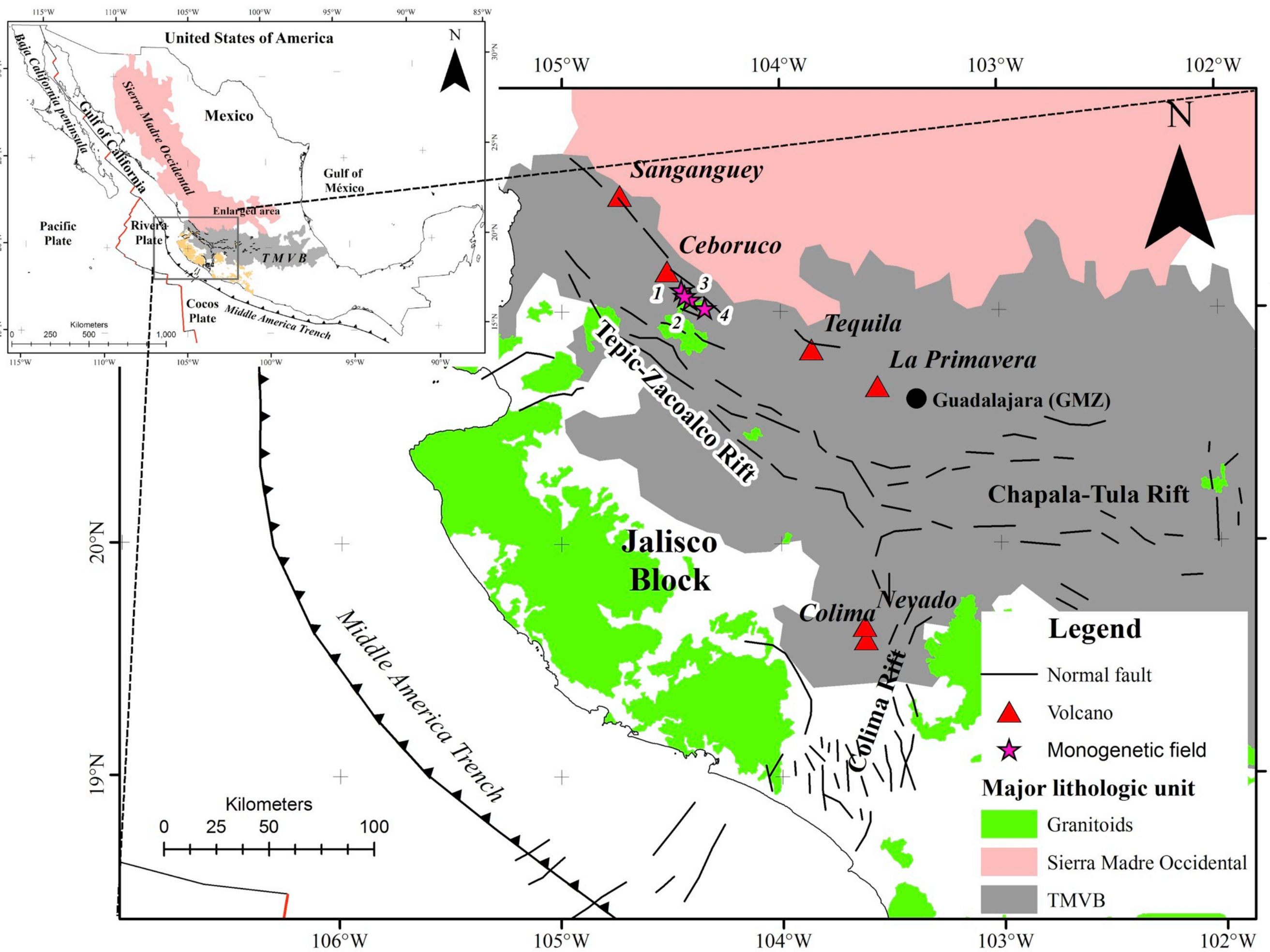

Fig. 1. Location of the study area and surrounding tectonic features. The enlarged figure shows the main normal faults associated with the Tepic-Zacolaco Rift and monogenetic volcanic fields indicated by red stars. The monogenetic volcanic fields have a NW-SE alignment and include: 1.- Pochotero, 2.- Molcajete, 3.- Pichancha and 4.- Pedregal. Significant stratovolcanoes in the region are indicated by red triangles. Other important regional structures include the Late Cretaceous-Eocene "Granitoids" (green shaded regions), the Oligocene-Miocene aged "Sierra Madre Occidental" (SMO) (pink shaded region), and the Late Miocene to Recent Trans Mexican Volcanic Belt (TMVB) (grey shaded region) (modified from Ferrari et al., 2005). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

episodes of this volcano, the volcanic hazards of Ceboruco are one of the greatest in Mexico and provide a compelling need for consistent volcano monitoring. Moreover, the continuous increase in population and socio-economic activities around the volcano necessitates a thorough evaluation of the hazards and risk similar to that done in Chile following the eruption of Chaitén volcano (Lara et al., 2006). In this paper, we present the first results of a systematic seismic survey of the Ceboruco volcano to characterize the seismicity and define its relationship with the main regional structural features.

2. Tectonic framework

The TMVB originated during the Middle Miocene and continues to the present (Gómez-Tuena et al., 2007; Ferrari et al., 2005, 2012). The volcanism along the TMVB is due to the subduction of the Rivera and Cocos plates beneath North America. The oblique position of the TMVB with respect to the Middle America Trench (MAT) gives rise to an intricate plate interaction that generates a complex magmatic history (Ferrari et al., 2005). The volcanic rocks have calc-alkaline to alkaline affinities, mafic to acid, together with the volcanic edifices ranging

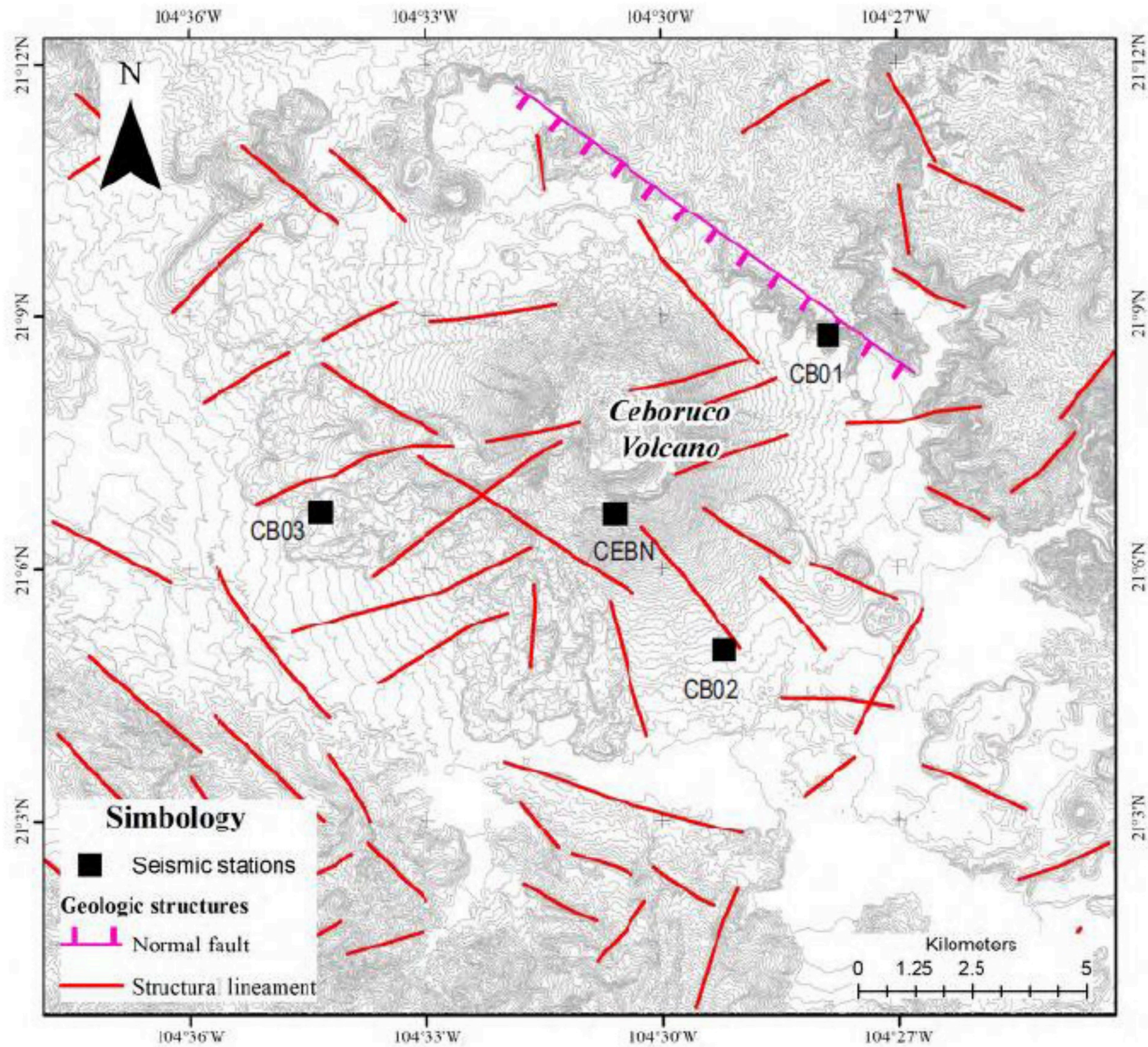

Fig. 2. Seismic network (black squares) and structural features of the study area. Structural lineaments (red) were interpreted from aerial photographs and the topography. The only normal fault (pink) on the map is from Ferrari et al. (2003). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

from stratovolcanoes to monogenetic volcanos and domes (Ferrari et al., 2005; Gómez-Tuena et al., 2007, 2016).

Deformation in the study area is to date associated with the TZR evolution. The origin of the TZR structure is associated with the opening of the Gulf of California during the Late Miocene (Ferrari et al., 2003). This rift has an NW-SE trending and is composed of segments of normal faulting, along some of which volcanism has occurred (Nieto-Obregón et al., 1992; Ferrari and Rosas-Elguera, 1999; Ferrari et al., 2003). The stress regime is extensional with σ_3 oriented towards the E-W to ENE-WSW with a lateral component (Nieto-Obregón et al., 1985; Rodríguez-Castañeda and Rodríguez-Torres, 1992; Duque-Trujillo et al., 2014). Whether the lateral component is right lateral (references) or left lateral (Ferrari et al., 2005) consistent with the Jalisco Block motion ~2 mm/year to the southwest (Selvans et al., 2011), local evidence of accommodation zones has been observed (Ferrari et al., 2005).

The NW-SE structures appear to have acted as pathways or conduits for magma ascent and emplacement at various scales, including monogenetic volcanoes, domes, and stratovolcanoes (Nelson, 1986; Ferrari et al., 2003; Sieron and Siebe, 2008). Volcanism along the TZR has occurred from the Pleistocene to Recent, including Ceboruco

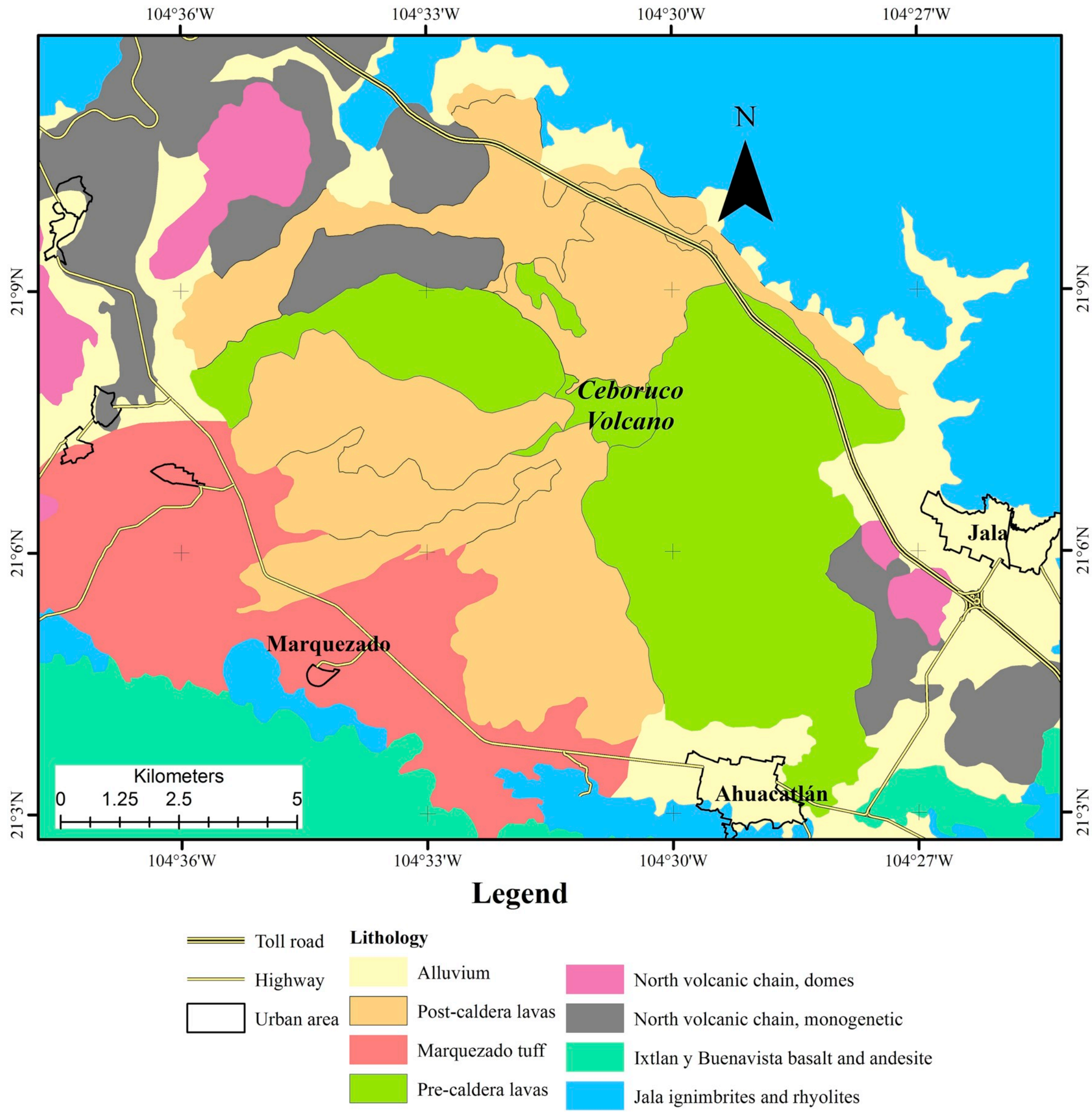

Fig. 3. Simplified geologic map of the Ceboruco Volcano, with names of the lithologic units after de Ferrari et al. (2003); Sieron and Siebe (2008). The subdivision of the Post-caldera lavas follows Nelson (1986).

volcano and its associated volcanic features. The initial stages of the geologic evolution imply that some volcanic episodes locate along the NW-SE trend of the TZR (Nelson, 1986; Petrone et al., 2001; Sieron and Siebe, 2008).

3. Structural features

The primary emphasis in previous Ceboruco volcano papers focused on the lithology and the evolution of this volcano. The structural features described the TZR, in a regional view, together with their tectonic implications; but local features were not described. Ferrari et al. (2003) described cinder cones and domes aligned WNW at the San Pedro-Ceboruco graben boundaries. They informally named as northern and southern volcanic chains whose emplacement is fault controlled. Though the main structural trend is NW-SE, it is not the only one; the tectonic history of the study area is complex since the Late Miocene and also exhibits faults systems oriented at N-S, NNW-SSE, E-W and ENE-WSW (Nieto-Obregón et al., 1985; Ferrari et al. 1994, 2012; Duque-

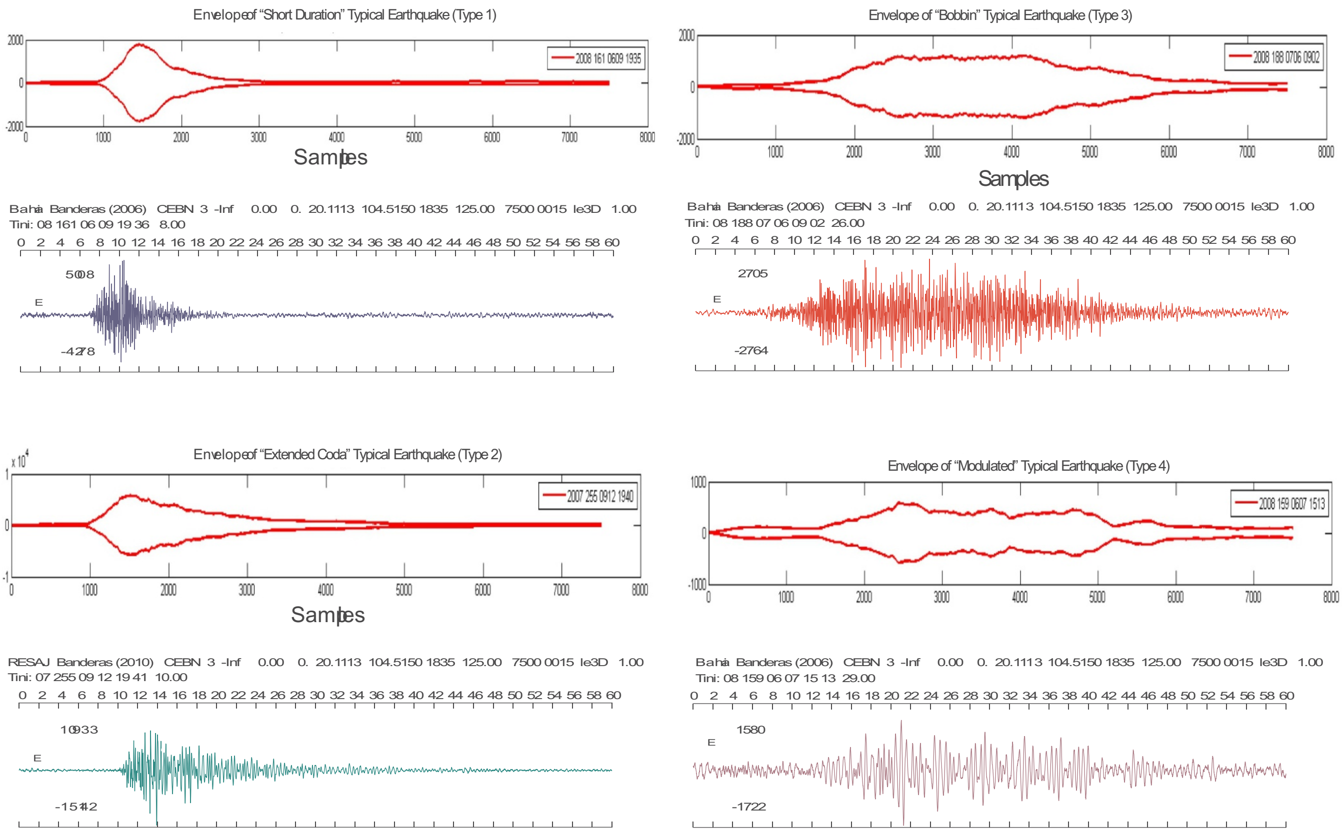

Fig. 4. Different types of low-frequency volcanic earthquakes at Ceboruco volcano recorded at CEBN as reported by Rodríguez-Uribe et al. (2013).

Table 1
Characteristics of the four types of families at station CEBN (Modified from Rodríguez-Uribe et al. (2013)).

	Type	Duration (s)	Dominant Frequency (Hz)	Frequency Range (Hz)
1	Short Duration	10–20	3–4	2–14
2	Extended Coda	40–60	2–3	1–6
3	Bobbin	20–70	7–9	2–14
4	Modulated	20–80	2–3	1–4

Table 2
Coordinates of RCEB stations.

Name	Longitude	Latitude	Altitude (m)
CB01	104°.4698	21°.1464	1420
CB02	104°.4918	21°.0836	1203
CB03	104°.5771	21°.1123	926
CB04	104°.5768	21°.1116	921
CEBN	104°.5152	21°.1114	1900

Table 3
P-Wave velocity model for Ceboruco volcano.

Velocity (Km/s)	Depth (Km)
2.5	0.0
3.0	2.0
5.9	5.0
6.2	8.0
7.0	19.0
7.7	36.0
8.0	42.0

Trujillo et al., 2014). It is beyond the scope of this paper to discuss the origin of each fault system; but we associate the last stage of faulting with the seismicity relevant to the current volcanic activity at Ceboruco.

The local structural features of the study area (Fig. 2) show two dominant trends, NW-SE and ENE-WSW. The NW-SE faults of Late Miocene (Selvans et al., 2011) are cross-cut by the ENE-WSW features of the Plio-Pleistocene (Ferrari et al., 2005). These fault systems intersect at the study area and may have provided a weak or tensional zone that enabled magma ascent and emplacement, including the formation of Ceboruco volcano. The role of pre-existing structures and the cross-cutting relationship between fault systems and magma movement to form volcanoes has been reported in other rift areas (e.g. Lloyd et al., 2018; Weinstein et al., 2017). The pre-existing structures are determinant in the emplacement of magma chambers and the development of volcanic structures, either monogenetic of stratovolcanoes. The tectonic setting and deformation style along the TZG are suitable for the magma ascent, and emplacement has been previously reported for the evolution of Ceboruco volcano (Nelson, 1986; Petrone et al., 2001; Ferrari et al., 2003; Sieron and Siebe, 2008).

4. Local geology

The stratigraphic sequence of Ceboruco volcano has been described with varying detail. This has promoted the use and abuse of the informal names for the lithologic units. The original description was associated with the evolution of the caldera (Nelson, 1986); afterward,

Table 4
Locations and uncertainty parameters for volcanic earthquakes (D: distance to the nearest stations; NR: number of readings).

Num	Y	MO	D	H	Mi	S	Lat	Long	Depth (km)	Mag	RMS(s)	ERH (km)	ERZ (Km)	Gap	D (km)	NR	Type
1	12	3	21	10	18	26.1	21.1130	−104.5205	−2.0	0.0	0.26	0.7	0.4	145	0.6	8	1
2	12	3	21	10	19	42.2	21.1198	−104.5158	−2.0	0.1	0.25	0.8	0.7	157	1.0	8	1
3	12	3	29	0	25	44.4	21 × 5380	−104.5078	−2.0	1.0	0.38	1.9	1.6	301	5.3	8	2
4	12	5	13	8	31	44.3	21.1500	−104.5552	−33	−0.1	0.08	0.8	0.4	287	4.8	6	2
5	12	5	14	20	33	44.0	21.0227	−104.5253	−3.7	1.7	0.05	0.9	0.3	304	7.6	6	4
6	12	5	20	3	33	24.7	21.1507	−104.5343	−3.9	0.2	0.40	2.4	0.9	228	4.8	8	4
7	12	6	14	20	14	8.3	21.0333	−104.5305	−0.1	0.9	0.28	0.9	0.8	295	6.9	8	4
8	12	6	23	2	30	12.5	21.1140	−104.4747	−0.3	0.9	0.07	0.2	2.5	200	3.6	6	1
9	12	7	5	20	34	34.6	21.0532	−104.4935	−3.4	0.8	0.33	3.9	1.0	327	3.4	6	2
10	12	7	17	0	55	10.7	21.1108	−104.4750	−1.4	−0.3	0.28	1.0	3.1	203	3.5	6	1
11	12	7	17	20	37	14.7	21.0548	−104.4935	−1.0	−0.3	0.21	1.5	0.8	327	32	6	2
12	12	7	20	4	37	24.4	21.1462	−104.5218	−0.4	0.3	0.16	0.8	5.5	280	3.9	6	2
13	12	7	24	20	27	23.3	21.0790	−104.6052	−15.0	1.7	0.26	9.3	7.3	335	10.5	6	4
14	12	7	24	20	28	40.7	21.0452	−104.5440	−0.1	1.0	0.38	1.3	0.9	330	6.8	6	4
15	12	7	29	6	46	10.5	21.1582	−104.4715	−5.2	1.1	0.37	3.9	2.9	288	1.3	8	2
16	12	7	29	6	57	13.3	21.1305	−104.5227	−0.6	−0.3	0.42	1.0	5.3	182	2.3	8	2
17	12	8	3	21	41	21.2	21.0933	−104.5785	−8.6	1.2	0.22	3.3	1.8	268	2.0	8	2
I8	12	8	10	21	5	3.4	21.0555	−104.4935	−79	2.0	0.31	3.5	3.1	292	3.1	8	2
19	12	8	21	21	3	52.0	21.0980	−104.5955	−22	0.8	0.24	1.5	0.7	315	2.6	8	2
20	12	8	24	8	48	51.6	21.1530	−104.5072	−43	0.8	0.15	0.8	0.3	223	3.9	8	2
21	12	8	27	19	33	29.6	21.0428	−104.5088	−4.4	1.3	0.34	2.7	0.8	296	4.9	8	2
22	12	8	27	12	36	57.5	21.0950	−104.5653	−83	02	0.03	1.0	0.6	225	2.1	6	2
23	12	10	24	8	48	51.7	21.1522	−104.5160	−1.3	0.5	0.17	0.2	2.2	223	4.5	8	1
24	12	10	31	0	33	33.5	21.0577	−104.5045	−8.6	1.1	0.26	2.9	2.5	284	3.2	8	4
25	12	10	31	1	6	35.3	21.0413	−104.5027	−4.4	0.4	0.31	2.5	0.7	302	4.8	6	4
26	13	1	21	16	24	28.5	21.1163	−104.4715	−22	−0.5	0.17	0.7	2.9	207	3.3	6	1
27	14	2	2	6	30	28.0	21.1145	−104.5250	−12.0	0.7	0.03	0.7	0.4	284	1.1	6	4
28	14	2	3	5	53	24.5	21.0395	−104.4223	−23	0.4	0.06	1.0	0.3	327	8.7	6	1
29	14	2	4	0	39	48.5	21.0820	−104.4807	−7.7	0.5	0.07	1.1	0.8	271	1.2	6	4
30	14	5	20	3	33	24.7	21.1450	−104.5442	−1.8	0.1	0.08	0.3	0.2	228	45	8	1
31	14	5	21	5	5	185	21.1412	−104.5472	–4X5	0.5	0.45	2.5	1.1	308	4.7	6	4
32	14	6	17	8	12	23.1	21.0980	−104.5482	−9.0	0.8	0.40	0.8	0.4	192	3.3	6	1
33	14	7	5	18	24	34.2	21.1593	−104.5108	−2.7	0.8	0.08	1.1	0.4	309	6.3	6	4

the lithology was redefined with on the basis of stratigraphic relationships, geochemistry, and age (Petrone et al., 2001; Ferrari et al., 2003; Sieron and Siebe, 2008). The original division included 19 informal lithodemic units (Nelson, 1986), whereas the currently accepted one only has eight (Ferrari et al., 2003; Sieron and Siebe, 2008). The actual division reflects the geochemical affinity of the lavas and their geochemical association with the change in the tectonic regime.

In Fig. 3 are shown the stratigraphic sequence of Ceboruco volcano (Ferrari et al., 2003; Sieron and Siebe, 2008). In the vicinity of the volcano, the lithologic units range in age from Pliocene to Recent. The oldest corresponds to the ignimbrites and rhyolites of the Jala unit of 4.9 to 4.1 Ma (Ferrari et al., 2003). The Jala unit is overlain by the Ixtlán and Buenavista basalt and andesite unit of 3.8 Ma that outcrops to south of the volcano. Ceboruco volcano development began ~50 ka with the extrusion of the monogenetic volcanoes and domes of the northern volcanic chain. These structures appear to have been emplaced along regional structures because they trend NW-SE. The earliest stages of evolution of Ceboruco volcano are recorded by the ~45 ka the Pre-caldera lavas; this unit forms the main structure of the stratovolcano. At ~1 ka the Marquezado tuff was erupted through domes of the southern flank of the volcano. The final stage of development is composed of the post-caldera lavas, and within this unit is the youngest (1870) lava flow that was erupted from the SW flank of the volcano.

5. Seismicity background

The first local studies of seismicity at Ceboruco Volcano were conducted in 1993–1994 with the installation of a temporary network composed of 2 MQ Spregnether analog stations and 2 Lennartz Mars88 digital stations with Le-3D sensors. Between 1996 and 1998, the BloJal Project (Núñez-Cornú et al., 2002) was carried out to study seismicity in

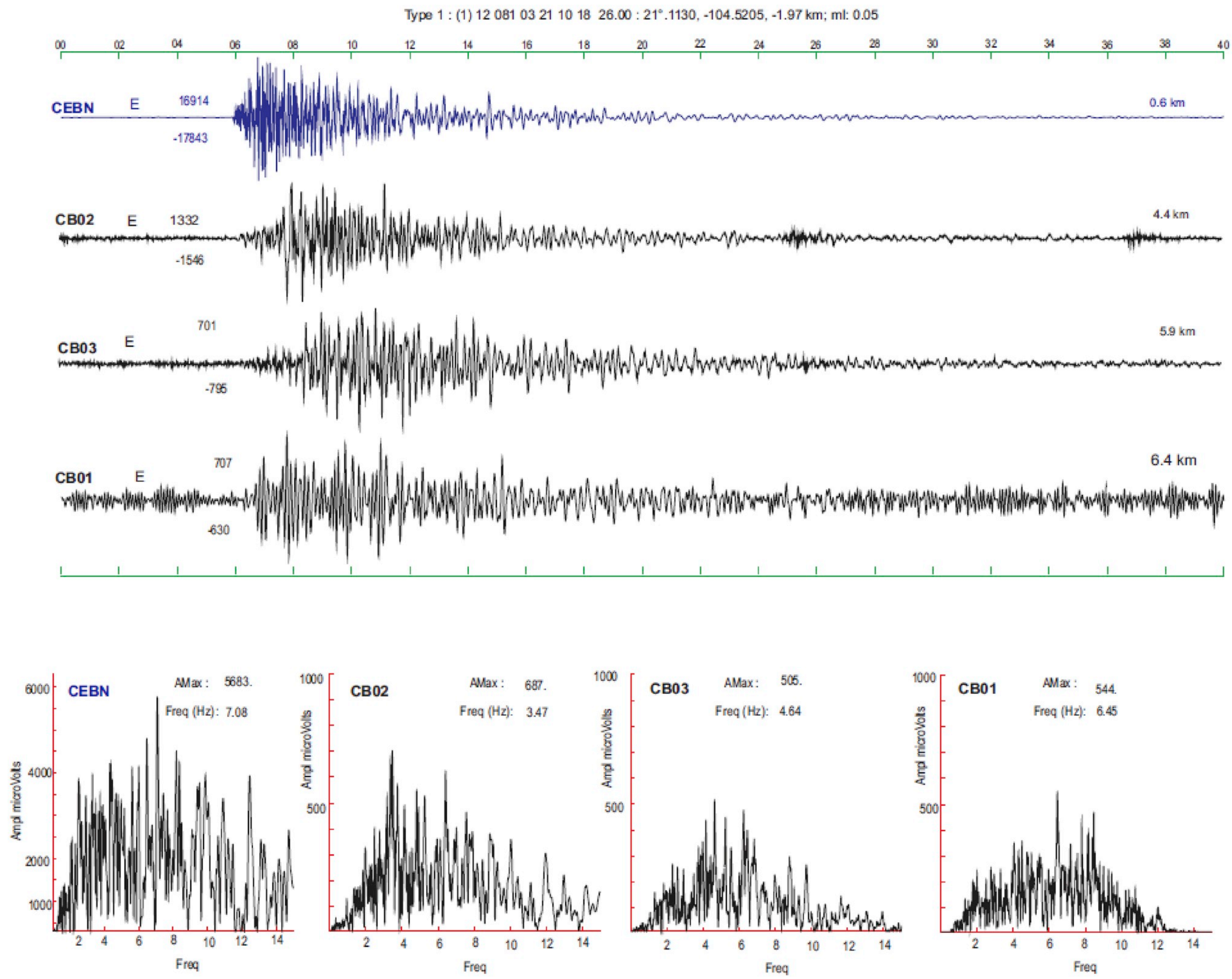

Fig. 5. Volcanic low-frequency earthquake Type 1 as recorded at station CEBN and the other stations of the RCEB network.

the Jalisco Block using 5 Lennartz Mars88 stations with Le-3D sensors in different network arrangements for different periods. As a result of the BloJal Project, Nava et al. (1997) and Núñez-Cornú et al. (1999) identified seismic activity at Ceboruco volcano.

In 2002, as a result of an agreement between the Research Group CA-UDG-276 - Centro de Sismología y Volcanología de Occidente (SisVOc) of the Universidad de Guadalajara and the Unidad Estatal de Protección Civil de Nayarit, a semi-permanent autonomous seismic station was installed on Ceboruco Volcano (CEBN). This station was located on the south flank of the volcano, the equipment used was a Lennartz MARSLite seismograph with Le3D 1 Hz sensor, 125 Hz sampling rate, and a GPS that synchronizes time every 3 h. The objective of this project was to establish the background seismicity of Ceboruco volcano, and classify the earthquakes by type. It was not possible to operate the station continuously due to power problems and vandalism; this station worked until 2009.

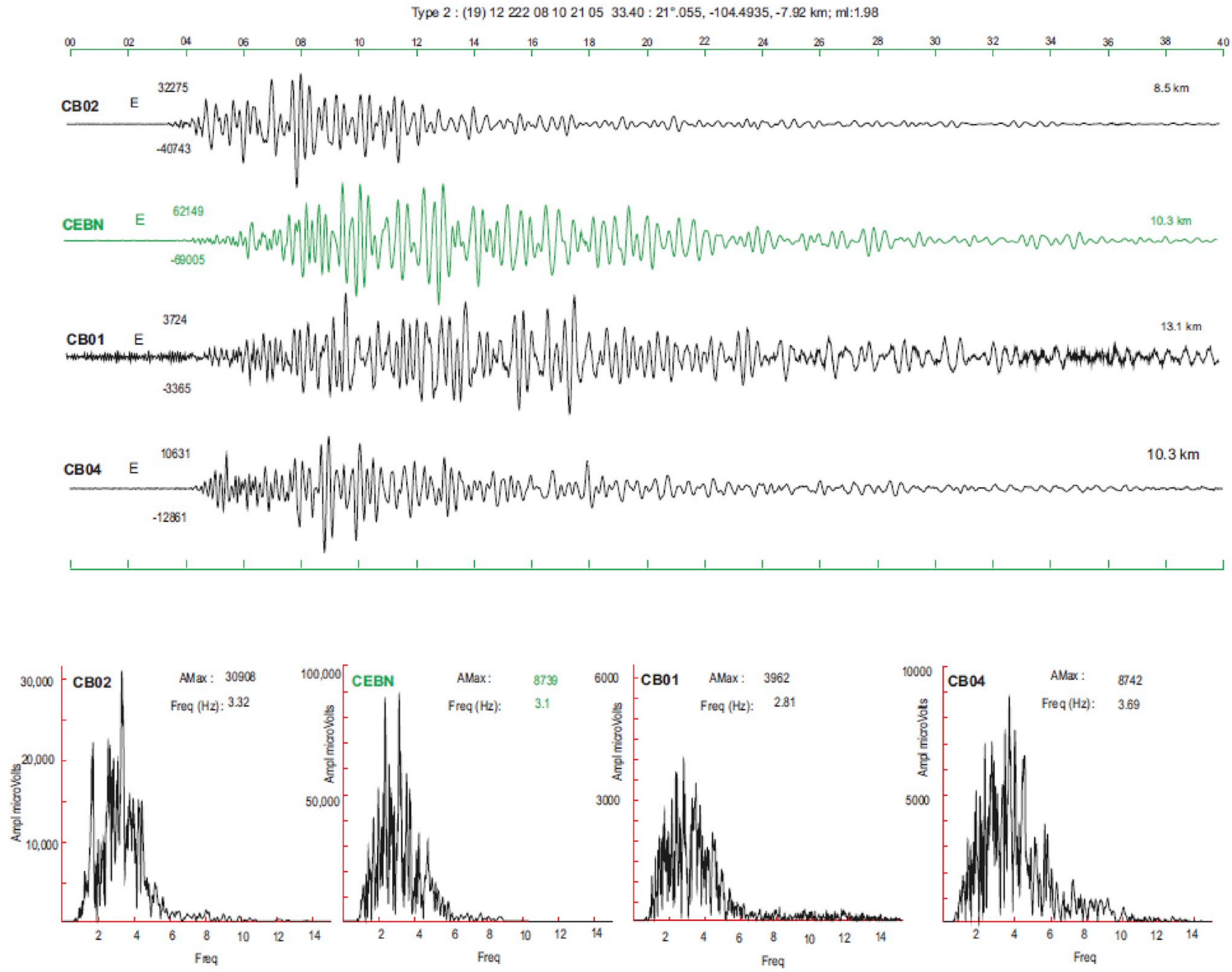

Fig. 6. Volcanic low-frequency earthquake Type 2 as recorded at station CEBN and the other stations of the RCEB network.

Using the best data available from the CEBN station for the period 2003–2008, Sánchez et al. (2009) studied the seismic events at Ceboruco volcano and identified volcano-tectonic (VT), low frequency (LF) and hybrid earthquakes according to McNutt (2000). These authors calculated a seismicity rate for VT earthquakes of 0.43 earthquakes per day (13 per month); and for LF earthquakes, 0.31 earthquakes per day (9 per month). They mainly analyzed VT earthquakes; using location techniques for a single three component station (azimuth and amplitude of the first arrival, and value of S-P). Sánchez et al. (2009) found that most of the epicenters were distributed within a radius of 6 km around the station (2.5 km to the SW of the summit).

Using the Sánchez et al. (2009) database, Rodríguez-Uribe et al. (2013) studied the LF or b-type earthquakes (Minakami, 1974) of Ceboruco volcano. These authors reported that earthquakes had a wide range of forms, durations, and spectral contents; however, these earthquakes were subclassified into four groups or families according to similar characteristics in the time and frequency domains: Short Duration, Extended Coda, Bobbin and Modulated Amplitude (Fig. 4;

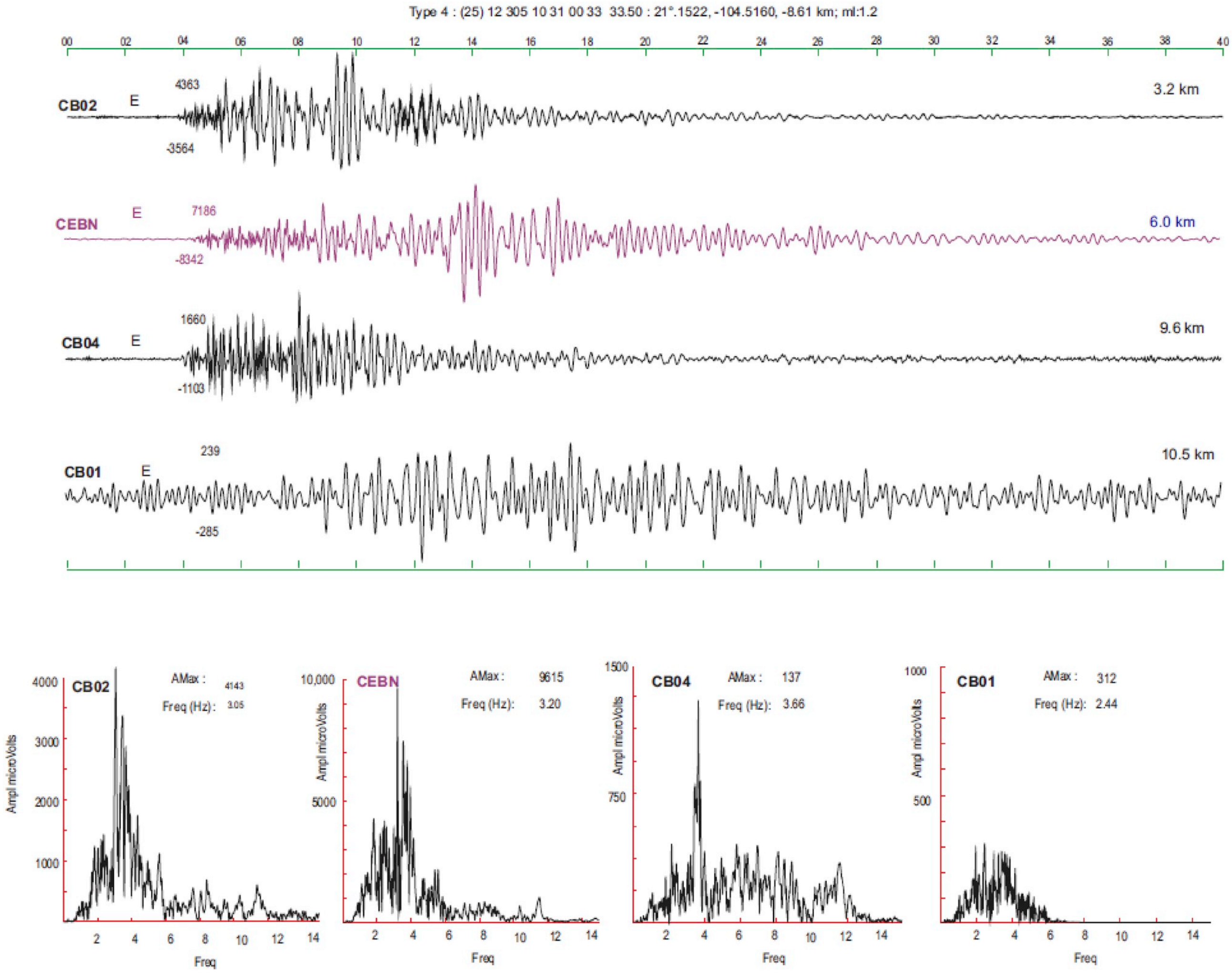

Fig. 7. Volcanic low-frequency earthquake Type 4 as recorded at station CEBN and the other stations of the RCEB network.

Table 1). Rodríguez-Uribe et al. (2013) located (see Fig. 11 of Rodríguez-Uribe et al., 2013) the low frequency earthquakes described by Sánchez et al. (2009) and found that most of the epicenters were randomly distributed within a radius of 9 km around the station. The complete set of seismograms, spectra, spectrograms, and determinations of particle movement can be found in Rodríguez-Uribe (2012).

6. Present study

In March 2012, SisVOc installed a temporary seismic network in the Ceboruco region (RCEB) with four seismic stations; three of them were installed according to the epicentral distribution obtained by Rodríguez-Uribe et al. (2013), and CEBN was reinstalled at the previous location. Each station includes a digital acquisition system TAURUS of Nanometrics and a Lennartz 3D lite (1 Hz) seismometer (Table 2, Fig. 2). The batteries were changed and data collected monthly. The aims of this network were: i) establish the average seismic activity rate; ii) obtain reliable hypocentral locations for the period of time studied; iii) use hypocentral locations to identify seismic sources; and, iv) characterize these sources based on their waveform characteristics, using the Rodríguez-Uribe et al. (2013) classification.

For this study, the area between latitudes 21°N and 21.3°N and longitudes 104.3°W and 104.7°W was considered. For the 29 months of March 2012 to July 2014 of this study, there is only information in 15

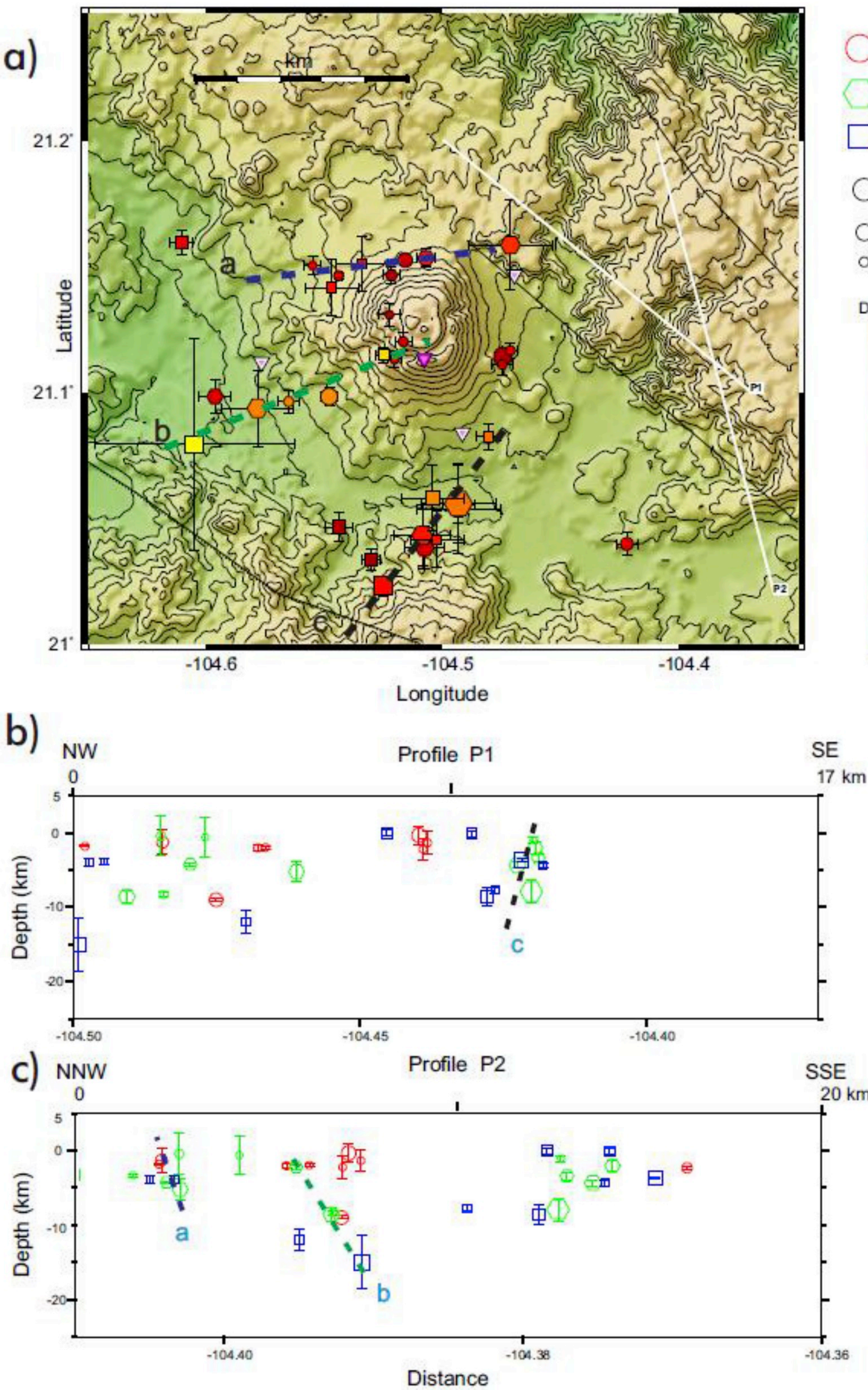

Fig. 8. a) Map of located epicenters for the period of study, with different types of volcanic earthquakes indicated by different symbols, and different depths indicated by colors shown in the color bar; epicentral error (ERH) bars marked. Proposed structural lineaments are indicated by dashed lines. b) Hypocenters projected along profile P1. Depth error (ERZ) bars marked; c) Hypocenters projected along profile P2. Depth error (ERZ) bars marked. In both b) and c), the proposed alignments are shown as dashed lines and marked as “a”, “b” and “c”.

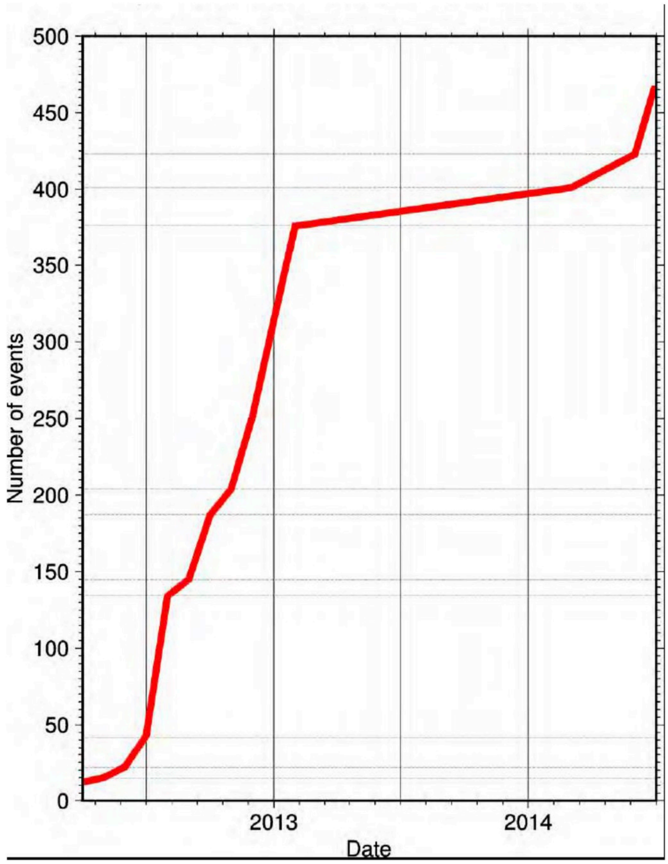

Fig. 9. a) Cumulative number of seismic events (all types) for periods between 2012 and 2014.

months, mainly due to technical problems including power failure, GPS failure, cable damage due to fauna or vandalism. Specifically, the records for March and April 2012 were partial. Until June 2012, stations CB01, CB02, CB03 and CEBN were operational, but on July 2012, CB03 suffered vandalism and had to be relocated to the new position of CB04.

The recorded data were integrated into a database using the Antelope system (Lindquist et al., 2007). The local events were reviewed directly using this system. A total of 489 possible volcanic events were identified, of which 291 were recorded at a single station, 52 at two stations, 109 at three stations and 37 at four stations. It is important to mention that during the period in which our stations were operating, the new Puerto Vallarta – Guadalajara highway was built, including a section across the southern part of the volcanic edifice, and for which blasting was required. We located only the events recorded by three and four stations. After eliminating the blasts, regional tectonic earthquakes, lightning, and other spurious signals, we obtained only 33 volcanic earthquakes that could be located, mainly due to the poor signal/noise of station CB01 station, for which phases of the smaller events could not be confidently read.

We read the P- and S- phases using particle motion, following Rodríguez-Uribe et al. (2013), and located the earthquakes using Hypo71 (Lee and Lahr, 1972). We adjust the MVC01 Colima Volcano V_P velocity model (Núñez-Cornú et al., 1994) (Table 3) for the study area, and used seven different trial depths as initial solutions to obtain the best residuals. The initial values solutions parameters accepted were: Root Mean Square (RMS) of time residuals was less or equal to 0.50 s; and standard errors of the epicenter (ERH), which represent the horizontal projection of the major axis of the uncertainty ellipsoid, and standard errors of the focal depth (ERZ) of less than 5.0 km. However, the error values obtained are lower, except for the deepest event (15 km). Of the total events, 32 earthquakes had ERH values than 4.0 km of which the 88% were less than 2.5 km, and ERZ values less than 5.5 km of which the 88% were less than 2.5 km (Table 4).

The local magnitude was calculated using the equation proposed by Lay and Wallace (1995) using the hypocentral distance to each station. In general, the magnitude values of each earthquake calculated in each station agree, however we observed consistent amplification at station CEBN. For CEBN, if we divided by a factor of two, the results were within the range of the other three stations. Finally, the magnitudes obtained at each station for each earthquake were averaged, and magnitude values range from −0.5 to 2.0.

7. Results

We found that only three types of volcanic earthquakes - 1, 2, and 4 - could be located (Figs. 5–7). Most of the located earthquakes occur, as in Rodríguez-Uribe et al. (2013), in a radius of about 9 km from station CEBN (Fig. 8a); we do not observe any patterns in the depth or location for the different types of volcanic earthquakes. Most of the hypocenters are shallow, between 0 and 10 km depth (Fig. 8b and c).

From Figs. 5–8, it is apparent that there are strong path and or site effects that alter the appearance of the waveforms. From Fig. 8a and profiles in Fig. 8b and c it is possible to infer three alignments (a, b and c) consistent with mapped structural lineaments (Fig. 2). Two intersect with the edifice of Ceboruco volcano and have ENE-WSW preferred trend ("a" and "b", Fig. 8a). While the third one, locates at the SE edge of the volcano, and is NE-SW oriented ("c" in Fig. 8a). Despite the slight differences in orientation, they all are roughly perpendicular to the TZR direction. During this period, a large part of volcanic earthquakes occurred in swarms separated by one or two days (Fig. 9). Among the locatable earthquakes, eight episodes could be identified (not all the earthquakes of each episode could be located, mainly due to their sizes). Within the same episode, we can find earthquakes of different types locate on different alignments (Fig. 10a–c, Table 4).

8. Discussion

In Fig. 2, the structural lineaments around the volcano have two preferred trends, NW-SE and ENE-WSW. Most of our located epicenters and inferred alignments seem to occur along the ENE-WSW structures (Fig. 11). In this Fig. 11, the interpreted structural trends show the dip direction of the structures (brown arrows), like those for normal faults, as suggested by the regional deformation pattern. These would form a graben-like structure at the SE edge of the volcano while most of the Ceboruco volcano would be built at the NW block.

Furthermore, the ENE-WSW and NE-SW proposed faults are parallel to the Plio-Pleistocene preferred trend along the TZR. On the basis of a

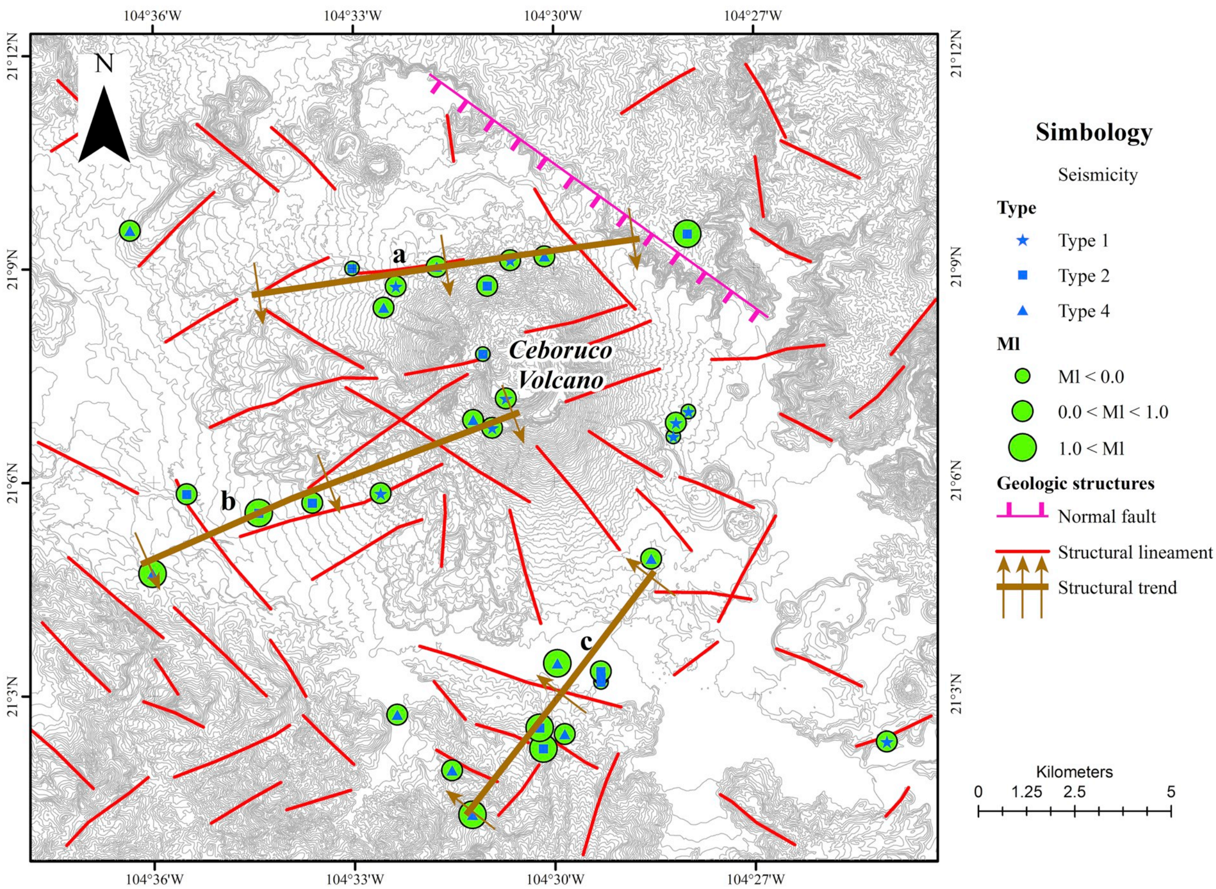

Fig. 10. a) Map of epicenters located in the studied period, with different types of volcanic earthquakes indicated with different symbols, time sequence in colors; b) Hypocenters projected along profile P1; c) Hypocenters projected along profile P2. Suggested alignments marked. Seismic episodes identified (e1, e2, e3, e4, e5, e6, e7, e8), Table 4. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

combined geologic and structural analysis, Duque-Trujillo et al. (2014) suggested that these trends could be basement-reactivated structures. Our new seismic evidence suggests fault reactivation along the main graben structures.

9. Conclusions

The volcanic seismicity located in this study seems to be related to structural features on the volcanic edifice, although there is no common seismic location for each of the different types of volcanic earthquakes observed; each type of seismicity occurs on different structural features throughout this study. The epicentral distribution could be interpreted to be consistent with the reports of Iglesias et al. (1877) regarding the existence of several vents for the expulsion of magmatic material in the 1870 eruption. The seismicity related to the magmatic processes seems to be located along reactivated ENE-WSW structures in a weakness area of the TZR. The seismic episodes could be the result of local tectonic stresses that affect the entire volcanic edifice. A permanent seismic network with a broader distribution of stations should be deployed to monitor Ceboruco volcanic seismicity and better understand its rates and earthquake types. Only with an understanding of the background rates and types of seismicity, can responsible authorities determine when a volcano is entering a period of unrest or eruption.

Data and resources

All seismic data collected by RCEB are in a database at CA-UDG-276 SisVOc Research Group. The data may be available for use in collaborative research projects between SisVOc and other interested institutions by specific agreements. For information, contact pacornu77@gmail.com.

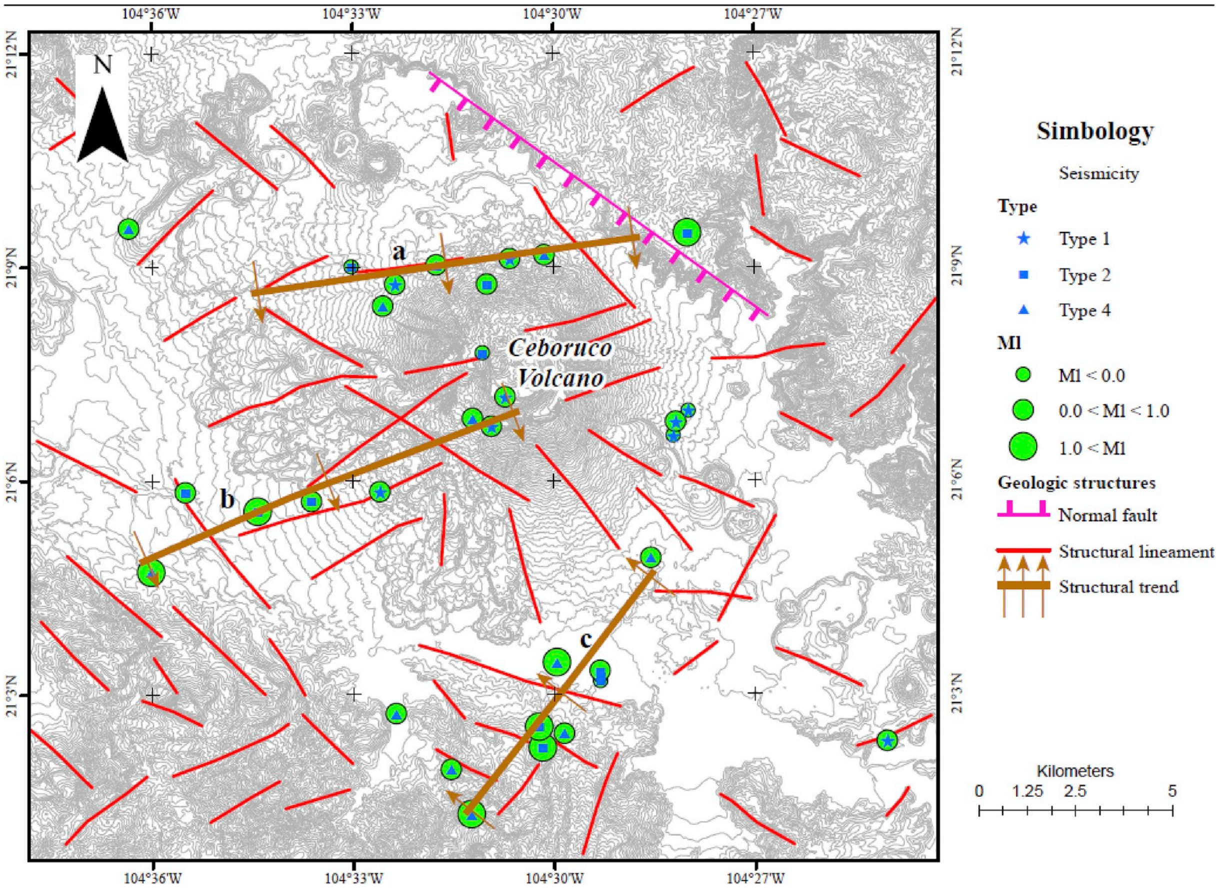

Fig. 11. Map of Ceboruco volcano region with structural features from Fig. 2 marked in red and pink. Located epicenters indicated by different type and magnitude indicated by the size of the green circle. Inferred alignments indicated by brown lines with arrows. The arrows along the structural trends indicate the dip direction of the structures interpreted in this study. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

CRediT authorship contribution statement

Francisco Javier Núñez-Cornú: Conceptualization, Supervision, Project administration. **Felipe de Jesús Escalona-Alcázar:** Investigation, Formal analysis, Writing - original draft. **Diana Núñez:** Investigation, Data curation, Writing - original draft. **Elizabeth Trejo-Gómez:** Visualization. **Carlos Suárez-Plascencia:** Formal analysis. **Norma Rodríguez-Ayala:** Data curation.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsames.2019.102473.

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