Analysis of the Seismicity in the Jalisco Block from June to December 2015

by Tatiana Marín-Mesa, Francisco J. Núñez-Cornú, and Carlos Suárez-Plascencia

ABSTRACT

We present the first study of seismicity in the region of the Jalisco Block using data recorded by the Jalisco Seismic Accelerometric Telemetric Network between June and December 2015. During this period, 683 local earthquakes with magnitudes between $1.0 < M_L \le 4.0$ were identified and relocated with Hypo71PC. From this catalog, we identify a heterogeneous hypocentral distribution with six continental crustal seismogenic areas. We also observed seismicity associated with the subduction process that extends 180 km from the Mesoamerican trench, which suggests an estimated dip angle of the slab between 22° and 31°. A subtle dip also suggests oblique subduction toward the Colima rift zone and bending of the Rivera plate. These observations are in agreement with previous partial regional studies using local seismic networks. Two seismic swarms were observed in this period, one in the Bahia de Banderas seismogenic zone, and a second in the Guadalajara Metropolitan zone. We note two areas on the northern coast of Jalisco with meager rates of seismicity.

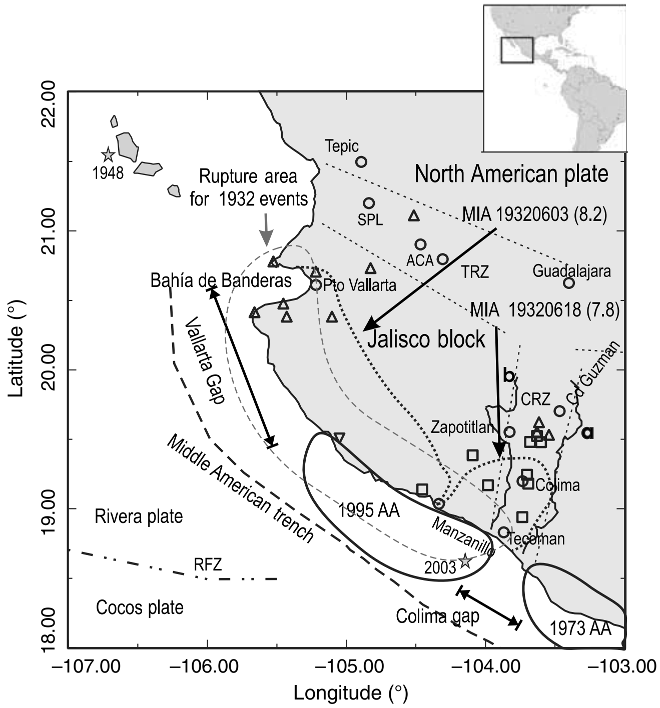
INTRODUCTION

Western Mexico is one of the most seismically active regions in the country; this region includes the states of Jalisco, Colima, and Nayarit where destructive historical earthquakes have occurred since 1544 (Núñez-Cornú, 2011). The highest magnitude earthquakes occurred along the coast. They include subduction earthquakes such as 3 June 1932 M_s 8.2 and 18 June 1932 M_s 7.8 earthquakes (Fig. 1), and inland, intraplate earthquakes such as the earthquakes on 27 December 1568 and 11 February 1875. Singh *et al.* (1985) estimated the recurrence time of events similar to 1932 earthquakes and found a repeat interval of large-scale earthquakes of about 77 yr in the Jalisco block (JB). In October 1995, another earthquake with a magnitude of M_s 8.0 (Fig. 1) occurred on the coast of Jalisco and Colima, which rupture area was the southern half of the rupture calculated for the 1932 earthquakes (Courboulex *et al.*, 1997; Pacheco *et al.*, 1997; Escobedo *et al.*, 1998). There are also other tectonic structures capable of generating moderate magnitude earthquakes, which represent a substantial seismic hazard; one such occurred near the Islas Marías on 3 December 1948, resulting in significant destruction on María Madre Island (Fig. 1). An unexpected shallow earthquake of M_w 7.4 that was not associated with subduction processes took place on the continental shelf (near of Colima rift zone [CRZ]) on 22 January 2003 (Núñez-Cornú *et al.*, 2004, 2010). Particular interest is therefore warranted in the investigation of the tectonic processes that occur in the region. Active volcanoes Sangangüey, Ceboruco, and Colima represent additional tectonic hazards in the region (Fig. 2). Three tsunamis have also occurred in the region in the last 100 yr (Trejo-Gómez *et al.*, 2015).

In the last 452 yr, there have been at least 22 earthquakes with $\mathbf{M} > 7.0$ in the Jalisco region (Núñez-Cornú *et al.*, 2018). Despite the high seismic hazard associated with the tectonic processes in the area, only one permanent seismic station from the Servicio Sismologico Nacional (SSN) was running at Chamela on the Jalisco coast until 2001 (Fig. 1). Another permanent network within the east border of JB, the Red Sísmica Telemétrica de Colima (RESCO), is operated by the University of Colima, whose main objective is surveillance of Colima Volcano. This network is therefore configured primarily around Colima Volcano in the southern part of CRZ (Fig. 1).

The first studies with temporary local seismic networks in the region began in 1994 (Núñez-Cornú *et al.*, 2002). The Universidad de Guadalajara (UdeG) and Protección Civil (Civil Defense) del Estado de Jalisco began a project in 2001 to deploy a 10-station digital seismic network (RESJAL), with 3D seismic sensors (Fig. 1). RESJAL operated until late 2004 (Rutz-López, 2007; Rutz-López *et al.*, 2013). From January 2006 to June 2007, the project "Mapping the Riviera Subduction Zone" (MARS) was conducted in collaboration between American and Mexican institutions. This project deployed a temporary seismic network using 50 broadband stations within the states of Michoacán, Colima, and Jalisco. However, the coverage of this temporary network did not cover the west side of the JB, which includes the northern coast of Jalisco, the Cabo Corrientes and Bahía de Banderas (BAB) areas. Seismic data obtained in this project have been used in a variety of studies (e.g., Gardine *et al.*, 2007; León-Soto *et al.*, 2009; Yang *et al.*, 2009; Spica *et al.*, 2014; Abbott and Brudzinski, 2015; Gutiérrez-Peña *et al.*, 2015; Ochoa-Chávez *et al.*, 2016; Pinzón *et al.*, 2016; Watkins *et al.*, 2018; and so on). The high level of seismicity in this region mandates long-term study and analysis using an adequate seismic network, with sufficient coverage for detection and robust hypocentral locations. Currently, besides RESCO, the SSN operates

doi: 10.1785/0220190107



▲ **Figure 1.** Seismotectonic framework along the Jalisco coast (modified from Núñez-Cornú *et al.*, 2018). a, Armería River; AA, aftershocks areas; ACA, Amatlan de Cañas – Ameca; b, Cohuayana River; CRZ, Colima rift zone; MIA, maximum intensity areas for earthquakes in 1932 (dates and magnitudes indicated); RFZ, Rivera fault zone; SPL, San Pedro Lagunillas; TRZ, Tepic–Zacoalco rift zone. Circles indicate locations of cities, and stars show the epicenters of the 4 December 1948 and the 2003 Armería earthquakes; seismic gaps proposed; triangles indicate Red Sismológica de Jalisco stations; squares indicate Colima Seismic Telemetric Network stations; inverted triangle indicates Chamela Servicio Sismologico Nacional station. (Inset) Location map of the study area within the North American continent.

two stations within the region. To monitor local seismic activity of the area more comprehensively and evaluate the seismic hazard, the Research Group "Centro de Sismología y Volcanología de Occidente (CA-UDG-276)" from UdeG initiated the deployment of the Jalisco Seismic Accelerometric Telemetric Network (RESAJ) a research project funded by Consejo Nacional de Ciencia y Tecnología—Fondos Mixtos Jalisco (Núñez-Cornú *et al.*, 2018). The first stage of this project began in 2010 with the deployment of 10 stations and the installation of the Central Lab at Puerto Vallarta Campus. RESAJ has better instrumental coverage than SSN and RESCO and is currently providing continuous data acquisition with 28 seismic stations covering a region from Islas Marías to CRZ.

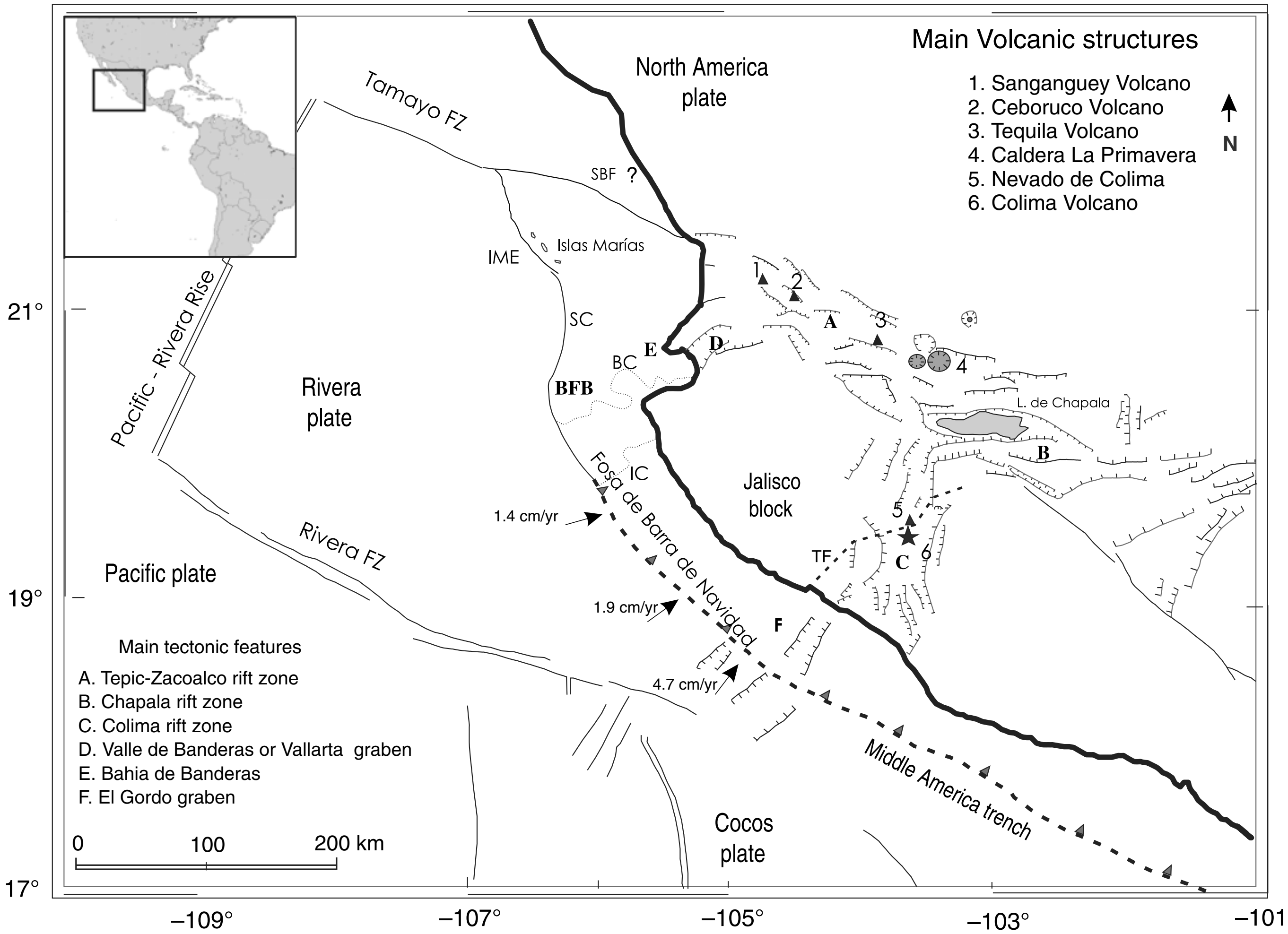
Between 2014 and 2016, the project "Crustal Characterization of the Rivera Plate–Jalisco Block Boundary and Its Implications for Seismic and Tsunami Hazard Assessment (TsuJal)" was undertaken by Mexican and Spanish institutions in this region and included an onshore–offshore geophysical and seismic (active and passive) experiment (Nuñez-Cornú *et al.*, 2016).

Núñez-Cornú and Sánchez-Mora (1999), published the first local seismicity studies in the region using RESCO data to observe the subduction angles of the Rivera plate (RP) below the southeast border of JB and the CRZ ranging between 12° and 20°. Using data from RESCO and a temporary seismic network deployed west and north of JB, Nuñez-Cornú *et al.* (2002) located ~250 earthquakes, which were distributed in three areas: BAB, Amatlán de Cañas - Ameca (ACA), and the coastal area associated with the Middle America trench (MAT). They used waveform analysis to identify two types of earthquakes in the MAT area: continental earthquakes located within the crust and in contact with the slab and oceanic earthquakes located inside the slab. The authors propose a subduction angle of 15° at 160 km inland from the trench and suggest that the slab bends and exhibits oblique subduction. Subsequent studies using data from RESJAL and RESCO have shown similar results (Núñez-Cornú *et al.*, 2003; Rutz-López *et al.*, 2003).

Núñez-Cornú *et al.* (2004) studied the Armería earthquake of 22 January 2003 M_w 7.4 and the related aftershocks, first using data from RESJAL and RESCO. After 72 hr, a portable seismic network was deployed to study aftershocks from 24 to 31 January 2003 (Núñez-Cornú *et al.*, 2010). They suggested that the Armería earthquake was the result of stress on the continental crust caused by oblique subduction, and found a subduction angle of 12° for the RP in agreement with Núñez-Cornú and Sánchez-Mora (1999).

Rutz-López *et al.* (2013) examined the seismicity in the area of BAB and the northern coast of Jalisco using data from RESJAL to characterize active crustal seismic structures. Based on the identification of seismic clusters using waveform cross correlation, they identified 404 earthquakes, which had magnitudes $M_L < 3.6$. Following earthquake relocation and estimation of focal mechanisms, they determined that 96 earthquakes were related to 17 potentially active continental structures.

Gutiérrez-Peña *et al.* (2015) analyzed and defined the geometry of the southern part of the RP and the northern part of the Cocos plate (CP) using the seismicity recorded by the MARS experiment. More than 2100 earthquakes were located using standard procedures and manually corrected phase and pick detections. They found that the slab of the CP subducts uniformly at an angle of ~30° with a slightly curved geometry, whereas the RP shows a low angle of subduction near the coast and then steepens inland. There is, however, no continuity of the hypocenters along with the projected RP slab in the profiles perpendicular to the trench that they presented. Both plates show oblique subduction toward the Colima graben; this is clear for the CP with a dip angle between 6° and 11°; however, again, there is no continuity of the hypocenters along with the projected slab for the RP in profiles parallel to the trench. Abbott and Brudzinski (2015) reprocessed the MARS seismic data adjusting the automatic location algorithm and obtained nearly 1600 earthquake locations for the 18 months. They identified two seismic clusters in the JB, one in the 2003 earthquake epicentral zone, and the second cluster north of this zone between Tamazula fault and the Armeria River. This latter cluster was previously studied by



▲ **Figure 2.** Tectonic framework of western Mexico: Rivera and Cocos plates subducting beneath the North American plate and transform faults zones associated with spreading. BC, Banderas Canyon; BFB, Banderas fore-arc block; IC, Ipala Canyon; IME, Islas Marías Escarpment; SBF, San Blas fault (proposed); SC, Sierra de Cleofas; SPL, San Pedro Lagunillas; TF, Tamazula fault. Modified from Núñez-Cornú *et al.* (2018). (Inset) Location map of the study area within the North American continent.

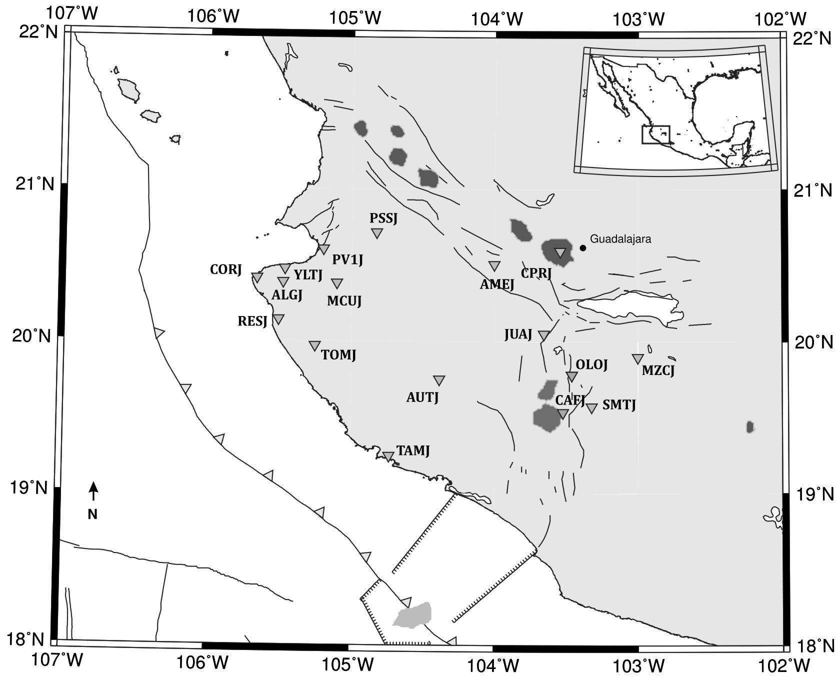
Núñez-Cornú and Sánchez-Mora (1999); seismic activity at the 2003 earthquake cluster can also be observed.

Using seismicity and wide-angle seismic data from a seismic profile, Nuñez-Cornú *et al.*, (2016) found that below BAB and Puerto Vallarta, the thickness of the subducted slab is about 10 km with a dip angle of 10°. Beneath Puerto Vallarta, the continental crustal depth is about 20 km.

To have an overview of the seismic patterns in the JB and get a preliminary seismogenic map of the JB, here we present the first study of seismicity in the region using RESAJ data recorded between June and December 2015, a period during which 17 stations were operating. Our results are then compared with results of seismicity studies carried out in the JB with temporal local seismic networks.

TECTONIC SETTING

Western Mexico (Fig. 1) resides at the intersection of the RP, CP, and North America tectonic plates (DeMets and Stein, 1990; DeMets *et al.*, 1994). Several triple junction locations have been proposed in the literature (Fig. 2), but the seismotectonic processes in operation remain poorly understood. The existence of a tectonic unit in this region, known as the JB, has been proposed by several researchers (Luhr *et al.*, 1985; DeMets and Stein, 1990; Allan *et al.*, 1991; Frey *et al.*, 2007). The JB is bounded on the east by the CRZ, 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, approximately northwest–southeast trend), defined as the northern limit of JB, and the Chapala rift zone (directions roughly from east to west). The connection between the northwest edge of JB and the continent (the Tamayo fault system) is not well defined. This border has been linked to the San Blas fault as a continuation of the TRZ, or the Islas Marías Escarpment (IME), west of the Islas Marías (Fig. 2). Recent studies (Dañobeitia *et al.*, 2016; Núñez-Cornú *et al.*, 2016) indicate that to the north of the Islas Marías there is no clear evidence of an active subduction zone (from north to south:



▲ **Figure 3.** Location of Jalisco Seismic Accelerometric Telemetric Network stations operating during 2015. (Inset) Location map of the study area within Mexico.

María Madre, María Magdalena, and María Cleofas). On the other hand, there are faults on the western flank of the Islas Marías, whereas to the south of María Cleofas Island, the subducted slab of the RP is delineated by the seismicity (Tinoco-Villa, 2015; Núñez-Cornú *et al.*, 2016). The BAB area is under substantial crustal stress due to the convergence of RP with the JB (Kostoglodov and Bandy, 1995). Shallow submarine hydrothermal activity (Núñez-Cornú *et al.*, 2000) on the northern side of BAB could be associated with these stresses.

DATA

The seismic data obtained for this analysis were recorded by the RESAJ using the Antelope system (Lindquist *et al.*, 2007); in 2015, RESAJ operated 17 seismic stations (Fig. 3) monitoring in real time (Núñez-Cornú *et al.*, 2018). The average interstation distance is 50 km. The stations are equipped with a Lennartz 3D 1 Hz sensor, a Quanterra Q330-6ch or Q330S-6ch Digital Adquisitation System digitizer and a model ES-T Kinemetrics episensor triaxial accelerometer; all stations have sampling frequency 100 samples per second. The data used for this study were recorded from June to December 2015.

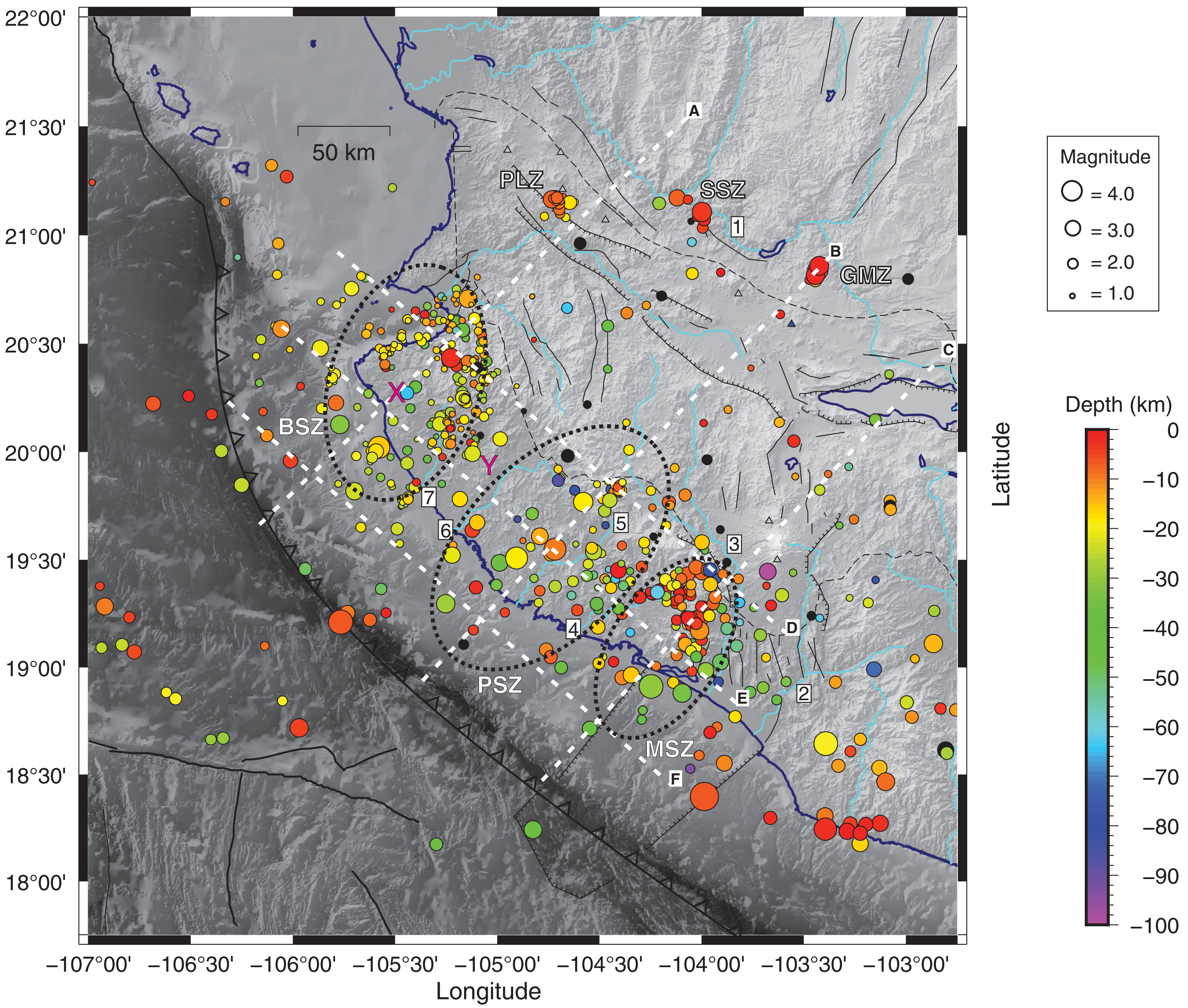
SEISMIC ANALYSIS

Automatic RESAJ preliminary locations are generated by Antelope system genloc algorithm (Lindquist *et al.*, 2007) and yielded 1034 detections for this period. The seismic records obtained by the RESAJ for the study period were read using the Antelope software, and the 1034 detections were revised. Earthquakes outside of the region and false detections were eliminated, and a total of 964 earthquakes were selected for relocation. To relocate the events, we used Hypo71PC (Lee and Valdés, 1985) with the *P*-wave velocity model proposed by Núñez-Cornú *et al.* (2002). The following criteria were used to select the earthquakes: at least four *P*-wave and two *S*-wave readings, root mean square of time residuals <0.5 s, epicentral error <10 km, and depth error <10 km; seven different depths were used as initial solutions.

The composite focal mechanism for seismic alignments was evaluated using the MEC93 code (Núñez-Cornú and Sánchez-Mora, 1999) operating on outputs from the Hypo71PC. MEC93 uses a probabilistic approach proposed by Brillinger *et al.* (1980) (also in Udías *et al.*, 1982). This program determines the orientation of the fault planes using the polarity of the first impulse of the *P*-wave arrivals to adjust the P and T axes to the observations, a probability function that combines the observations and the orientation of a model is maximized. It also calculates the strike, dip, and slip of both nodal planes, the direction of the P and T axes and the statistical uncertainty of each parameter. It uses a parameter p (or score), a relation between readings and theoretical amplitude values, as a measure of the fit of a set of observations concerning the joint solution.

RESULTS

From the 964 earthquakes selected, a total of 683 earthquakes met the Hypo71PC parameters defined for the location. These earthquakes had magnitudes $1.0 < M_L \leq 4.0$. From the epicentral distribution shown in Figure 4, we suggest three seismogenic crustal zones along the coast: (a) The BAB zone (BSZ), which includes the seismicity between the Tomatlan River (TR) and BAB; (b) The Purificación River zone (PSZ), which consists of the seismicity between the San Nicolas River (NR) and Marabasco River (MR), showing an southwest–northeast alignment; and (c) The Minatitlan seismogenic zone (MSZ), which includes seismicity between the MR and the Armería River (AR) and the seismicity along the as the west border of the CRZ. On the northern coast of Jalisco, two areas with relatively low rates of seismicity are observed, aseismic areas (ASA) X and Y (Fig. 4). Inland, we found three zones: San Pedro Lagunillas (PLZ); The Santiago River, in the area where the Bolaños River joins, Santiago seismogenic zone (SSZ), which is the epicentral area of the 11 February 1875 **M** 7.8 and 22 March 1878 **M** 7.1 earthquakes (Núñez-Cornú *et al.*, 2018); and the Guadalajara Metropolitan zone (GMZ). In the study period, we observed two earthquakes swarms: one at the BSZ between September and November with 34 earthquakes located south of Puerto Vallarta with magnitudes $1.4 < M_L < 3.5$ (Fig. 5a). To identify the type of faulting, we calculated a composite focal mechanism grouped in two, one with 10 earthquakes and other with seven

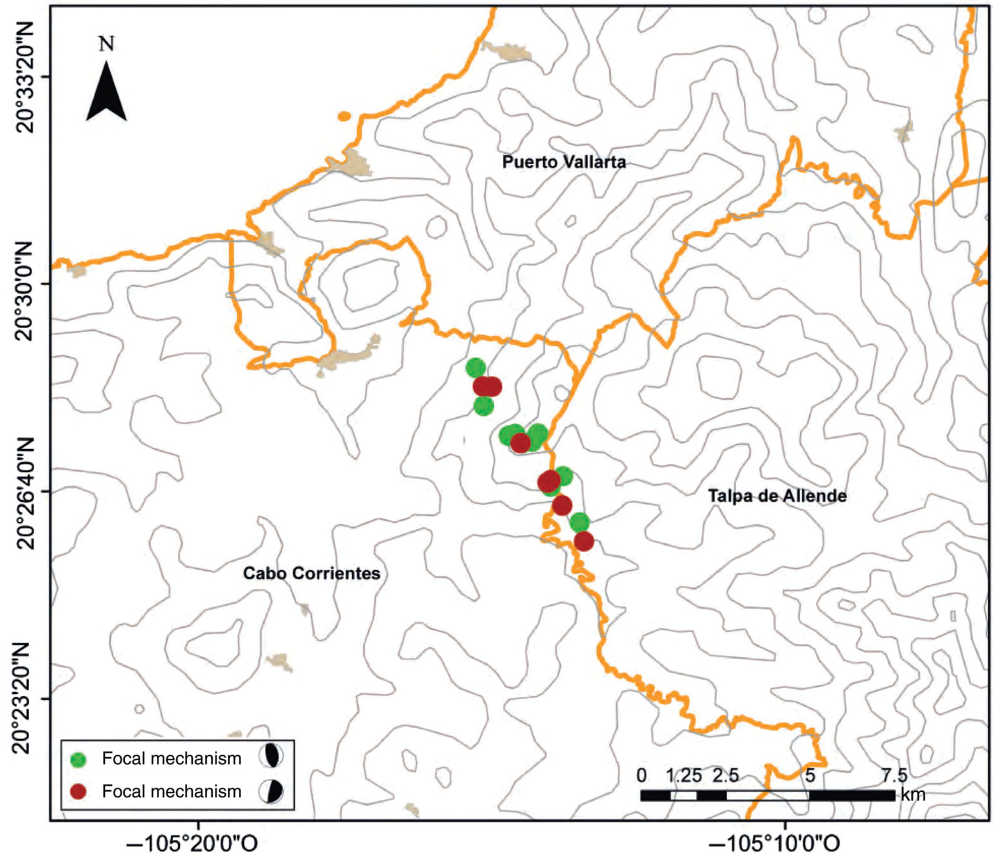


▲ **Figure 4.** Epicentral distribution of earthquakes for period June–December 2015. Seismogenic zones proposed: Bahía de Banderas zone (BSZ), Purificación River zone (PSZ), Minatitlan seismogenic zone (MSZ), Guadalajara Metropolitan zone (GMZ), SSZ, San Pedro Lagunillas zone (PLZ). X and Y: areas with low rates of seismicity (ASA). Profiles: A, B, C, D, E, and F indicated. Rivers: (1) Santiago (SR), (2) Cohuayana (CR), (3) Armería (AR), (4) Maravasco (MR), (5) Purificación (PR), (6) San Nicolas (NR), and (7) Tomatlan (TR).

earthquakes, both having a reverse-type focal mechanism (Fig. 5b). Fault planes were consistent with the hypocentral alignment direction (Fig. 5a); the second swarm with seven earthquakes located in the GMZ beneath the city of Zapopan, it has a northeast–southwest alignment direction with depths <20 km, $M_L < 3.0$, and a length of 7.8 km (Fig. 6a). The resulting composite focal mechanism using three earthquakes indicated normal fault on a plane in agreement with the epicentral alignment (Fig. 6b). In the study period, we did not observe seismicity in the ACA zone (Núñez-Cornú *et al.*, 2002) and the region of Islas Marias and Sierra de Cleofas (Tinoco-Villa, 2015). Other seismogenic zones could be identified considering the historical seismicity in the area, but there is still not enough seismic information to accurately define them.

It is clear that the number of hypocenters determined in this period is not sufficient to define the geometry of the slab, but some measurements can be inferred and compared with results of previous studies. To examine the depth distribution of the located earthquakes, three profiles (A, B, C) were constructed in a southwest–northeast direction from the trench, and three more (D, E, F) parallel to the trench (Fig. 4), to capture the areas where the most significant number of locations is grouped. Each profile is 300 km long and 100 km deep. In Figure 4, profile A has a width of 70 km, whereas profiles B and C have a width of 40 km. From these profiles (Fig. 7), we observed that the crustal seismicity is generated in the first 30 km of depth. The seismicity related to the subduction process ends about 160 km from the trench. We also observe that

(a)



(b)

I

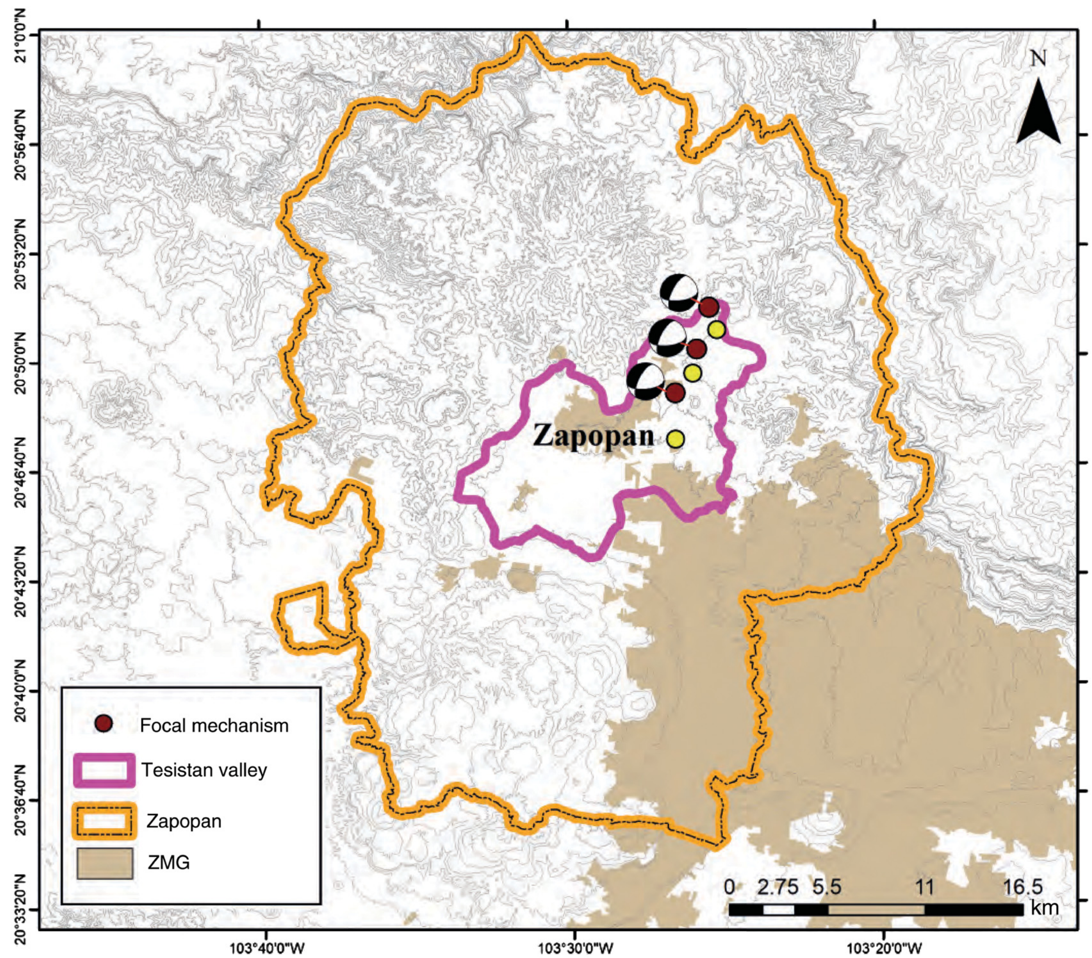
Vallarta mechanism 1														
Yr	mo	day	ho	min	sec	Ml	Npol	%	Planes(°)	Strike(°)	Dip(°)	Axis	Plunge(°)	Azim(°)
2015	06	29	15	22	52.62	1.12	35	0.94	A	353.02	36.02	P	9.75	57.69
2015	09	24	06	46	1.12	1.56			B	165.77	54.2	T	80.9	258.82
2015	09	24	20	25	1.14	1.25								
2015	09	28	21	36	1.04	1.20								
2015	09	29	07	04	26.45	1.50								
2015	09	29	07	44	12.36	1.17								
2015	10	01	16	40	47.81	1.08								
2015	10	20	22	59	29.30	1.08								
2015	11	13	00	17	33.98	1.17								
2015	11	17	18	24	35.69	2.52								

II

Vallarta mechanism 2														
Yr	mo	day	ho	min	sec	Ml	Npol	%	Planes(°)	Strike(°)	Dip(°)	Axis	Plunge(°)	Azim(°)
2015	09	24	05	16	1.58	1.48	23	0.88	A	48.49	16.78	P	32.66	87.94
2015	09	24	21	42	1.62	1.54			B	191.19	76.52	T	59.19	289.47
2015	09	25	00	14	1.03	1.32								
2015	09	27	03	41	1.55	1.18								
2015	10	10	04	35	1.85	2.24								
2015	10	10	04	35	1.85	2.51								
2015	10	20	02	56	1.79	1.66								

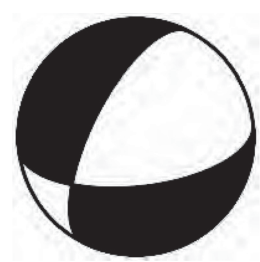
▲ **Figure 5.** (a) Epicentral distribution for seismic swarm in BSZ; (b) the composite focal mechanism for both solutions, earthquakes, focal planes, and score *p* (%).

(a)



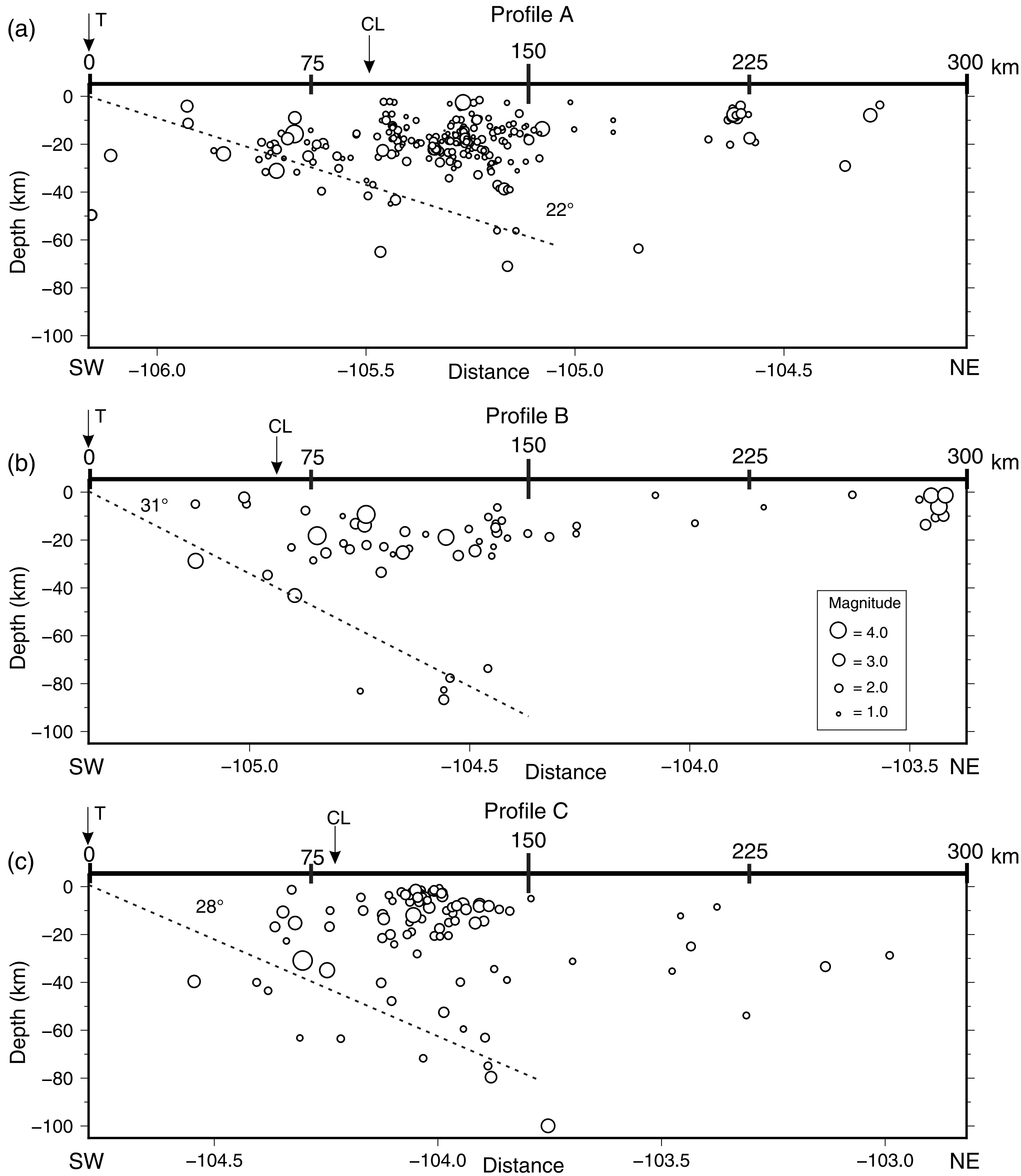
(b)

Zapopan mechanism														
Yr	mo	day	ho	min	sec	Ml	Npol	%	Planes	Strike(°)	Dip(°)	Axis	Plunge(°)	Azim (°)
2015	12	17	07	59	12.08	3.83	25	0.92	A	83.94	51.59	P	33.13	58.08
2015	12	15	16	09	23.36	4.08			B	206.64	55.73	T	87.64	324.46
2015	12	15	17	49	49.35	3.65								

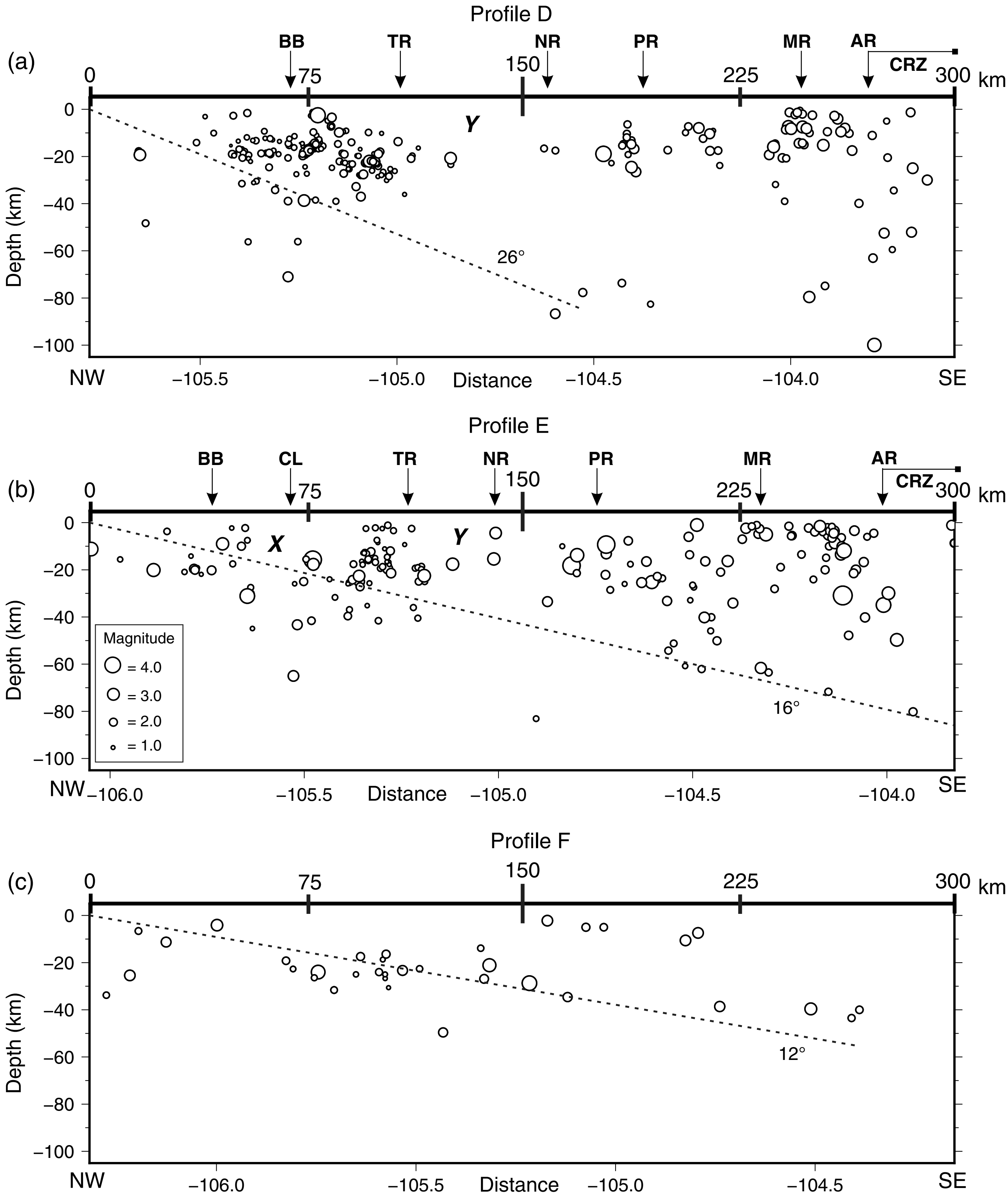


▲ **Figure 6.** (a) Epicentral distribution for seismic swarm in GMZ; (b) composite focal mechanism, earthquakes, focal planes, and score *p* (%).

the subduction angle for the RP varies along the JB. With the distribution of hypocenters available, different options can be drawn in the different profiles, for the hypocenters in profile A (Fig. 7a), we estimate a dip angle of 20° and 75 km is the maximum depth at which an earthquake is obtained. For profile B (Fig. 7b), the estimated subduction angle is 29°, and hypocenters reach a maximum depth of 70 km. The estimated dip angle for profile C is 22° (Fig. 7c). To observe the subduction geometry of RP parallel to the trench, we use profiles D, E, and F (Fig. 4), each one with a width of 40 km. In profile D (Fig. 8a), the Y ASA in the continental crust is determined between TR and NR; although there are not enough hypocenters to delimit the slab, the dashed line marks a dip angle of 26°. In profile E (Fig. 8b), the lack of hypocenters is obtained in the X ASA,



▲ **Figure 7.** Profiles (a) A, (b) B, and (c) C direction southwest (SW)–northeast (NE) (Fig. 4). CL, coastline; T, trench.



▲ **Figure 8.** Profiles (a) D, (b) E, and (c) F direction northwest (NW)–southeast (SE) (Fig. 4). BB, Bahia de Banderas coast. Symbology same as Figures 1 and 4.

between Bahía de Banderas (BB) and coastline (CL), and Y ASA in the continental crust can be observed between TR and NR: there is a lack of hypocenters in the slab between TR and MR; nevertheless, a 16° dip angle can be estimated. In profile F (Fig. 8c), a 12° dip angle is discernable.

DISCUSSION

Using the MARS Project data, Gutiérrez-Peña *et al.* (2015) and Abbott and Brudzinski (2015) extracted a catalog of 2100 and 1600 earthquakes, respectively. In both cases, roughly half of the earthquakes are located in the JB and the other half in the CRZ and Michoacán region. In these studies, 350 and 265 earthquakes were obtained on average per semester in the JB, respectively. Although these catalogs do not include the seismicity of BSZ, Rutz-López *et al.* (2013) reported a list of 400 earthquakes in that zone for the year 2003. Ultimately, our sample of 683 earthquakes can be considered representative of the seismicity of one semester in the JB. Because of the station's distribution in the RESAJ network, the seismicity relocated provides reasonable confidence in solution quality for most of the events.

Locations are consistent with seismicity reports by Núñez *et al.* (2019) and agree with the epicentral map from Abbott and Brudzinski (2015). The seismicity map from Núñez *et al.* (2019) supports the existence of X and Y ASAs. There are historic seismic reports for the SSZ and GMZ. In the case of PLZ, no previous instrumental or historical seismicity is known, but a newly installed geothermal power plant in the epicentral zone; although no information about the operation of the plant is available, the activity in this zone could be related to fluid extraction and injection processes at the power plant. In the case of the swarm in the GMZ, there are historical reports of seismic swarms, some of which were very destructive. Another such swarm occurred in May 2016, and the resulting focal mechanism for this alignment indicated normal faulting, in agreement with the work of Rengifo-Alcantara (2017) and Singh *et al.* (2017). The seismic swarm that took place in the BSZ confirms the existence of active crustal faults in the zone reported by Rutz-López *et al.* (2013) as result of the complex tectonic stresses in the zone (Kostoglodov and Bandy, 1995).

Our profiles in perpendicular and parallel direction to the trench do not have the same orientations or width of those profiles used in the different studies published (Núñez-Cornú *et al.*, 2002, 2003; Rutz-López and Núñez-Cornú, 2004; Abbott and Brudzinski, 2015; Gutiérrez-Peña *et al.*, 2015; Núñez *et al.*, 2019; and so on). In addition, Abbott and Brudzinski (2015) and Gutiérrez-Peña *et al.* (2015) do not take into account the magnitude of the earthquakes, which is essential to define the structural features. More specifically, in the case of Abbott and Brudzinski (2015), a different *P*-wave velocity model was used, which implies that the measured depths could be significantly different. Hence, it is difficult to compare their dip subduction angles to ours. However, all the studies failed to employ enough hypocenters to define the slab clearly. Our profiles B is approximately similar to profiles b from Gutiérrez-Peña *et al.* (2015); our profile C to profile d from Gutiérrez-Peña *et al.* (2015) and profile 3b from Núñez-Cornú and Sánchez-Mora (1999) in both cases hypocenter distributions are roughly in agreement with one another although the interpretation differs.

Our profiles D, E, and F are similar to profiles A, C, and D from Gutiérrez-Peña *et al.* (2015), again hypocenter distributions roughly coincide, but the interpretation is slightly different. In this case, besides the oblique subduction tilted toward the CRZ observed in profiles D, E, and F (Fig. 8), the change in the estimated dip angles estimated in these profiles indicates a bending of RP as suggested by Núñez-Cornú *et al.* (2002). It is not clear what is the origin or causes of ASA's X and Y, in the case of Y is clearly observed in profiles D and E in the continental crust and lack of hypocenters in the area of the slab is observed in profile E and profiles B and C from Gutiérrez-Peña *et al.* (2015).

CONCLUSIONS

This first study of the seismicity in the JB region using the RESAJ network data shows its importance in understanding local seismotectonic processes and confirming the complex tectonics of the region. The analysis of 683 earthquakes that were relocated for the period June–December 2015 provides a general vision of the seismicity in the region and supports the results of studies conducted in different times and areas of the JB (Núñez-Cornú and Sánchez-Mora, 1999; Núñez-Cornú *et al.*, 2002, 2003; Rutz-López and Núñez-Cornú, 2004; Rutz-López *et al.*, 2013; Abbott and Brudzinski, 2015; Gutiérrez-Peña *et al.*, 2015). Besides the seismicity associated with the subduction process, our study sheds light on the following crustal continental seismogenic areas: BSZ, PSZ, MSZ, GMZ, and SSZ. The origin of the seismic activity at PLZ remains unclear at this point. During the study period, two seismic swarms are obtained, and no relevant seismicity was observed in the Islas Marias and ACA regions. The subduction angles estimated with this dataset for the RP up to 150 km from the trench vary between 20° and 29° (profiles A, B, and C). Furthermore, profiles D, E, and F suggest oblique subduction and bending of the RP.

We consider Figure 4 as a preliminary seismogenic map for JB. More data from RESAJ is required to carry on detailed studies for each seismogenic zone to efficiently evaluate the seismic hazard in the JB. One of the first achievements of this study is the deployment of a local telemetric seismic network at the GMZ.

DATA AND RESOURCES

All geophysical data collected by Jalisco Seismic Accelerometric Telemetric Network (RESAJ) are in a database at Centro de Sismología y Volcanología de Occidente (CA-UDG-276) (SisVOc). The data may be available for use in collaborative research projects between CA-SisVOc and other interested institutions by specific agreements. For more information, please contact at pacornu77@gmail.com. Hypocenters were located using HYPO71PC (Lee and Valdés, 1985). Focal mechanisms were evaluated using MEC93 code (Núñez-Cornú and Sánchez-Mora, 1999). Maps and profiles were generated using Generic Mapping Tools (GMT) v.5.5 (Wessel and Smith, 1998).

ACKNOWLEDGMENTS

The authors are grateful to Charlotte Rowe for her fruitful observations and valuable comments, including the revision of the English language, which significantly improved the article. The authors are grateful for thoughtful reviews by anonymous reviewers. This research is funded by Projects: Proyecto (Centro Mexicano de Inovación en Energía Geotérmica [CeMIEGeo]). P24 Secretaría de Energía MEXICO-Consejo Nacional de Ciencia y Tecnología (SENER-CONACyT) 201301-207032, CONACyT-Fondos Mixtos Jalisco (FOMIXJal) 2008-96567 (2009), CONACyT–FOMIXJal 2008-96539 (2009), CONACyT-FOMIXJal 2010-149245 (2010), and Universidad de Guadalajara (UdeG) internal Projects; Tatiana Marín-Mesa was funded by a Master Scholarship from CONACYT, CVU 705850, Reg. 436649. The authors thank Quiriart Gutierrez Peña for his help in data processing and Claudia B. M. Quinteros Cartaya for the elaboration of the figures.

REFERENCES

Abbott, E. R., and M. R. Brudzinski (2015). Shallow seismicity patterns in the northwestern section of the Mexico Subduction Zone, *J. S. Am. Earth Sci.* **63,** 279–292, doi: 10.1016/j.jsames.2015.07.012.

Allan, J. F., S. A. Nelson, J. F. Luhr, I. S. E. Carmichael, M. Wopat, and P. J. Wallace (1991). Pliocene recent rifting in SW México and associated volcanism an exotic terrane in the making in Dauphin, in *The Gulf and Peninsular Province of the Californias*, J. P. Dauphin and B. R. T. Simoneit (Editors), American Association of Petroleum Geologists Memoir, Vol. 47, 425–445.

Brillinger, D., A. Udías, and B. A. Bolt (1980). A probability model for regional focal mechanism solutions, *Bull. Seismol. Soc. Am.* **70,** 149–170.

Courboulex, F., M. A. Santoyo, J. F. Pacheco, and S. K. Singh (1997). The 14 September 1995 (M=7.3) Copala, Mexico, earthquake: A source study using teleseismic, regional, and local data, *Bull. Seismol. Soc. Am.* **87,** 999–1010.

Dañobeitia, J. J., R. Bartolomé, M. Prada, F. J. Nuñez-Cornú, D. Córdoba, W. L. Bandy, F. Estrada, A. L. Cameselle, D. Nuñez, and A. Castellón (2016). Crustal architecture at the collision zone between Rivera and North American plates at the Jalisco block: Tsujal project, *Pure Appl. Geophys.* **173,** 3553–3573, doi: 10.1007/s00024-016-1388-7.

DeMets, C., and S. Stein (1990). Present-day kinematics of the Rivera plate and implications for tectonics in southwestern México, *J. Geophys. Res* **95,** no. B13, 21,931–21,948.

DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein (1994). Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions, *Geophys. Res. Lett.* **21,** 2191–2194.

Escobedo, D., J. Pacheco, and G. Suarez (1998). Teleseismic body-wave analysis of the 9 October 1995 (M_w 8), Colima-Jalisco, Mexico earthquake, and its largest foreshock and aftershock, *Geophys. Res. Lett.* **25,** 547–550.

Frey, M., R. A. Lange, C. M. Hall, H. Delgado-Granados, and S. E. Carmichael (2007). Al Pliocene ignimbrite flare-up along the Tepic-Zacoalco rift: Evidence for the initial stages of rifting between the Jalisco block (Mexico) and North America, *Geol. Soc. Am. Bull.* **119,** nos. 1/2, 49–64.

Gardine, M., T. Dominguez, M. West, S. Grand, and S. Suhardja (2007). The deep seismic structure of Volcan de Colima, Mexico, *Eos Trans. AGU* **88,** no. 23 (Jt. Assem. Suppl.), Abstract T51A–02.

Gutiérrez-Peña, Q. J., C. R. Escudero, and F. J. Núñez-Cornú (2015). Geometry of the Rivera-Cocos subduction zone inferred from local seismicity, *Bull. Seismol. Soc. Am.* **105,** no. 6, 3104–3113.

Kostoglodov, V., and W. Bandy (1995). Seismotectonic constraints on the convergence rate between the Rivera and North American plates, *J. Geophys. Res.* **100,** no. B9, 17,977–17,989.

Lee, W. H. K., and C. M. Valdés (1985). HYPO71PC; a personal computer version of the HYPO71 earthquakes location program, *U.S. Geol. Surv. Open-File Rept. 85-749*.

León-Soto, G., J. F. Ni, S. P. Grand, E. Sandoval, R. W. Valenzuela, M. Guzmán Speziale, J. M. Gómez González, and T. Domínguez Reyes (2009). Mantle flow in the Rivera-Cocos subduction zone, *Geophys. J. Int.* **179,** 1004–1012, doi: 10.1111/j.1365-246X.2009.04352.x.

Lindquist, K. G., R. L. Newman, and F. L. Vernon (2007). The antelope interface to PHP and applications: Web-based real-time monitoring, *Seismol. Res. Lett.* **78,** no. 6, 663–670, doi: 10.1785/gssrl.78.6.663.

Luhr, J., S. Nelson, J. Allan, and I. Carmichael (1985). Active rifting in southwestern Mexico: Manifestations of an incipient eastward spreading-ridge jump, *Geology* **13,** 54–57.

Núñez, D., F. J. Núñez-Cornú, F. J. Escalona-Alcazar, D. Córdoba, J. Y. López Ortiz, J. L. Carrillo de la Cruz, and J. J. Dañobeitia (2019). Seismic structure of southern Rivera plate and Jalisco block subduction zone, *Seismol. Res. Lett.* doi: 10.1785/0220180399.

Núñez-Cornú, F. J. (2011). Peligro Sísmico en el Bloque de Jalisco, México, *Rev. Geofís.* 23, 199–229, doi: 10.5209/rev_FITE.2011.v23.36919 (in Spanish).

Núñez-Cornú, F. J., and C. Sánchez-Mora (1999). Stress field estimations for Colima volcano, Mexico, based on seismic data, *Bull. Volcanol.* **60,** 568–580.

Núñez-Cornú, F. J., D. Córdoba, J. J. Dañobeitia, W. L. Bandy, M. Ortiz Figueroa, R. Bartolome, D. Núñez, A. Zamora-Camacho, J. M. Espindola, A. Castellon, *et al.* (2016). Geophysical studies across Rivera plate and Jalisco block, Mexico: TsuJal project, *Seismol. Res. Lett.* **87,** 59–72, doi: 10.1785/0220150144.

Núñez-Cornú, F. J., M. López, V. Márquez, C. Suarez, and E. Trejo (2010). Using an enhanced dataset for reassessing the source region of the 2003 Armerıa, Mexico earthquake, México, *Pure Appl. Geophys.* **168,** 1293–1302.

Núñez-Cornú, F. J., R. L. Marta, F. A. Nava, G. Reyes-Dávila, and C. Suárez-Plascencia (2002). Characteristics of the seismicity in the coast and north of Jalisco block, Mexico, *Phys. Earth Planet. In.* **132,** 141–155.

Núñez-Cornú, F. J., R. M. Prol, A. Cupul-Magaña, and C. Suarez-Plascencia (2000). Near shore submarine hydrothermal activity in Bahia Banderas, *Geofís. Int.* **39,** no. 2, 171–178.

Núñez-Cornú, F. J., G. A. Reyes-Davila, M. Rutz Lopez, E. Trejo Gomez, M. A. Camarena-Garcia, and C. A. Ramirez-Vazquez (2004). The 2003 Armería, Mexico earthquaque (M_w 7.4): Mainshock and early aftershocks, *Seismol. Res. Lett.* **75,** 734–743.

Núñez-Cornú, F. J., M. Rutz-López, C. Súarez-Plascencia, F. A. Nava, and G. Reyes-Davila (2003). Seimotectonics of Jalisco Block, *Geol. Soc. Am. Abstr.* **35,** 71–72.

Núñez-Cornú, F. J., J. M. Sandoval, E. Alarcón, A. Gómez, C. Suárez-Plascencia, D. Núñez Escribano, E. Trejo-Gómez, O. Sanchez-Mariscal, J. Guadalupe Candelas Ortiz, and L. M. Zúñiga-Medina (2018). The Jalisco Seismic Accelerometric Telemetric Network (RESAJ), *Seismol. Res. Lett.* **89,** 363–372, doi: 10.1785/0220170157.

Ochoa-Chávez, J., C. Escudero, F. J. Núñez-Cornú, and W. Bandy (2016). P-wave velocity tomography from local earthquakes in western Mexico, *Pure Appl. Geophys.* **173,** 3487–3511, doi: 10.1007/s00024-015-1183-x.

Pacheco, J. F., S. K. Singh, J. Domínguez, A. Hurtado, L. Quintanar, Z. Jiménez, J. Yamamoto, C. Gutierrez, M. Santoyo, W. Bandy, *et al.* (1997). The October 9, 1995, Colima-Jalisco, Mexico earthquake (M_w 8): An aftershock study and a comparison of this earthquake with those of 1932, *Geophys. Res. Lett.* **24,** 2223–2226.

Pinzón, J., F. J. Núñez-Cornú, and C. A. Rowe (2016). Magma intrusion near Volcan Tancítaro: Evidence from seismic analysis, *Phys. Earth Planet. In.* **262,** 66–79, doi: 10.1016/j.pepi.2016.11.004.

Rengifo-Alcantara, W. M. (2017). Estudio de la Secuencia Sísmica Ocurrida en el Norte de la Zona Metropolitana de Guadalajara (ZMG) el 11 de Mayo de 2016, *Ms. Sc. Thesis, Maestría en Ciencias en Geofísica*, Univ. de Guadalajara, 50 pp. (in Spanish).

Rutz-López, M. (2007). Peligro Sísmico en Bahía de Banderas, *Ms. Sc. Thesis, Maestría en Ciencias en Geofísica*, Univ. de Guadalajara, 77 pp. (in Spanish).

Rutz-López, M., and F. J. Núñez-Cornú (2004). Sismotectónica del Norte y Oeste del Bloque de Jalisco usando datos sísmicos regionales, *GEOS* **24,** no. 1, 2–13 (in Spanish).

Rutz-López, M., F. J. Núñez-Cornú, M. Camarena-García, E. Trejo-Gómez, G. Reyes-Davila, and C. Suárez-Plascencia (2003). Seismicity at Jalisco-Nayarit Border, Mexico, *Eos Trans. AGU* **84,** no. 46, F1139.

Rutz-López, M., F. J. Núñez-Cornú, and C. Suárez-Plascencia (2013). Study of seismic clusters at Bahía de Banderas región, Mexico, *Geofis. Int.* **52,** no. 1, 59–72.

Singh, S. K., D. Arroyo, X. Pérez-Campos, A. Iglesias, V. H. Espíndola, and L. Ramírez (2017). Guadalajara, Mexico, earthquake sequence of December 2015 and May 2016: Source, Q, and ground motions, *Geofis. Int.* **56-2,** 173–186.

Singh, S. K., L. Ponce, and S. P. Nishenko (1985). The great Jalisco, Mexico, earthquakes of 1932: Subduction of the Rivera plate, *Bull. Seismol. Soc. Am.* **75,** 1301–1313.

Spica, Z., V. M. Cruz-Atienza, G. Reyes-Alfaro, D. Legrand, and A. Iglesias (2014). Crustal imaging of western Michoacán and the Jalisco Block, Mexico from ambient seismc noise, *J. Volcanol. Geoth. Res.* **289,** 193–201, doi: 10.1016/j.jvolgeores.2014.11.005.

Tinoco-Villa, M. E. (2015). Detección y Análisis de Enjambres Sísmicos en la Corteza Oceánica al Sur de las Islas Marías, *Ms. Sc. Thesis, Maestría en Ciencias en Geofísica*, UdeG, 69 pp. (in Spanish).

Trejo-Gómez, E., M. Ortiz-Figueroa, and F. J. Núñez-Cornú (2015). Source model of the October 9, 1995, Jalisco-Colima tsunami as constrained by field surveys reports, and on numerical simulation of the tsunami, *Geofis. Int.* **54,** 149–159.

Udías, A., E. Buforn, D. Brillinger, and B. Bolt (1982). Joint statistical determination of fault-plane parameters, *Phys. Earth Planet In.* **30,** 178–184.

Watkins, D. W., C. H. Thurber, E. R. Abbott, and M. R. Brudzinsk (2018). Local earthquake tomography of the Jalisco, Mexico region, *Tectonophysics* **724**/**725,** 51–64, doi: 10.1016/j.tecto.2018.01.002.

Wessel, P., and W. H. F. Smith (1998). New, improved version of generic mapping tools released, *Eos Trans. AGU* **79,** 579.

Yang, T., S. P. Grand, D. Wilson, M. Guzman-Speziale, J. M. Gomez-Gonzalez, T. Dominguez-Reyes, and J. Ni (2009). Seismic structure beneath the Rivera subduction zone from finite-frequency seismic tomography, *J. Geophys. Res.* **114,** doi: 10.1029/2008JB005830.

Tatiana Marín-Mesa
Francisco J. Núñez-Cornú
Carlos Suárez-Plascencia
Centro de Sismología y Volcanología de Occidente (SisVOc)
Universidad de Guadalajara
Avenida Universidad 203
CP 48280 Puerto Vallarta, Jalisco, Mexico
tata11mm@gmail.com
pacornu77@gmail.com
carlos.csuarez@gmail.com

Published Online 7 August 2019