SHORT NOTE

Earthquake families in the seismicity of Popocatépetl volcano

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RESUMEN
El análisis de la sismicidad asociada al volcán Popocatépetl (Meseta Central, México) en el periodo 1 de septiembre a 31 de diciembre de 1995 permitió la identificación de 3 familias de temblores. El coeficiente de correlación encontrado para todos los miembros de las familias es mayor de 0.5 en todas las componentes de 3 estaciones cercanas a los epicentros. Los eventos de dos de las familias son de similar magnitud y ocurren dentro de un período relativamente largo. Esto sugiere que sean generados por la acción de una misma aspereza. Los hipocentros de los eventos se localizan bajo el edificio volcánico a profundidades de hasta 4 km bajo el nivel del mar y fueron generados probablemente por el paso de magma a través de los conductos volcánicos superiores.

PALABRAS CLAVE: Volcanes mexicanos, sismicidad volcánica, familias de temblores, volcán Popocatepetl.

ABSTRACT
Analysis of the seismicity of Popocatepétl volcano (Central Mexico) over the period September 1 to December 31, 1995, shows the existence of three earthquake families, with correlation coefficients better than 0.5 in all components of three stations. For two families the events have similar magnitudes and occur over a relatively long period of time. This suggests that they are of the asperity type. They occur up to a depth of 4 km below sea level underneath the volcano, and may be generated by the passage of magma through the upper volcanic conduits.

KEY WORDS: Mexican volcanoes, volcano seismicity, Popocatépetl volcano, earthquake families.

INTRODUCTION

Popocatépetl volcano in central Mexico (19.023 N, 98.622 W, 5465 m.a.s.l.) is the second largest volcano in the country. Rising at the margins of the valleys of Mexico and Puebla, the two most populated areas in Mexico, it poses the highest volcanic risk in the nation. This circumstance is clearly perceived nowadays due to its present stage of unrest, which began in late 1994, and is characterized by a persistent seismicity accompanied by explosions and frequent emission of ash. For these reasons, a systematic monitoring effort has been carried out by the National Center for Disaster Prevention (CENAPRED), an organism of the federal government in charge of the technical aspects of disaster prevention, in collaboration with the Institutes of Geophysics and Engineering of the National Autonomous University of Mexico (UNAM).

In all active volcanoes the forerunner, and most consistent process revealing their internal state, is the associated seismic activity. Thus, the monitoring activities to forecast volcanic behavior rely strongly on the observation of this phenomenon.

Some of the characteristics of the seismicity associated to the present stage of activity in Popocatépetl have been reported in several works (*i.e*. Valdés *et al*., 1995; Arciniega-Ceballos, 1997; Martínez-Bringas, 1998; Arciniega-Ceballos *et al*., 1999; Ortiz-Osornio, 2001). However, many aspects of the seismicity are yet to be studied.

In particular the existence of earthquake families, which have been observed in several volcanoes, had not been reported at Popocatépetl. In this paper we present a sample of such families as found in a small data set from the early recordings of the seismic activity (September 1 to December 31, 1995).

EARTHQUAKE FAMILIES

Earthquake families are sets of events with the same or very close hypocenters, and similar waveforms; features that suggest a common source. Earthquake families have been observed in tectonic and volcanic seismicity as outlined below.

Hamaguchi and Hasegawa (1975) located the aftershocks of the 1968 Tokachi Oki earthquake in Japan and noticed similar waveforms for events occurring roughly at the same depth. They concluded that the events were generated under the same mechanical conditions. Ishida and Kanamori (1980) found that 5 precursory events occurring some 2 years before the 1971 San Fernando earthquake had similar waveforms. Because the aftershocks did not show similarity with the foreshocks nor among themselves, they suggested this characteristic could be useful to discriminate foreshock sequences. Geller and Muller (1980) studied pairs of small earthquakes that occurred in November 1978 and December 1979 along the St. Andreas Fault, in Central California. They found that the events were similar at low frequencies and further deduced that those events occurred at distances not exceeding $\lambda/4$, where λ is the shortest wavelength in the similitude range. They further suggested a common asperity as the generating source, and proposed that this fact could be employed to target likely areas of future large events.

In the case of volcanic earthquakes, Okada *et al.* (1981) recognized sets of similar events in the seismicity associated to the 1977-78 doming activity at Usu volcano. In one of these sets the similitude included the amplitude, which varied little among the members of the family. Within a second group the amplitudes varied more than an order of magnitude but their spectra shared the same corner frequency. Aki (1984) proposed that the first class could be explained with the asperity model of Kanamori and Stewart (1978), and the second with the barrier model of Das and Aki (1977). Hence he applied the names of asperity-type and barrier-type earthquake families to such groups of similar earthquakes. Nishimura *et al.* (1992) further concluded that because the strength of the asperity and the dynamic friction are nearly constant the asperity-type families last for a relative long time with little change in magnitude, whereas members of barrier-type families occur successively in a short time, as the fault plane is broken heterogeneously

Mizukoshi and Moriya (1980) and Okada *et al.* (1981) observed asperity-type earthquake families during the 1977-1978-eruption period of Usu volcano. Fremont and Malone (1987) also reported earthquake families in the seismicity of Mount Saint Helens. Nishimura *et al.* (1992) analyzed 143 low-frequency events that occurred during the period January-February 1988 in Tarumai volcano, Japan, and found 21 earthquake families with hypocenters falling in small limited regions not wider than 50 m across.

The relevance of the existence of earthquake families in volcanic environments, particularly those of the tectono-volcanic type, has not been completely assessed, however it could offer clues to the understanding of the internal state of a volcano. It would be important to establish, for example, if earthquake families occur only during phases of overpressure in the magma chamber and not after decompression when the sudden accommodation of the country rocks leads to more chaotic faulting.

SEISMIC DATA AND METHOD OF ANALYSIS

Popocatépetl volcano began its present stage of unrest probably in 1993 but it was manifest around June 1994, with conspicuous fumarolic and seismic activity. Such behavior climaxed on December 21, 1994 with the first important ash emission in several decades. Prompted by such activity CENAPRED, in collaboration with UNAM, deployed a seismic network around the volcano. By August 1995, after several modifications, the temporal network became permanent and composed basically of the present-day stations: Altzomoni (PPAV), Tlamacas (PPM), Colibrí (PPC), Canario (PPP), Chipiquixtle (PPX) and Bonsai (PPBH). With the exception of Bonsai, which is equipped with a horizontal sensor and Altzomoni, which has a vertical sensor, the rest are three-component stations. Digital recording of the events (100 samples per sec) began on September 1, 1995. We were provided with data for the period beginning that date and ending on December 31,1995. Of 1033 events, 190 were recorded by at least 3 stations. All these events are A or volcano-tectonic type; thus, we read P and S phase arrival times and located the hypocenters with code HYPO71PC (Lee and Lahr, 1978) and the seismic model shown in Figure 1. This model was constructed from velocity models for the nearby Valley of Mexico (Havskov and Singh, 1978) for the shallower layers and by trial and error for the deeper layers. The model shown in Figure 1 yielded the lowest residuals.

Coda magnitude was obtained through the formula given by González-Ruiz, (1980):

$$M_C = 1.87 \log C - 0.86 ,$$

where C is the duration of the event in seconds. The comparison of the seismic waveforms was carried out at station PPPV (Canario) and confirmed at PPXV (Chipiquixtle). Of the 190 located events we selected 113 ($Mc>2$) that were suitable for comparison. Unfortunately the instruments were not calibrated and, therefore, the signals could not be deconvolved to obtain ground motion; however, since we are comparing records from the same stations and the events are not too far apart in time, similitude in the velocity records would not be downgraded in the displacement records. Following Pechmann and Kanamori (1982), the events were band-pass filtered in the range 1 to 16 Hz and then cross-correlated in the time domain through the standard formula:

$$C_{xy} = \frac{\left[\frac{1}{N-|m|}\right]\sum_n x(n)y(n+m) - \overline{x(n)y(n+m)}}{\sqrt{\overline{x^2(n)} - x(n)^2}\sqrt{\overline{y^2(n+m)} - y(n+m)^2}} ; n = \begin{cases} 0,...,N-m-1 & for \;\; 0<m \\ m,...,N-1 & for \;\; m<0 \end{cases}$$

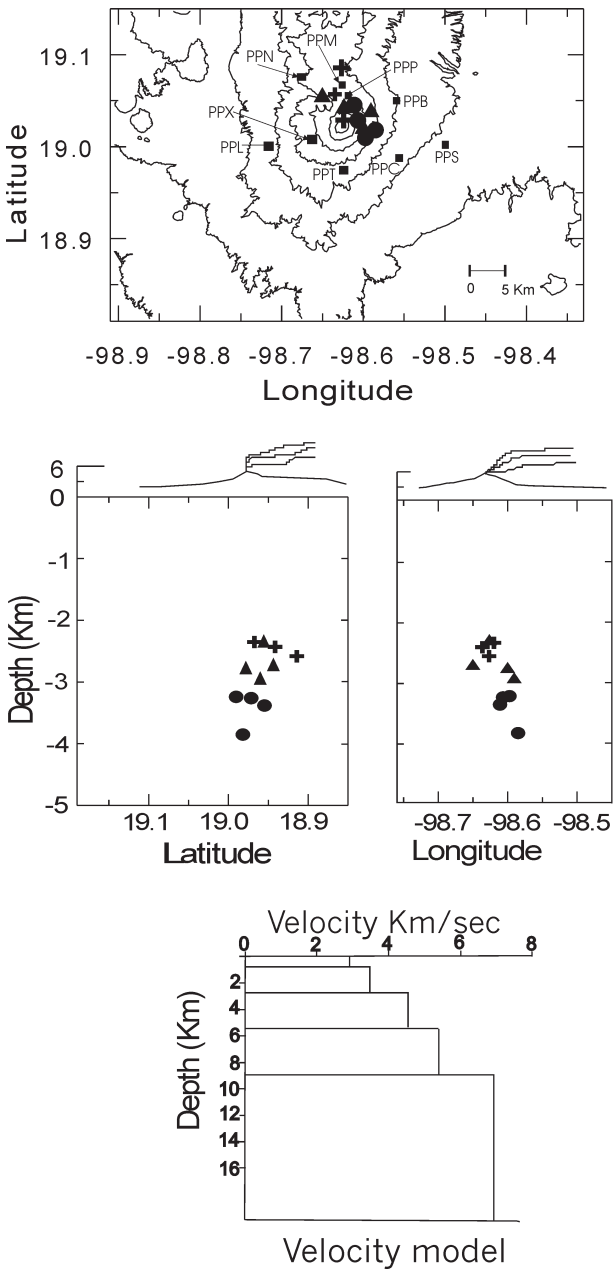


Fig. 1. (Top) Plane view of hypocenters of families 1 to 3. (Middle right) E-W section. (Middle left) N-S section. Symbols: filled circles, family 1; triangles, family 2; crosses, family 3; squares, seismic station. (Bottom) Velocity model.

In the above formula x and y are the two time series, N is their length, n the length of overlap, m the lag position and the bar indicates mean value. In order to avoid unnecessary operations the events were cross-correlated after a first selection via visual inspection.

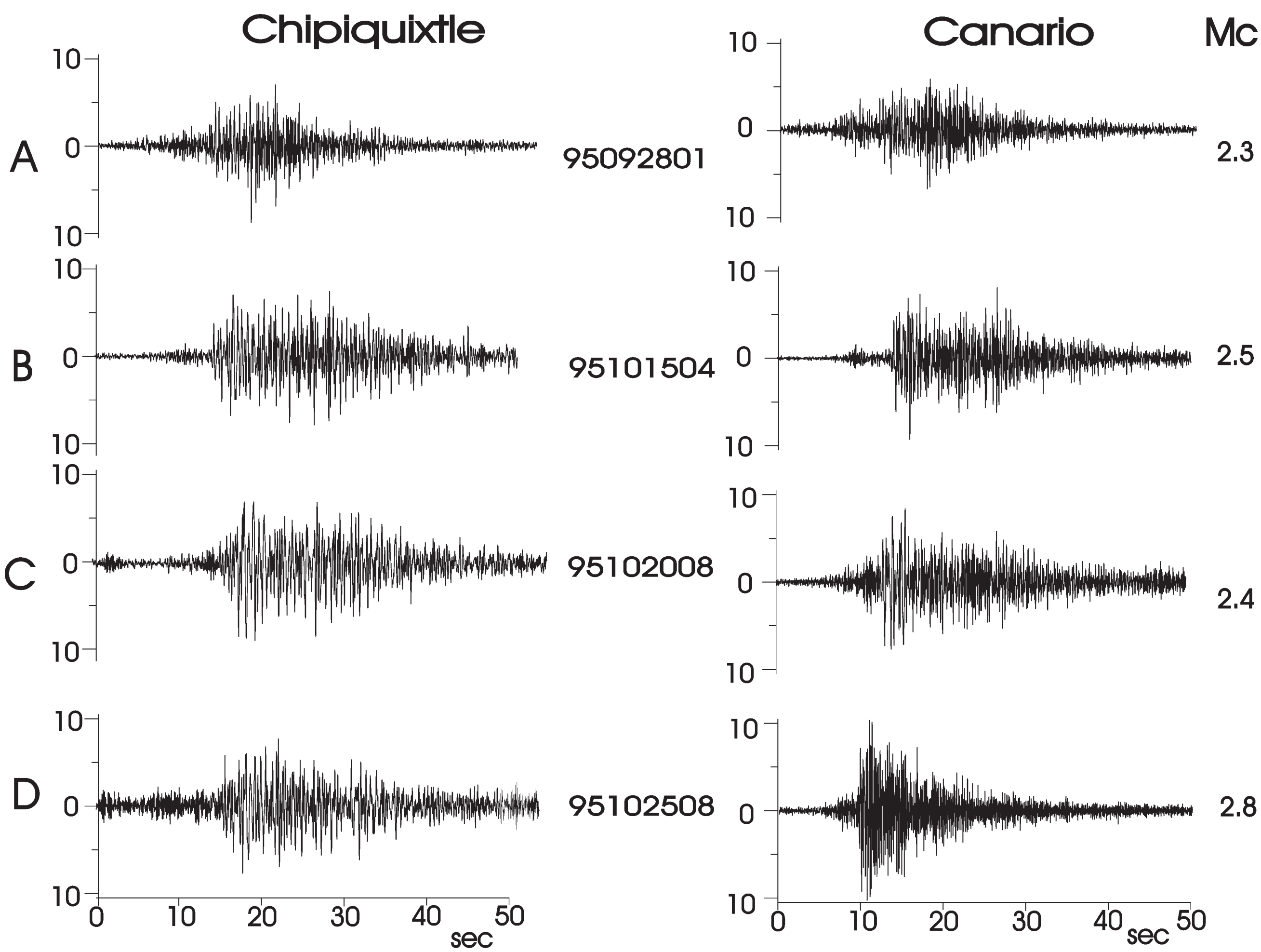
RESULTS AND DISCUSSION

We compared all 113 events on the 3 components of all stations. Our analysis yielded three earthquake families. The families, hereafter called families 1 to 3, are shown in Figures 2, 3 and 4 respectively. The cross-correlation matrices shown in these figures are the average values over the 3 components at the two stations shown. We show only these results for the sake of conciseness and because those stations are closer to the epicenters; for all families, however, the correlation values are similar, being in all cases greater case better than 0.5. Family 1 consists of events located at depths between 3 and 4 km below sea level. Events of families 2 and 3 are located between 2 and 3 km below sea level. For the range of frequencies considered in our scheme, values greater than 0.6 are considered good correlation values (Pechman and Kanamori, 1982; Nishimura *et al.*, 1992). We consider values of 0.5 between pairs of stations acceptable when the events correlate at a good level with the other events of the family. The hypocenters of the members of these families are shown in Figure 1 and the errors in the locations in Table 1. To further check the similarity of events in each family we computed the amplitude spectra of the z component at PPX and PPP. We note that some spectral peaks are present at the same site for two families. For example, the peak at approximately 4 Hz is present at PPX (thin curves) for families 1 and 2 events. This suggests a site effect. On the other hand, some spectral peaks are conserved at both stations although weighted differently. Thus the spectra in Figure 5 are product of the similarity in the source spectra of the events of each family, and the site effect of each station.

It is difficult to establish the correspondence of the families reported here to any of the types mentioned above because the period analyzed is small, although the variation in the spectral amplitude of the events of families 1 and 2 is not large. Nevertheless, since both processes arise from overpressure in the magmatic system, earthquake families, particularly those of the long lasting asperity-type, could serve as the system's pressure gauges if a causal relationship can be established with an eruption. This would require the analysis of the seismicity leading to an eruption along these guidelines. The purpose of this research note is to call attention to this aspect of the seismicity.

A gravity model presented by Mena *et al.* (1997) shows a body with a volume of about 18 km^3 and a density contrast of 400 kg/m^3, some 6 km below sea level. If this model of the volcano is close to reality and the body represents the magma chamber, then family 1 occurs at the top of the magma chamber and families 2 and 3 higher up, probably reflecting the stresses generated by the passage of magma in the volcanic conduits within the brittle upper medium.

As stated before, in order to obtain information on the pressure changes in the system from the behavior of the earthquake family, it is necessary to correlate the families' life span and event characteristics with the eruptive activity.

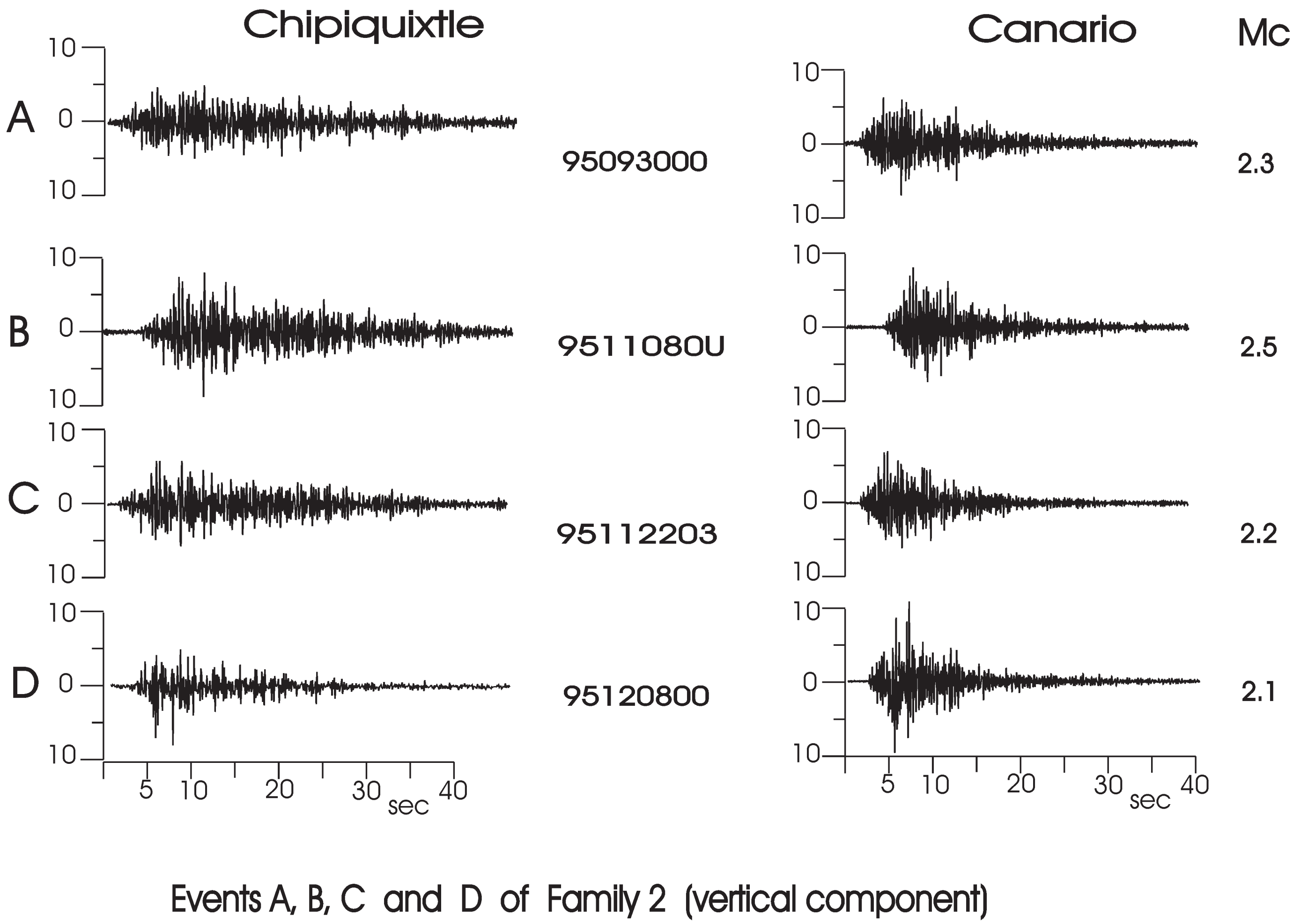


Events A,B,C and D of Family 1 (vertical component)

Correlation Values

	N	E	V
AB	0.52	0.59	0.52
AC	0.55	0.52	0.55
AD	0.51	0.53	0.65
BC	0.65	0.61	0.61
BD	0.65	0.55	0.71
CD	0.55	0.66	0.69

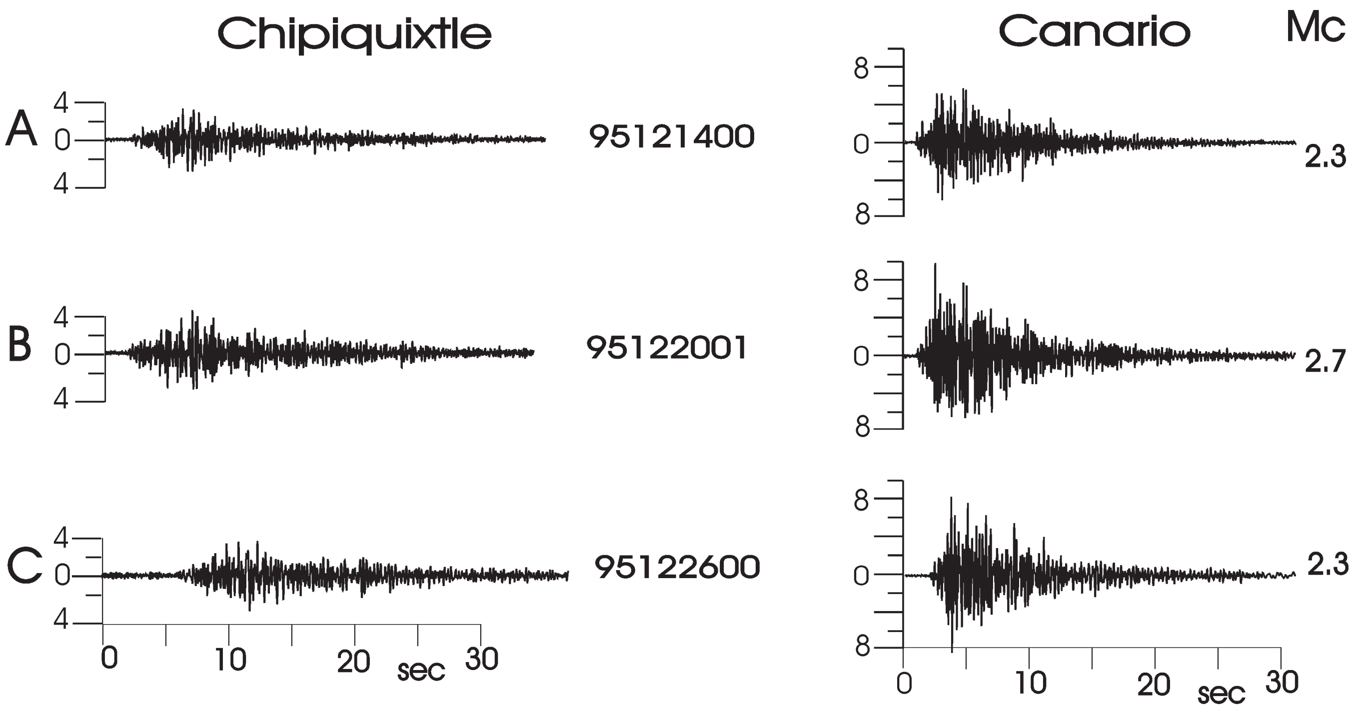
Fig. 2. Top: waveforms of earthquake family 1. The identification number consists of the year's last two digits, month, day and hour. Bottom: Average correlation values for N-S, E-W and vertical components at stations.



Correlation Values

	N	E	V
AB	0.69	0.57	0.59
AC	0.72	0.60	0.61
AD	0.58	0.62	0.72
BC	0.91	0.85	0.87
BD	0.86	0.83	0.67
CD	0.87	0.82	0.67

Fig. 3. Same as Figure 2 for earthquake family 2.



Eventos A, B and C of Family 3 (vertical component)

Correlation Values

	N	E	V
AB	0.61	0.52	0.54
AC	0.71	0.70	0.61
BC	0.60	0.55	0.60

Fig. 4. Same as Figure 2 for earthquake family 3.

However the period covered by this study is too short with respect to the history of activity of the volcano. The activity of Popocatépetl increased only the following year, presenting a strong emission of ashes in March 1996 (CENAPRED, WWW).

In addition to a follow-up study of the earthquake family, it would be important to extract basic information on the nature of these events, *i.e.* focal mechanism, and dislocation characteristics through standard seismic modeling. Unfortunately, the data employed shows that neither the instruments were maintained with a uniform polarity, nor a record of the polarities kept.

CONCLUSIONS

The seismicity associated to the activity of Popocatépetl volcano occurring between September 1 and December 31, 1995 shows at least three earthquake families. Families 1 and 2 consist of 4 events each, and family 3 of 3 events. All events are A- or volcano-tectonic type, of comparable magnitude ($2.0 \leq Mc \leq 2.5$) and occurred in the depth range 2 to 4 km below sea level. Good correlation values and the characteristics of the spectra suggest that the similarity between the events stems from similarity in the source. If this is the case then the events of families 1 and 2 could be of the asperity type, and probably occurred from the stresses caused

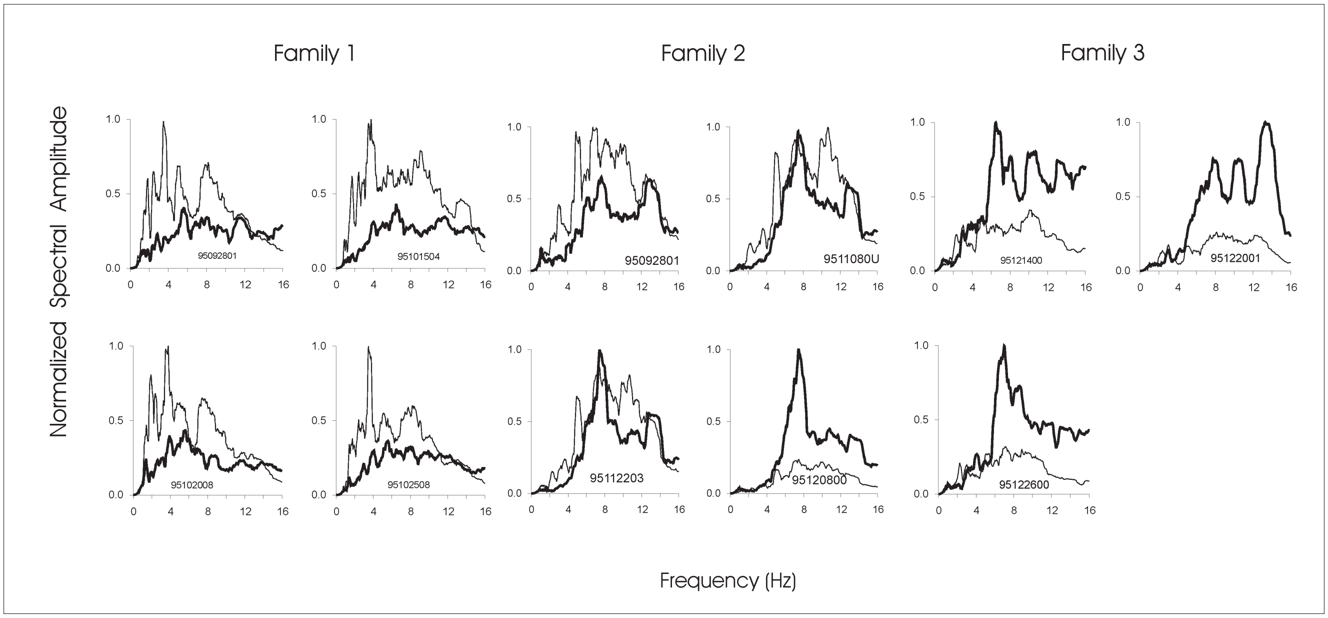


Fig. 5. Amplitude spectrum of the vertical component of the events of family members 1 to 3 at stations PPX (thin line) and PPP (thick line).

Table 1

Errors in the location of the events of families 1 to 3

EVENT	RMS (sec)	ERH (km)	ERZ (km)
95092801	0.29	0.7	2
95093000	0.38	2.5	1.2
95101504	0.15	0.5	0.3
95102008	0.28	3	0.7
95102508	0.07	0.2	0.6
9511080U	0.41	1	0.9
95112203	0.3	1.8	0.5
95120800	0.15	0.6	3.5
95121400	0.21	0.5	0.2
95122001	0.13	0.3	0.2
95122600	0.18	0.8	0.3

by the passage of magma through the volcanic conduits that connect the magma chamber with the surface.

It is very improbable that earthquake families were generated only during the period of study, whence the study of their evolution, and of the new ones that probably arose later, should be carried out to better understand the internal dynamics of the volcano.

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