Study of Seismic Clusters at Bahía de Banderas Region, Mexico

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Resumen

La costa de Jalisco y el sur de Nayarit es una región con un fuerte desarrollo turístico donde el incremento en la población es grande y se encuentran en una zona de alto potencial sísmico. Esto motivó a las autoridades de Protección Civil de Jalisco y la Universidad de Guadalajara a iniciar en el año 2000 estudios para evaluar el riesgo sísmico en la región. Este trabajo se enfocó en el estudio de la sismicidad en el área de Bahía de Banderas y la costa norte de Jalisco, área considerada un Gap Sísmico. Se realizó un análisis de los sismogramas disponibles para identificar estructuras corticales activas, su relación con la morfología superficial y la posible prolongación de estas estructuras a la parte somera de la bahía. Los datos utilizados en el presente trabajo son los registrados en el año 2003 cuando se desplegó una red sísmica en la región. El método está basado en la identificación de acumulaciones sísmicas o familias usando correlación-cruzada de los sismogramas, relocalización de sismos y modelado de planos de falla. A partir de un conjunto inicial de 404 sismos localizados, se seleccionaron 96 sismos con M_L < 3.6 que están relacionados con 17 estructuras continentales potencialmente activas. Se obtuvo un modelo del plano de falla para 11 estructuras. Un subgrupo de 7 estructuras se encuentra alineado paralelamente a la trinchera mesoamericana, lo cual puede ser una consecuencia de un proceso de subducción oblicuo. Los focos de los sismos se agruparon en acumulaciones sísmicas que se pueden correlacionar con fallas con dimensiones de cientos de metros, éstas pueden ser consideradas como asperezas o barreras en estructuras tectónicas con longitudes entre 10 y 30 km. Estas estructuras pueden generar terremotos someros con magnitudes entre 5.0 y 6.0, y representan una amenaza sísmica adicional en la región.

Palabras clave: Gap sísmico, placa de Rivera, bloque de Jalisco, Bahía de Banderas, familias sísmicas, correlación-cruzada.

Abstract

The coast in the state of Jalisco and south of Nayarit is located within a region of high seismic potential, increasing population, and tourism development. This motivated Civil Defense authorities of Jalisco and the Universidad de Guadalajara to launch in the year 2000 the assessment of the seismic risk of the region. This work focuses in the seismicity study of the area of Bahía de Banderas and northern coast of Jalisco, which is actually a seismic gap. We perform an analysis of available seismograms to characterize active crustal structures, their relationship to surface morphology, and possible extent of these structures into the bay shallow parts. The data consist of waveforms recorded during 2003 when the seismograph network spanned the region. Our method is based on the identification of seismic clusters or families using cross-correlation of waveforms, earthquake relocation and modeling of fault planes. From an initial data set of 404 located earthquakes, 96 earthquakes with M_L < 3.6 are related to 17 potentially active continental structures. We present fault plane model for 11 structures. A subgroup of 7 structures is aligned parallel to the Middle America Trench, as a possible consequence of oblique subduction. The foci of the earthquakes were grouped into clusters corresponding to fault dimensions of hundred of meters, may be considered as asperities or barriers in tectonic structures with lengths between 10 and 30 km. These structures could generate shallow earthquakes with magnitudes between 5.0 and 6.0 and represent an additional seismic threat to the region.

Key words: seismic gap, Rivera plate, Jalisco block, Bahía de Banderas, seismic clusters, cross-correlation.

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Introduction

Bahía de Banderas is located in the Jalisco Block (JB) (Figure 1). This region undergoes different deformation stages from the Mezosoic to the present, producing several active linear structures due to its proximity to a triple junction. The seismic activity recorded by temporary and permanent seismic networks, as well as the structures observed in the continental crust are manifestations of the tectonic deformation that accommodates the JB.

The 1932 (M=8.2) earthquake, the largest event in Mexico during the twentieth century occurred in the JB was followed 15 days later by another large event (M=7.8). Singh *et al.* (1985) studied these events and concluded that the surface expression of the composite rupture area extends across the entire coast of the states of Jalisco and Colima. They suggested a recurrence time of 77 years for the occurrence of a major earthquakes in this region. In 1995 a Mw=8.0 earthquake near Manzanillo involved the central part of the 1932 rupture area, leaving undisturbed patches to the north and south, which are now termed the Vallarta and Colima gaps, respectively (Figure 2).

In addition to the large subduction earthquakes (M>7.6), the complexity of the region of the coast in the state of Jalisco and south of Nayarit is reflected in the existence of poorly known tectonic structures where earthquakes of moderate magnitude occur (7.0<M<7.6); for example the December 3, 1948 event occurred near the Marías Islands (Figure 2). More recently, on 14 September 2010 a thrust fault earthquake (M=6.0) followed by 25 aftershocks in 24 hours with M_L>4.0, recorded by a local seismic network, took place to the south of Marías Islands. Of particular interest is the Mw=7.4 earthquake of 22 January 2003; a shallow earthquake off the state of Colima, México, near the town of Armería. Both, the damage pattern and the surface effects of this earthquake in the neighboring states of Colima and Jalisco were stronger than those caused by recent large earthquakes in these regions and affected different areas; especially in Colima City and Zapotitlan de Vadillo, Jalisco, on the western flank of Colima volcano. An analysis of its aftershocks (Núñez-Cornú *et al.* 2004, 2010) indicates that the earthquake was caused by a continental intraplate reverse fault. These earthquakes may be related to the possible oblique subduction of the Rivera Plate.

The microseismicity at the north of Jalisco and south of Nayarit coasts was studied during the CORTES96 project (Dañobeitia *et al.*, 1997); a joint project between the Universidad de Guadalajara (UG) and the Centro de Investigación Científica y Educación Superior de Ensenada (CICESE) was carried out during 1996-1998 aimed to study the microseismicity occurring north of the JB. Based on the analysis of these results and historical data the spatial distribution of earthquakes, Núñez-Cornú *et al.*, 2002 suggested the existence of various seismogenic zones. Thus, the purpose of this work was to
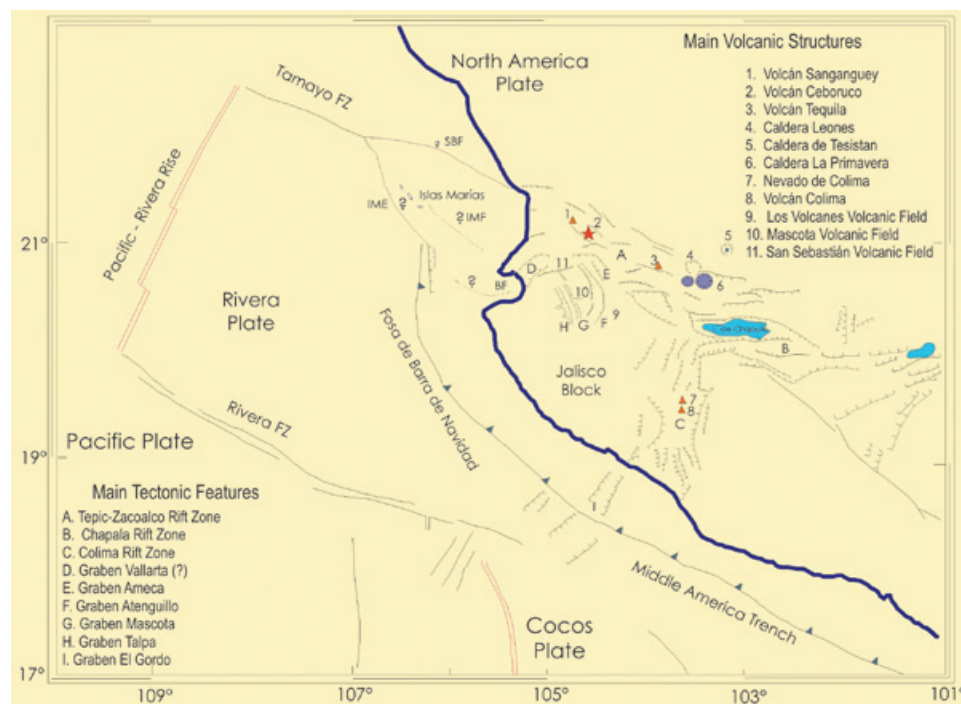
Figure 1. Tectonic frame of Jalisco Block region: SBF, San Blas Fault; IME, Islas Marias Escarpment; IMF, Islas Marías Fault; BF, Banderas Fault (Bahía de Banderas). (Modified from Núñez-Cornú *et al.* (2002).
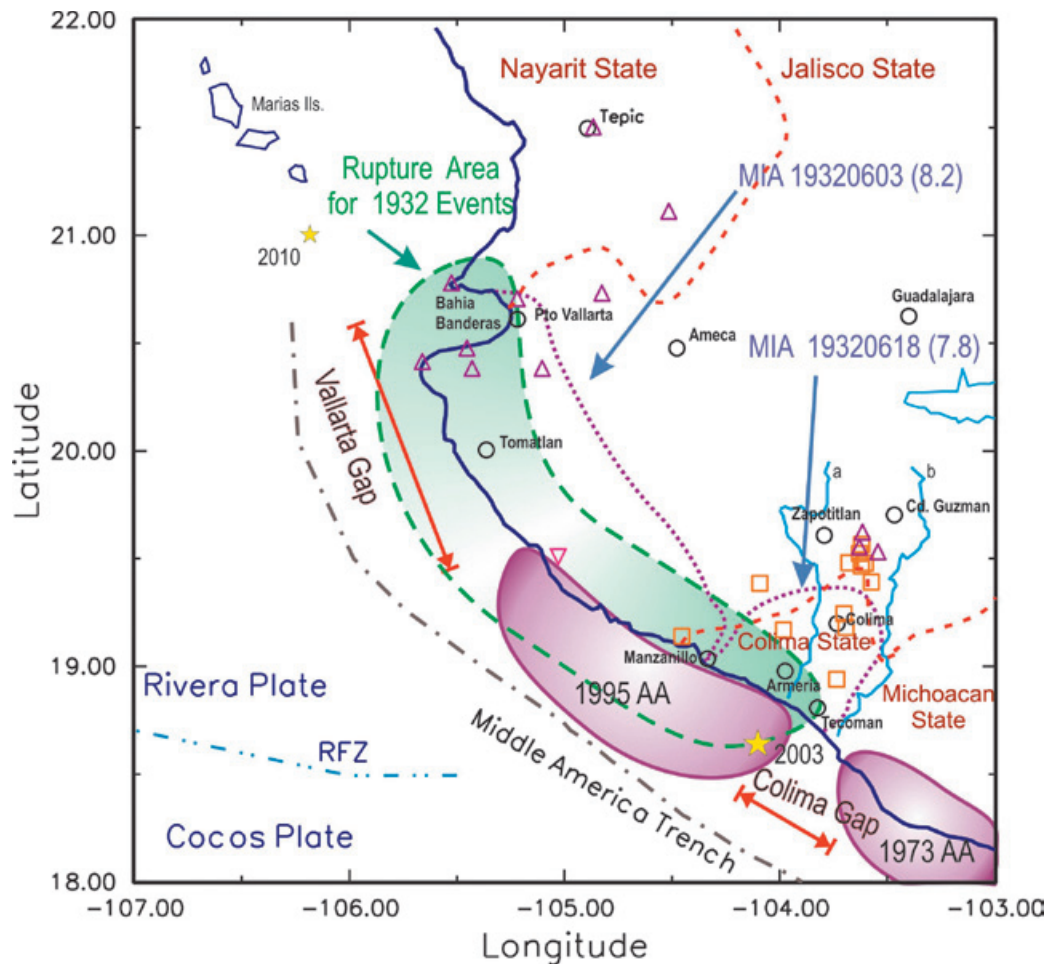
Figure 2. Seismotectonic features of the Jalisco region. RFZ: Rivera Fault Zone; a: Armería River; b: Cohuayana River; MIA: Maximum Intensity Areas for earthquakes in 1932 (dates and magnitudes indicated); AA: Aftershocks Areas. □ Seismograph station (RESCO network), △ (RESJAL network), ▽ CJIG, SSN network; ○ Cities; ☆ 2003 Epicenter of the Armería earthquake (after Núñez-Cornú *et al*., 2004); ☆ 2010 Islas Marías earthquake.

obtain a more detailed knowledge of the regional seismicity and active structures in the northern coast of Jalisco. For this purpose we used data from the Red Sismológica de Jalisco (RESJAL) deployed by Unidad Estatal de Protección Civil Jalisco (PCJal) and the Centro de Sismología y Volcanología de Occidente UG, composed of ten seismograph stations, six telemetric and four autonomous, distributed between the states of Jalisco and Nayarit (Figure 2) comprising sites on Colima and Ceboruco volcanoes. In some cases data from the Red Telemétrica de Colima (RESCO) was used.

Tectonic Setting

According to Núñez-Cornú *et al.* (2002) and others authors the North America, Pacific, Cocos, and Rivera lithospheric plates interact in the western Mexican Volcanic Belt. Several triple point locations have been proposed (Figure 1), however the seismotectonic processes still are not fully known. The existence of a tectonic unit in this region, known as the JB, has been proposed by several researchers (Luhr *et al*., 1985; Bourgois *et al*., 1988; Garduño and Tibaldi, 1991; DeMets and Stein, 1990; Allan *et al*., 1991; Ferrari *et al*., 1994; Rosas-Elguera *et al*., 1996). The JB is limited to the east by the Colima Rift Zone, which extends northward from the Pacific coast and connects at its northern end with two other major extensional structures: the Tepic-Zacoalco Rift Zone (TRZ) (trending roughly NW-SE) defined as the northern boundary of the JB, and the Chapala Rift Zone (trending roughly E-W). The connection between the northwestern border of the JB and the continent (the Tamayo Fault System) is not well defined. This border has been related to the San Blas Fault as continuation of the TRZ, or to the Islas Marías

Escarpment [west of Tres Marías Is.] and the Banderas Fault (BF), which crosses the Bahía de Banderas and continues through the Vallarta Graben (VG) to join the TRZ (Figure 1) another possible connection to the Tres Marías Fault. The last two possibilities suggest the existence of a small block [the Tres Marías Block (?)]. Álvarez (2007) suggest that the BF and the VG are part of the same tectonic structure, and is part of the NW limit of JB. The Bahía de Banderas area may be undergoing strong crustal stresses as a convergence of the Rivera Plate (Kostoglodov and Bandy, 1995). The existence of shallow submarine hydrothermal activity in the Bahía de Banderas (Núñez-Cornú *et al.*, 2000) could be a result of these stresses.

Data

The RESJAL stations were deployed between late 2001 and 2002. The stations deployed in the study area revealed that the regions of Bahía de Banderas-Valle de Tomatlán and Ameca, formerly thought as regions of scarce seismicity, exhibit high seismic activity. A seismicity consisting of small magnitude events was observed in the Bahía de Banderas area, and of larger magnitudes in the southern coast of Jalisco and the region of Ameca (Figure 2). By 2003 a total of 404 earthquakes with local magnitudes between 0 and 5.0 were detected and located within an area bounded by the coordinates 20°N-21°N and 104°W-106°W

(Figure 3). We focused the study in those areas. By 2004 telemetric stations deployed at north of Jalisco and Bahía de Banderas stop operation.

Stations BSSJ and MCUJ (Figure 3) were not operational during the last trimester of 2003 while stations YELJ and CORJ operated intermittently. During that time 400 low-magnitude earthquakes occurred in various swarms. This activity was recorded by station AGUJ and partially by YELJ; the events showed S-P times usually less than 10 s., we observed that north of parallel 21°N the seismicity was scarce.

During a preliminary revision of the data, we observed the occurrence of many earthquakes of similar waveforms. This observation was already noted during a preliminary study in 1998 (Núñez-Cornú *et al*., 2002) when on some days swarms of 20 to 30 similar waveform earthquakes were detected, mostly by the AGUJ station (Figure 3). With the deployment of additional stations the coverage improved and many of this type of earthquakes could be located. However, the earthquakes of small magnitude and were recorded by only one or two stations, locations were estimated using 3 component analysis. In the present study we relocated the earthquake foci using a method based on cross-correlation of seismic phases. This methodology improves the study of the seismic activity.
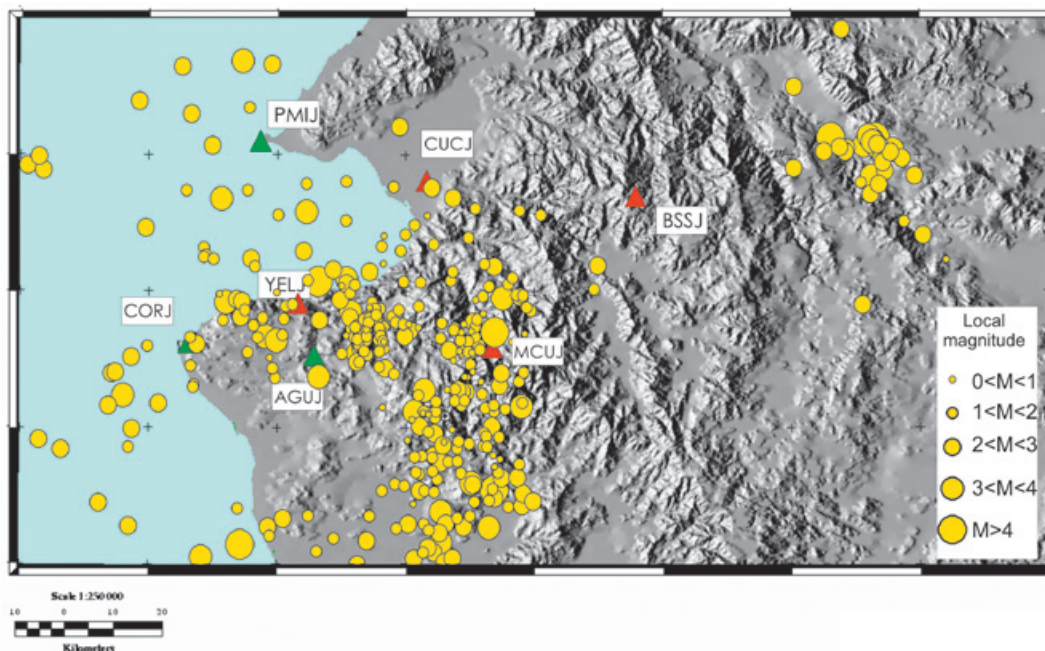
Figure 3. Seismicity in the Bahía de Banderas region in 2003, includes earthquake located with one or two stations. Red triangle: Telemetric stations; green triangle: Autonomous stations.

Correlation method

The methodology used was developed by Deichmann and García-Fernández (1992), improved by Maurer and Deichmann (1995) and applied to seismic swarms recorded by a regional network in northern Switzerland. When two earthquakes have similar waveforms we assume that the source and the propagation media are the same. If the source of a particular waveform can be determined, earthquakes with that same waveform can be located even if they are recorded by only a few stations. The sources are not considered as point sources, but rather faults with finite dimensions that can include asperities or barriers where the earthquake originates.

The cross-correlation and relocation method has been applied to other swarms data set in different locations, e.g. in Spain the 1993-1994 swarm in Almería (Stich *et al.*, 2001), the 1988-1989 swarm in Granada (Saccorotti *et al*., 2002), and the 2005 swarm in Murcia (Ocaña, 2006).

The method is applied as follows: 1) Use initially the earthquakes recorded by three or more stations; 2) Correlate all seismograms in the time domain for a particular seismic station; 3) Group by seismic families those waveforms with large correlation values; 4) Choose the best located epicenter, which will be the master event for each family; 5) Relocate all earthquakes in a group as a function of the master event; 6) Estimate the plausible fault plane with the hypocenters located in each group; 7) Compute the focal mechanism of the Master Event based on the polarity of the first P-arrivals of all records.

We applied the cross-correlation algorithm (Saccorotti *et al.*, 2002) to estimate the degree of similarity pairs of earthquakes recorded initially at stations MCUJ and AGUJ to identify the families, in some cases other stations were also used when good quality data was available. To homogenize the differences on the waveforms among located earthquakes we filtered each seismogram with a 1-15 Hz band-pass filter. We used the direct **P** and **S** phases in our analysis. To find similarities in **P** waves, we chose the vertical component and for **S** waves the N-S component since most of the arrival times of the **S** phases were determined using that component. For completeness, we also tried the program using data in the E-W component and obtained similar results. We defined a time window of 2 s starting 0.4 s before the **P**-arrival. In the case of **S**-waves, the time window was of 3 s starting 0.5 s before its arrival. The waveforms analyzed had S-P times that varied between 2 and 10 s.

The criteria to group earthquakes into certain families are as follows: 1) Correlation threshold for **P** phase; 2) Correlation threshold for **S** phase; 3) Those earthquake pairs within thresholds 1 and 2 are analyzed again and compared with respect to the other earthquakes and a correlation threshold value is set between rows with **P** and **S** phases. For the earthquakes used in this study we used the following threshold values: **P**-threshold = 0.8, **S**-threshold = 0.8, and **S*P** threshold = 0.7.

From the total 404 earthquakes initially located by Rutz-López (2007) using the Hypocenter code (Lienert *et al*., 1986), 96 were classified into 17 families; each family composed of 3 to 12 earthquakes. Figure 4 shows the waveforms for the vertical components of four representative families recorded at station MCUJ. The hypocenters of the 17 families are shown in Figure 5 (a to c). Seismograms from the MCUJ station were used to characterize and classify14 of the families, while the other three families were characterized using AGUJ station seismograms; although earthquakes were recorded at both stations, we used data from the station nearest to each family. Figure 5d shows the occurrence times of the earthquakes from the different families; although the data may not be representative of long-term behavior, since they span only one year, it shows that the activity of some families, e.g. M09, M17, M18, and M19, lasted one day only, whereas other families had longer periods of activity.

In order to have a very similar appearance at one or more stations, the earthquakes of a given family must have similar rupture mechanisms and similar paths to each station, which means that their hypocenters should cluster together. It can be seen in Figure 5 that the hypocenters determined by the initial location do not present the expected clustering, which indicates the need for relative relocation of the earthquakes in each family.

According to Wells and Coppersmith (1994) the subsurface rupture length for a magnitude 4.0 earthquake (Table 1) is 550 m which agrees with the hypothesis of same source, so relative relocation of the earthquakes of each family is necessary.

Correlating the Master Event with its family members

Three of the 17 families (A16, M08, and M16) were discarded from the analysis because we cannot adjust the arrival times in the waveforms. In Figures 6 and 7 we show the waveforms of four well-defined families (M07, M09, M14 and M15). Here the correlation program adjusted the arrival times for each earthquake in the families. We also show the correlation values obtained for each station.
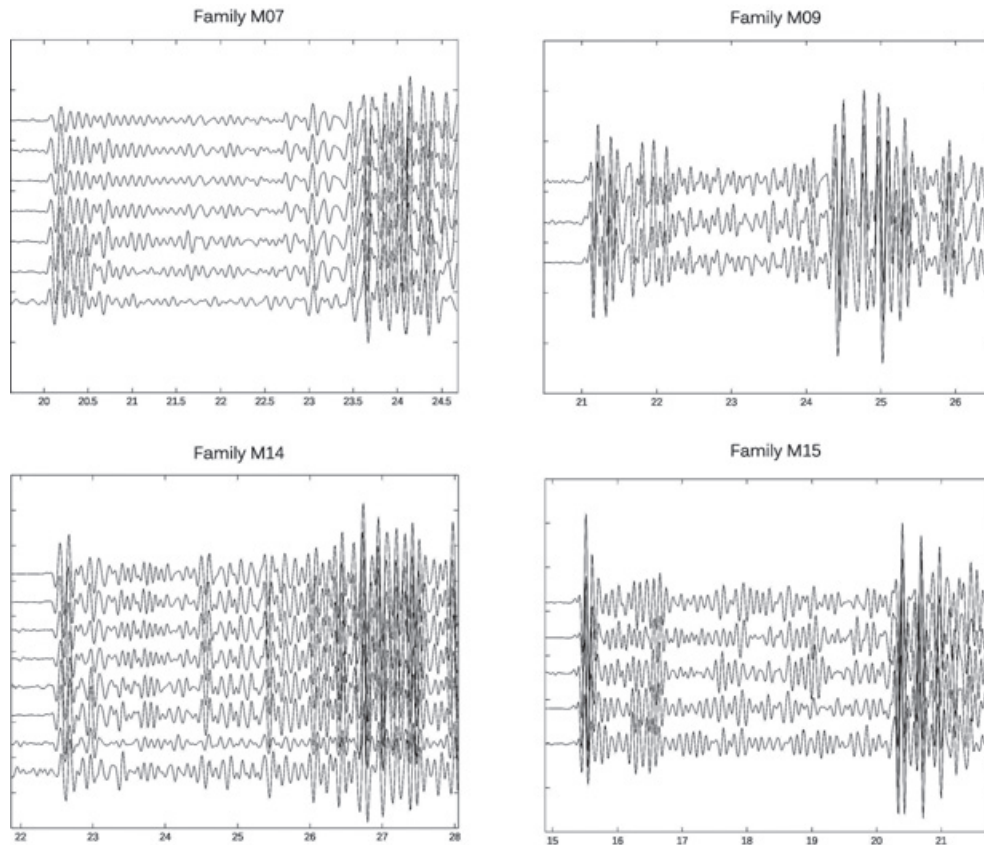
Figure 4. Waveforms showing P and S waves of four seismic families identified in the Bahía Banderas region.
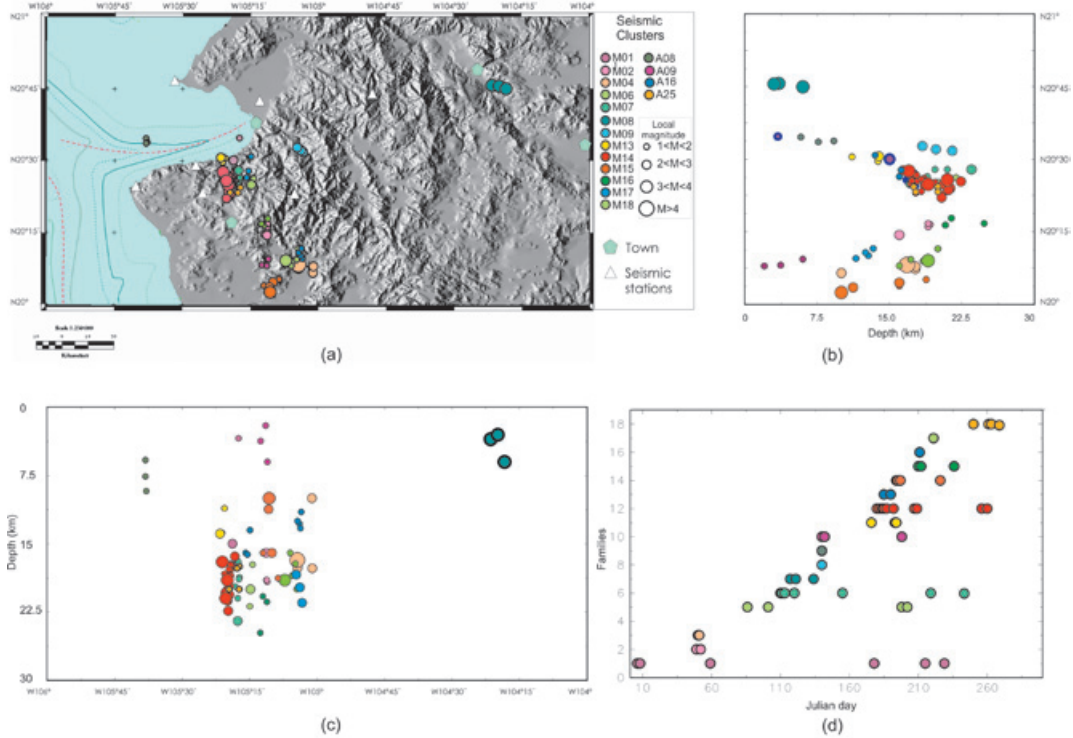
Figure 5. Seismic families identified in this work. A) Epicenters. B) Profile North-South. C) Profile East-West. D) Chronological order of occurrence, Y-axis: Number of family, X-axis: day of year.

Table 1. Hypocenter data for master event in each family; relative relocation for the earthquakes in each family; Adjusted fault plane data for each family.

M01	Date	hour	Sec	Lat	Long	Depth	mag	n lec	rms	erh	erz
Master Ev	30627	20:45	2.34	20.4135	-105.3105	19.72	1.2	8	0.12	1.5	1.5
Relocated	date	hour	x(km)	dx	y(km)	dy	z(km)	dz			
1	30228	02:45	0.31	0.064	1.434	0.227	-0.246	0.047			
2	30803	19:39	0	0.064	-0.027	0.227	0.036	0.047			
3	30817	07:28	0.375	0.064	0.083	0.227	-0.24	0.047			
4	30817	16:16	0.379	0.064	0.184	0.28	-0.194	0.059			
	Azi(°)	Dip(°)	rms	NEq							
Plane	175.3	58.5	0.015	5							

M02	Date	hour	Sec	Lat	Long	Depth	mag	n lec	rms	erh	erz
Master Ev	30218	03:51	10.36	20.2575	-105.1947	20.55	1.7	8	0.07	0.9	0.6
Relocated	date	hour	x(km)	dx	y(km)	dy	z(km)	dz			
1	30218	356	0.790	0.031	1.804	0.088	-1.914	0.067			
2	30218	414	-0.013	0.031	0.008	0.088	-0.036	0.067			
3	30218	542	-0.104	0.031	0.296	0.088	-0.415	0.067			
4	30221	1923	-0.327	0.025	-3.005	0.069	3.532	0.059			
	Azi(°)	Dip(°)	rms	NEq							
Plane	97.9	40.9	0.035	5							

M06	Date	hour	Sec	Lat	Long	Depth	mag	n lec	rms	erh	erz
Master Ev	30721	14:52	14.93	20.1312	-105.0823	17.32	3.5	8	0.35	4	2.8
Relocated	date	hour	x(km)	dx	y(km)	dy	z(km)	dz			
1	30717	535	0.071	0.133	0.18	0.517	-0.285	0.882			
2	30717	814	0.109	0.133	0.571	0.517	-0.924	0.882			
	Azi(°)	Dip(°)	rms	NEq							
Plane	16.4	3.5	0.000	4							

M07	Date	hour	Sec	Lat	Long	Depth	mag	n lec	rms	erh	erz
Master Ev	30604	15:57	38.97	20.4568	-105.3047	22.91	1.8	10	0.41	3.6	3.7
Relocated	date	hour	x(km)	dx	y(km)	dy	z(km)	dz			
1	30420	58	-0.079	0.08	-0.166	0.272	-0.038	0.063			
2	30421	340	-0.048	0.08	-0.097	0.272	-0.041	0.063			
3	30430	310	0.13	0.06	0.337	0.211	0.034	0.057			
4	30807	1651	-0.039	0.06	-0.045	0.211	-0.061	0.057			
5	30825	2156	-0.276	0.08	-0.314	0.272	-0.23	0.063			
	Azi(°)	Dip(°)	rms	NEq							
Plane	6.9	48.0	0.012	6							

M09	Date	hour	Sec	Lat	Long	Depth	mag	n lec	rms	erh	erz
Master Ev	30520	09:27	30.58	20.5418	-105.0828	18.64	2.6	20	0.25	0.8	0.6
Relocated	date	hour	x(km)	dx	y(km)	dy	z(km)	dz			
1	30520	706	-0.007	0.039	0.078	0.043	0.032	0.034			
2	30520	707	-0.013	0.082	-0.022	0.054	0.019	0.064			
	Azi(°)	Dip(°)	rms	NEq							
Plane	7.4	27.9	0.000	3							

Table 1. (Cont.)

M14	Date	hour	Sec	Lat	Long	Depth	mag	n lec	rms	erh	erz
Master Ev	30711	02:53	16.73	20.4527	-105.349	17.62	3.7	40	0.46	1	0.8
Relocated	date	hour	x(km)	dx	y(km)	dy	z(km)	dz			
1	30629	626	0.049	0.031	0.043	0.077	-0.007	0.041			
2	30629	627	0.029	0.038	0.025	0.105	0.013	0.058			
3	30629	729	0.01	0.054	0.018	0.167	0.009	0.046			
4	30701	1844	0.027	0.068	0.058	0.219	0.001	0.047			
5	30703	1436	-0.004	0.068	-0.032	0.219	0.053	0.047			
6	30704	659	0.106	0.054	0.142	0.167	0.08	0.046			
7	30706	1831	-0.032	0.068	-0.076	0.219	-0.001	0.047			
8	30726	200	-0.031	0.068	0.043	0.219	0.113	0.047			
9	30728	2303	0.096	0.054	0.092	0.167	0.092	0.046			
10	30913	643	0.067	0.054	0.016	0.167	-0.037	0.046			
11	30917	1143	0.111	0.054	0.191	0.167	-0.061	0.046			
	Azi(°)	Dip(°)	rms	NEq							
Plane	34.2	8.0	0.022	12							

M15	Date	hour	Sec	Lat	Long	Depth	mag	n lec	rms	erh	erz
Master Ev	30714	11:02	54.47	20.0477	-105.1855	11.37	3.6	32	0.39	1.3	2.6
Relocated	date	hour	x(km)	dx	y(km)	dy	z(km)	dz			
1	30713	33	-0.016	0.048	0.03	0.061	-0.308	0.21			
2	30814	1915	0.021	0.048	0.016	0.061	0.047	0.21			
3	30814	2000	0.06	0.171	0.058	0.537	-0.112	2.239			
	Azi(°)	Dip(°)	rms	NEq							
Plane	54.8	5.6	0.002	4							

M19	Date	hour	Sec	Lat	Long	Depth	mag	n lec	rms	erh	erz
Master Ev	30827	06:27	58.99	20.1898	-105.1888	6.08	2.5	18	0.36	2.5	6.7
Relocated	date	hour	x(km)	dx	y(km)	dy	z(km)	dz			
1	30827	1548	0.022	0.053	0.099	0.061	-0.085	0.182			
2	30827	1855	0.024	0.148	0.200	0.404	-0.962	2.699			
	Azi(°)	Dip(°)	rms	NEq							
Plane	13.7	1.4	0.000	3							

M20	Date	hour	Sec	Lat	Long	Depth	mag	n lec	rms	erh	erz
Master Ev	30520	15:01	38.13	20.1358	-105.1865	11.01	1.6	10	0.28	3.2	7.9
Relocated	date	hour	x(km)	dx	y(km)	dy	z(km)	dz			
1	30520	1506	0.008	0.032	0.049	0.188	0.040	0.270			
2	30520	2235	-0.012	0.032	-0.013	0.188	-0.025	0.270			
	Azi(°)	Dip(°)	rms	NEq							
Plane	158.3	32.5	0.000	3							

A09	Date	hour	Sec	Lat	Long	Depth	mag	n lec	rms	erh	erz
Master Ev	30522	20:05	37.89	20.116	-105.1772	3.49	1.7	10	0.29	7.9	10.8
Relocated	date	hour	x(km)	dx	y(km)	dy	z(km)	dz			
1	30520	1819	-0.088	0.592	0.401	2.75	0.733	4.923			
2	30717	1901	-0.076	0.592	0.83	2.75	1.293	4.923			
	Azi(°)	Dip(°)	rms	NEq							
Plane	32.9	21.7	0.000	3							

A25	Date	hour	Sec	Lat	Long	Depth	mag	n lec	rms	erh	erz
Master Ev	30907	12:39	24.74	20.3832	-105.3033	19.64	1.2	8	0.13	1.9	1.3
Relocated	date	hour	x(km)	dx	y(km)	dy	z(km)	dz			
1	30918	2357	-0.002	0.066	0.030	0.221	-0.010	0.075			
2	30920	643	0.072	0.066	0.223	0.221	-0.061	0.075			
	Azi(°)	Dip(°)	rms	NEq							
Plane	64.6	70.3	0.000	4							
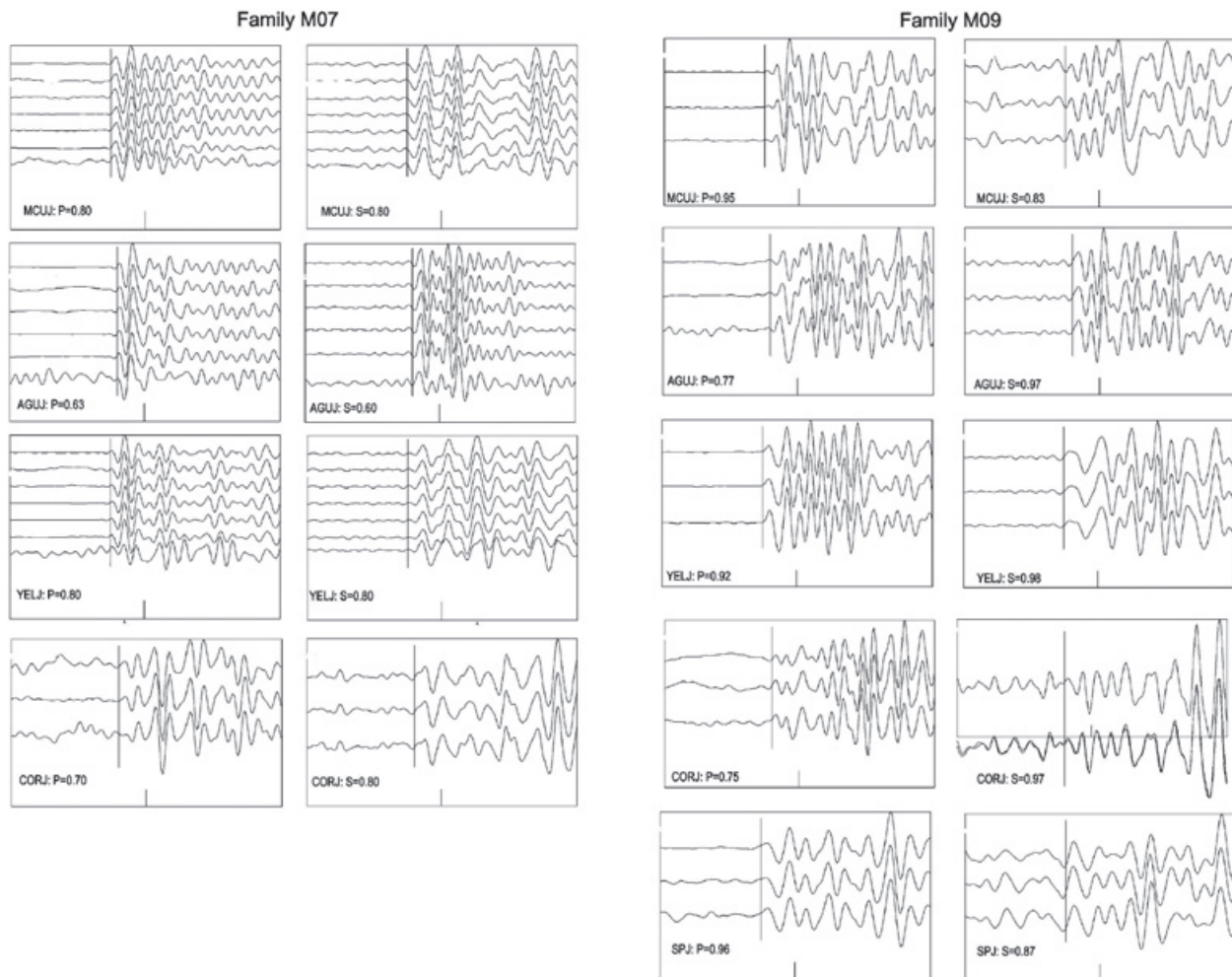
Figure 6. Wave forms (P and S) for Families 07 and 09 (Two seconds windows).

We chose as master event for each family a representative earthquake, which usually had the largest magnitude and the best determined location. The location accuracy of this event is critical because the rest of family members are relocated based on the master's hypocenter.

Family relocation relative to Master Event

With the correlation between master event and its family result we used a linear method (Console and DiGiovambattista, 1987) to find relocated hypocenters of earthquakes relative to the master event. The hypocenter coordinates and the associated errors are given in Table 1. Based in this cluster of dots, we can estimate plausible fault planes near the master event with a least squares method. Only 11 families yielded reliable fault planes. The relocation results, alignments

and possible fault planes for families M01, M02, M06, M07, M09, M19, M20, A09 and A25 are shown in Figure 8. For master events of Families M14 and M15 we had an adequate number of polarity data to obtain focal mechanisms; the solutions of these focal mechanisms agree with the fault planes obtained with the least squares method (Figure 9).

Geomorphological analysis

Topographic lineaments greatly reflect the tectonic structures of the bedrock, which are enlarged in the surface by topography, drainage and vegetation (Rahiman and Pettinga, 2008). Therefore an analysis of these features was carried out in the region. Their identification along the Puerto Vallarta inland of the Jalisco north shore was made using a digital terrain model
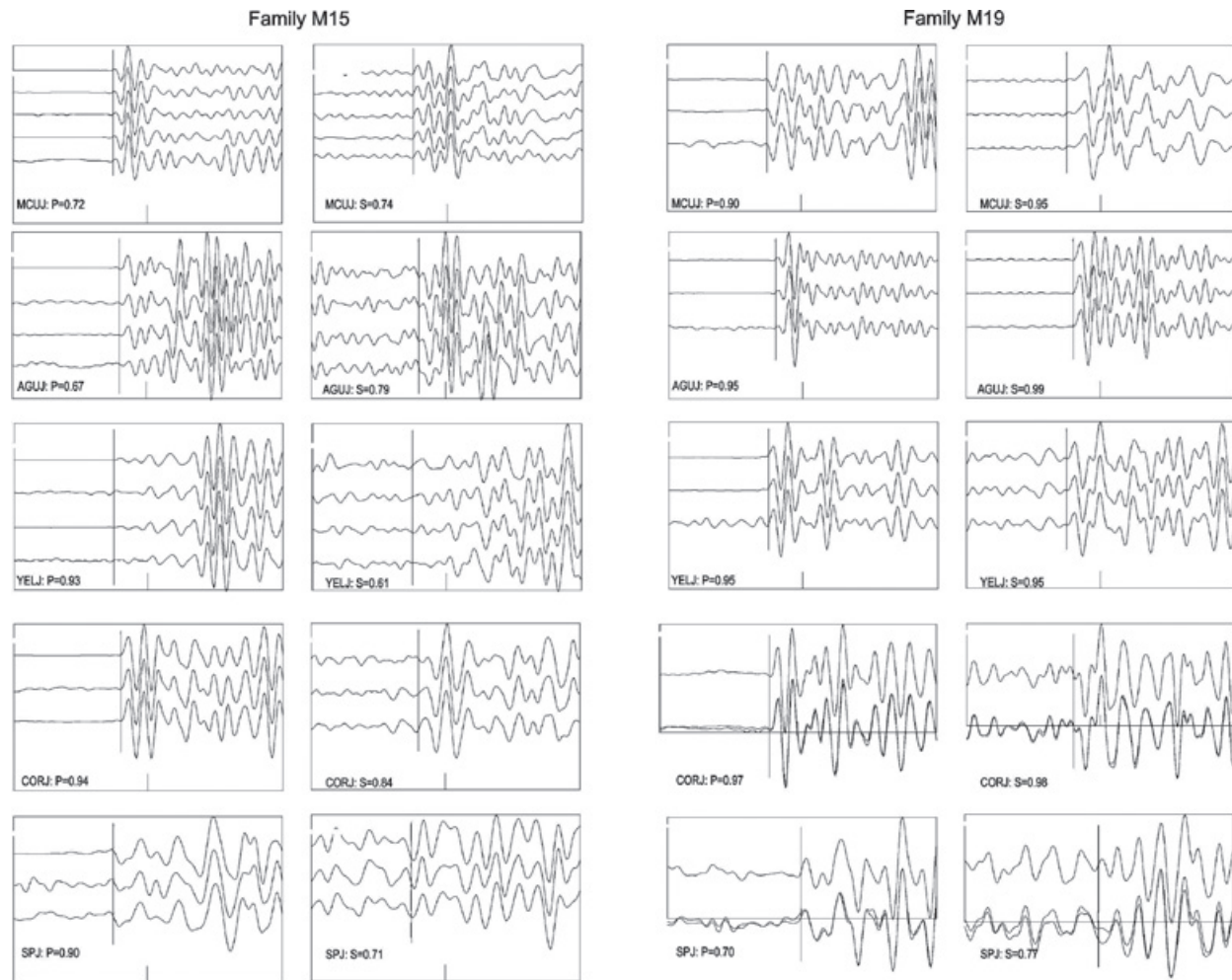
Figure 7. Wave forms (P and S) for Families 14 and 15 (Two seconds windows).

(DTM). The DTM was built based on a vector model with 20 m contour line intervals from the Instituto Nacional de Geografía e Informática and using triangle based interpolation with a 20 m grid in ErMapper ver. 7.1. The results show that the studied region is dissected by a complex lineament system that affects Mesozoic granite stocks, lavas, and Quaternary volcanoclastic sediments.

We identify parallel systems of 20 km long lineaments with preferred orientations N-S, WNW-ESE, and NE-SW. These results indicate a complex deformation fracture system that affects the studied region and could be related to active tectonism in the zone. From bathymetric studies, Álvarez (2007) propose a half-graben structure for the Banderas Canyon (a structure in the Bahía de Banderas), and propose a fault system oriented NE at north and south sectors of the bay, the faults at south of the bay do not agree with our results.
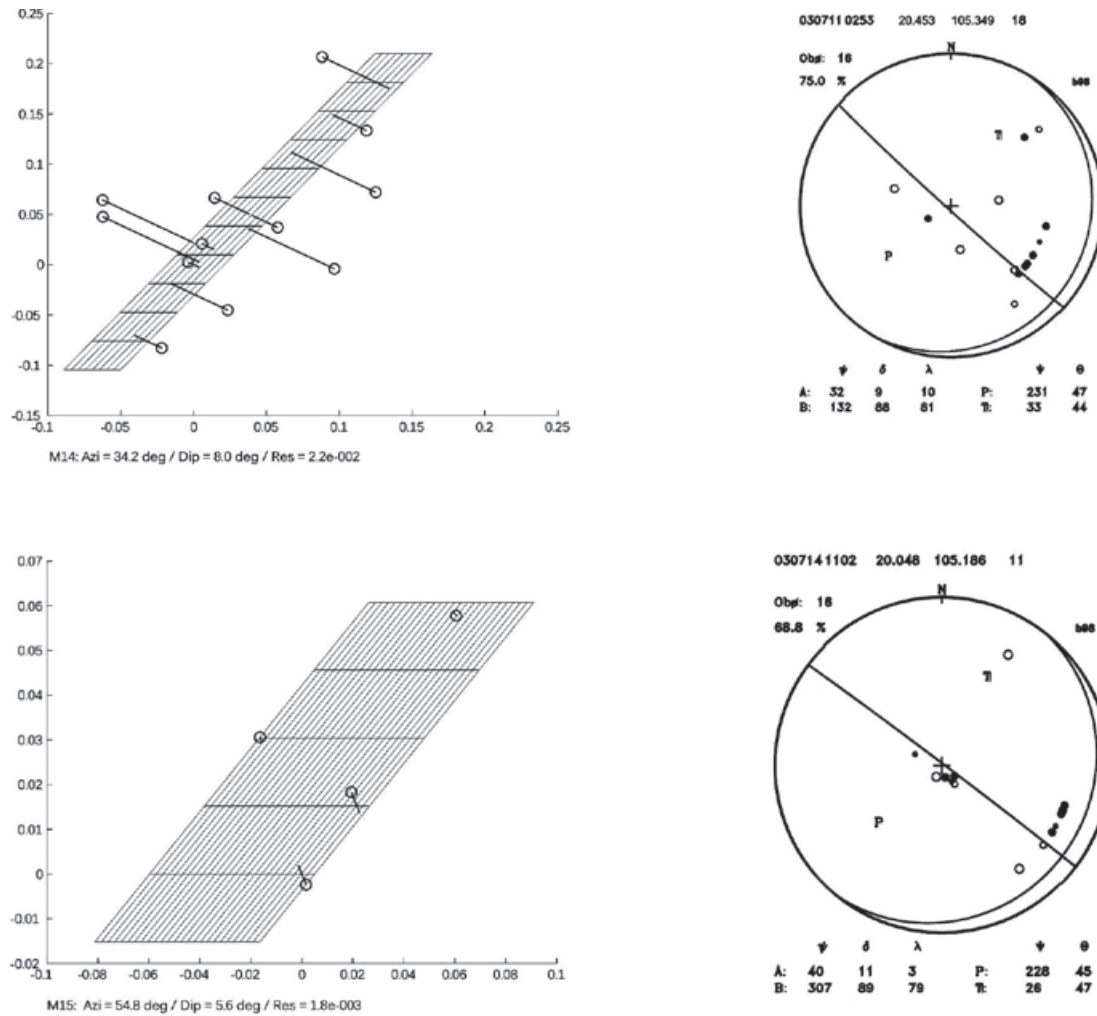
Most of the master events are located on the lineaments and the orientation of the fault planes calculated roughly agree with the direction of the lineaments (Figure 10).

Conclusions

From the available data and the analysis of cross-correlation, we define 17 families of events, which could be associated with sources mechanisms and stationary paths in an area south of Bahía de Banderas. For 14 families we obtain a relative relocation using a master event technique. The largest earthquake recorded at as many stations as possible was chosen as the master event in each family. Relocation of earthquakes in each family reduced the spatial scatter of epicenters to areas with radii less than 1 km. These 14 families have foci within the continental crust, at depths of 10-22 km, except for families M19 and A09 which are located within the upper 10 km of the crust. Using a least squares approach, we
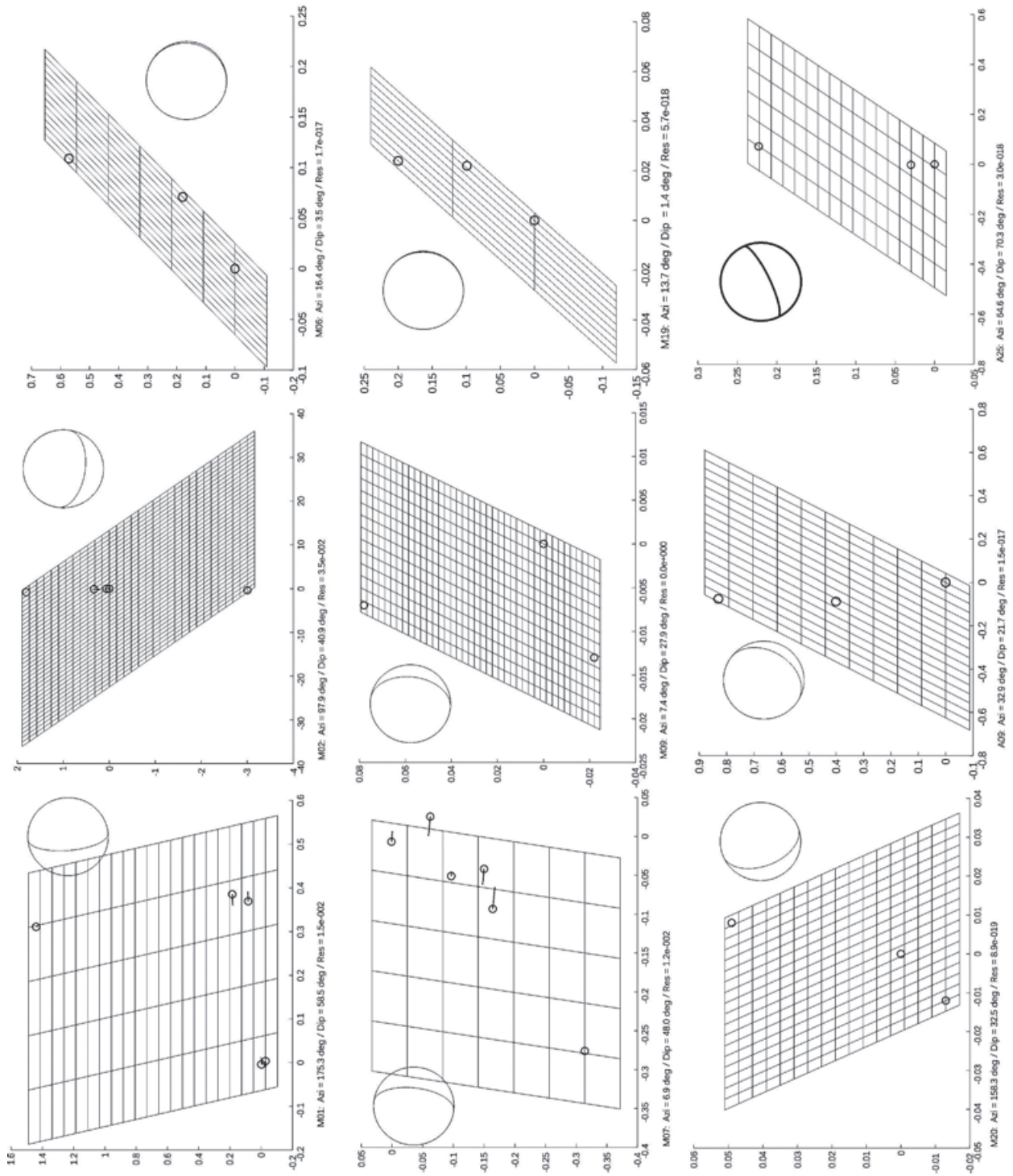
Figure 8. Fault planes for families M01, M02, M06, M07, M09, M19, M20, A25 and A09 obtained adjusting the relocated earthquakes by least squares method; projection of the plane in focal sphere.

M06: Azi = 16.4 deg / Dip = 3.5 deg / Res = 1.7e-017

M19: Azi = 13.7 deg / Dip = 1.4 deg / Res = 5.7e-018

A25: Azi = 84.6 deg / Dip = 70.3 deg / Res = 3.0e-018

M02: Azi = 97.9 deg / Dip = 40.9 deg / Res = 3.5e-002

M09: Azi = 7.4 deg / Dip = 27.9 deg / Res = 0.0e+000

A09: Azi = 32.9 deg / Dip = 21.7 deg / Res = 1.5e-017

M01: Azi = 175.3 deg / Dip = 58.5 deg / Res = 1.5e-002

M07: Azi = 6.9 deg / Dip = 48.0 deg / Res = 1.2e-002

M20: Azi = 158.3 deg / Dip = 32.5 deg / Res = 8.9e-019

Figure 9. Fault planes obtained for families M14 and M15 and focal mechanism obtained for their master events.

could model fault planes for 11 of the families. Focal mechanisms were determined for two of the master events (M14 and M15) and in both cases they were consistent with modeled planes, which support our results.

This analysis shows the existence of 17 tectonic active sources of which 11 fault planes were identified. The hypocenter of the master event and their fault planes of these sources agree with some of lineaments structures observed in the region. A group of 7 structures are aligned parallel to the Middle America Trench, as a possible consequence of oblique subduction. These sources can be identified as asperities or barriers in active crustal lineament structures, some of them with a length greater than 20 km, that could generate an earthquake with 6.5 magnitude (Wells and Coppersmith, 1994). This represents a high seismic hazard for the region in addition to the threat of the occurrence of an interplate event in the Vallarta gap.

These studies can yield a more complete evaluation of the seismic hazard associated to crustal structures, independently of the subduction process of Rivera plate under JB, in the region of Bahía de Banderas and the northern coast of Jalisco, if the number of seismic stations is increased and operated continuously.
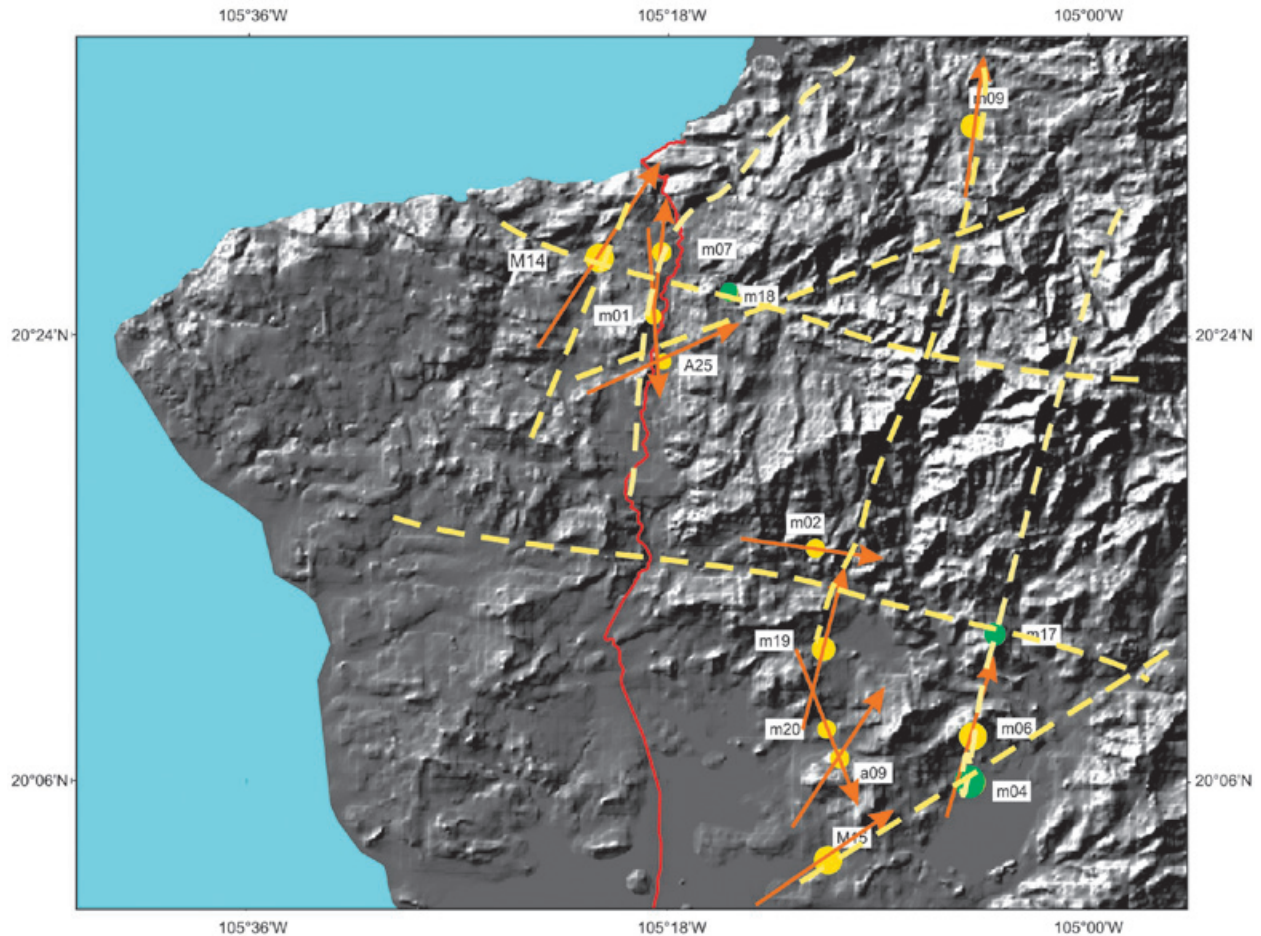
Figure 10. Digital terrain model of the region with main lineaments traced and azimuth of fault planes obtained for the different families referred to location of master event.

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