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Analysis of the Unusual Earthquake of 13 August 2006 in Michoacán, México[1]

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Abstract—The moderate earthquake of 13 August 2006 which occurred in the coastal area of Michoacán, México, offered the first opportunity to study an earthquake that has a focal mechanism oriented practically perpendicular to the vast majority of the earthquakes occurring along the subduction zone of the Mexican Pacific continental margin. The location and focal mechanism estimated in this study are in close agreement with those estimated by the Global Centroid Moment Tensor (CMT) project and the US Geological Survey, National Earthquake Information Center (NEIC) and place the earthquake in a complex tectonic region where 3 lithospheric plates converge. Our review shows that for the most severe historical earthquakes in the area the seismic recurrence period has expired, consequently the seismic hazard of this region is high and the analysis of the unusual event must be considered important. The main purposes of this study are (i) re-estimate the location and focal mechanism of the unusual event by using available seismic records close to the source, (ii) conduct a tectonic analysis of the area in relation with the previous fault plane estimated, (iii) evaluate the peak ground accelerations generated for this particular thrust event relative to those occurring during the more common events and (iv) generate the isoseismal map. The analysis of the intensities of this event together with a tectonic analysis of the area where this event occurred, attest to an unexpected behavior of this event in this region.

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1. INTRODUCTION

On the 13 August 2006 an unusual earthquake occurred at 15:14:28.4 GMT. The Global Centroid Moment Tensor (CMT) project database (henceforth referred to as the Global CMT Project) reported: a centroid location (latitude, longitude, depth) = (18.45° N, 103.63° W, 23.5 km), a centroid moment tensor solution with a seismic moment of Mo = 6.89e+20 Nm, equivalent to an M_w = 5.3 event; and focal mechanism (strike, rake, Dip) = (211°, 87°, 67°). The magnitude reported by the official seismological agency of México, Servicio Sismológico Nacional (SSN) is M_w = 5.2. Although several severe earthquakes have been located and studied in this region of subduction (e.g. Singh et al, 2003; Reyes et al., 1979; Mendoza and Hartzell, 1999; Yagi et al., 2004; Quintanar et al., 2011; Ramírez-Gaytán et al., 2010, 2011), the 13 August 2006 earthquake is interesting to study for the following reasons.

First, it has a focal mechanism that is uncommon for this area (Fig. 1). Namely, the nodal planes of the focal mechanism for this event strike perpendicular to the trench axis, nearly perpendicular to the nodal planes of the vast majority of the earthquakes occurring along the subduction zone of the Mexican Pacific margin. Due to the complex tectonics of this region of México, the occurrence of seismic events with these characteristics could be a normal but scarce seismic phenomenon, as has been observed in many regions of the world. For example, Astiz

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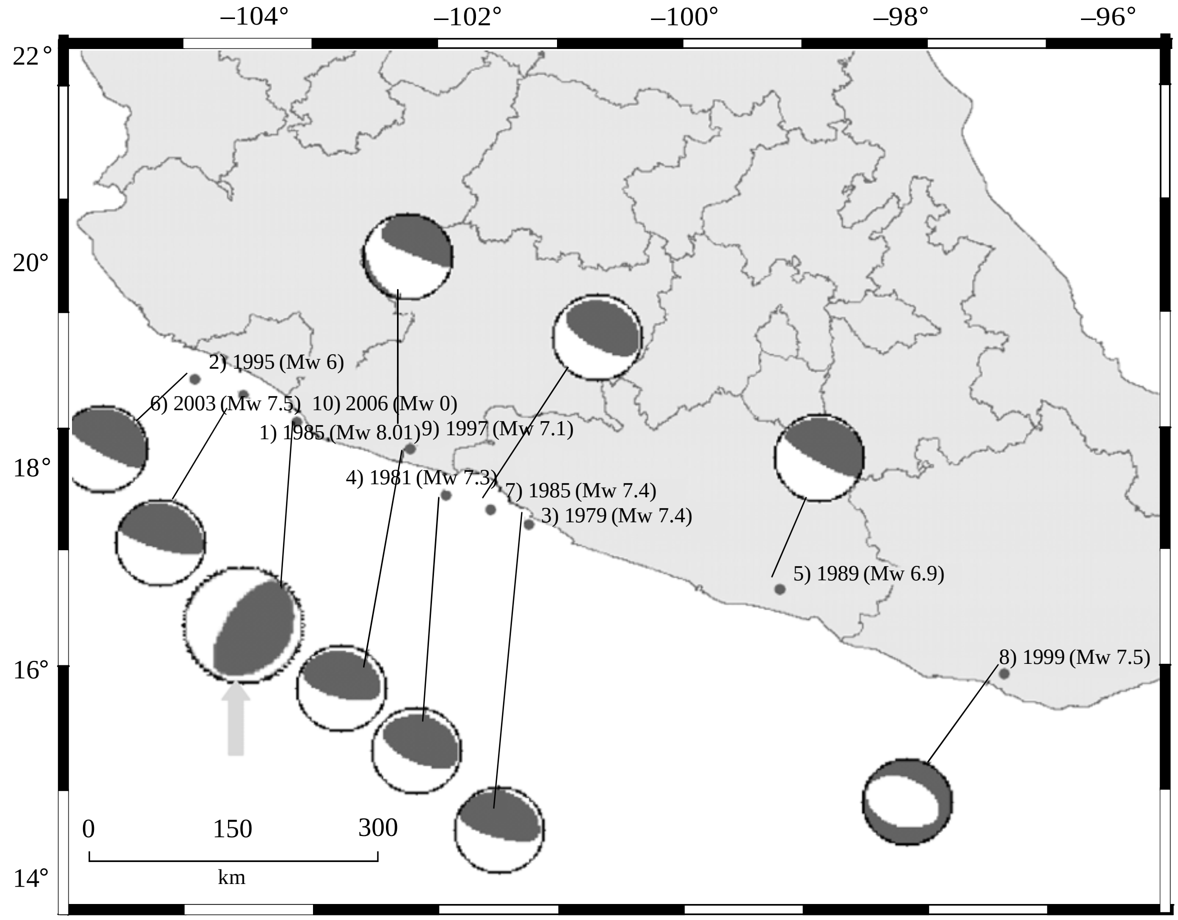

Fig. 1. Focal mechanisms of important earthquakes occurring in the Mexican Pacific coast. The large gray arrow shows the 13 August 2006 unusual earthquake studied herein (event number 10). Note that the strike of the nodal planes is perpendicular to that of typical earthquakes occurring in this subduction zone.

et al. (1988) conducted a study of the larger, tectonically significant events around the world, and explored the relation of intermediate-depth earthquakes to shallower seismicity. They compiled a worldwide catalog of focal mechanisms for events that occurred between 1960 and 1984 with $M > 6$ and depth between 40 and 200 km. Their final catalog includes 335 events grouped into four categories: (1) Normal-fault events (44% of the database), (2) Reverse-fault events (33% of the database), both with a strike nearly parallel to the trench axis, (3) Tear-faulting events (13% of the database), and (4) Normal or reverse-fault events with a strike significantly oblique to the trench axis (similar to event address in this study), which comprises 10% of the database. However, although these types of events represent 10% of the global database, none of the events listed in the database of Astiz et al. (1988) are located in the subduction zone of México. For this reason we consider that events with strike perpendicular to the trench axis are uncommon in the subduction region of México. Currently, the SSN is not officially reporting the focal mechanism of these events, so the most complete catalog of this type of information is the Global CMT project. Our reviews of this catalog from 1974 to the present show no other event with these characteristics in this region. Indeed, our seismic catalogs derived from the events recorded in our temporal and permanent seismic networks in the region show no other event with this characteristic. Astiz et al. (1988) discuss extensively the relation between the events type 1, 2, 3 and 4 and their relation with tectonic; also Lay et al. (1989), Astiz et al. (1989), and Astiz et al. (1986) discuss the temporal variation of focal mechanism and stresses in coupled subduction zones, however until now, the intensities of events whose nodal planes strike nearly perpendicular to the trench axis have not been considered in the construction of any empirical Ground Motion Prediction Equation (GMPE) in México.

Second, the specific region where this event locates has a particular seismic importance. Figure 2 shows that this event is located near the border of a small seismic gap (as defined by Quintanar et al., 2011) situated between the rupture area of the 2003 Tecomán earthquake and the rupture area of the 30 January 1973 earthquake (M_w 7.3)

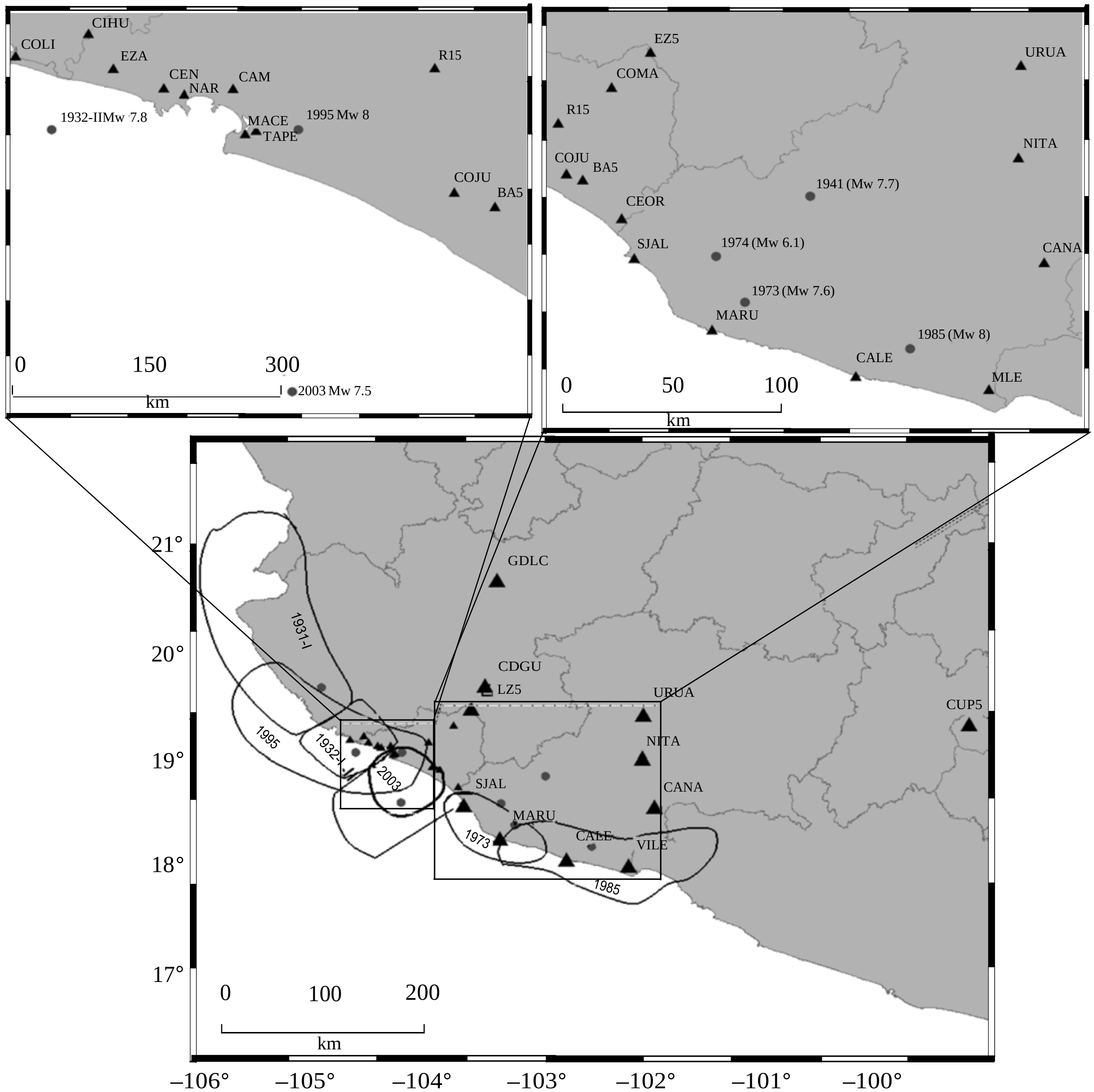

Fig. 2. Rupture areas of historic earthquakes in the region and acceleration stations used in this study. The areas enclosed by black curves show the rupture areas of historic earthquakes in this region (modified from Singh et al., 2003). Red filled circles mark the epicentral location of the most important events in region. Black filled triangles show the acceleration stations from IINGEN of UNAM, and the temporary network used in this study. Stations EZ5 and Rl5 correspond to the broadband stations from RESCO used in this study.

defined by Reyes et al. (1979); therefore, the seismic hazard of this region must be considered to be high. Specifically, Quintanar et al. (2011) show that the location of aftershocks of the Tecomán earthquake lies north of the southern boundary of the southern Colima Graben and that the aftershock area encompassed part of the rupture area of the 1932 and 1995 earthquakes. The region between the limits of the rupture areas of the 1995 and the 1973 earthquakes has been called the Colima seismic gap. The northwest half of this gap ruptured with the 2003 Tecomán earthquake. The other half of the gap, roughly to the southeast, remains quiet (Quintanar et al., 2011). For the adjacent region defined by the 30 January 1973 earthquake (M_w 7.3), Reyes et al. (1979) estimate an average slip of 144 cm. For this region plate motion models predict a convergence rate between the Cocos and North American plates of between 5.0 to 6.0 cm/yr (e.g., DeMets et al., 2010). This suggests a repeat time of about

25 to 30 years, which, considering the various uncertainties are in very good agreement with the interval of 32 years between the 1973 and the preceding 1941 earthquakes (Reyes et al., 1979). The possible occurrence of an earthquake is a sensitive topic in seismology and should be considered with caution. However from the above analysis of historical severe earthquakes in region, in addition to the studies of Quintanar et al. (2011), Reyes et al. (1979), and since it has been 38 years since the occurrence of the last major earthquake (the 1973 event), we conclude that recurrence period in the region has expired and therefore the seismic hazard in the region is high, consequently the analysis of the unusual event must be considered important.

There are some alternative methods to assess the differences between the intensities of the more common events recorded in the region and those generated by the unusual event. The use of recorded data of several Mexican subduction zone earthquakes with magnitudes ranging between 5.1 and 5.5 and with a strike nearly parallel to the trench axis could be an easy and convincing way to assess such differences. However, this possibility presents several difficulties: (i) available events to be used for the comparison are not close to our studied event, therefore any differences between Peak Ground Acceleration (PGA) for both events could be influenced by the differences of the crustal structure along the path of the two events and (ii) because of the differences in location of these events and our studied event with respect to recording stations, and considering their magnitude (5.1–5.5), not all stations recorded both events. Also, from the 24 records of accelerations analyzed in our study, 50% of these data (12 records) were derived from a temporal network that was installed for a period of 5 months in 2006. Thus, the records for events occurring before or after the operation of our temporal network are not available for these 12 stations. Another option is to take events recorded at other stations different from those that we used but with source-station distances similar to those used in our study. However, in addition to the case described above (differences between PGA of both events could be influenced by the differences of the crustal structure along the paths of the two events), it is possible that differences between PGA of both events could be influenced by the particular site effect of each station. The details described above are unacceptable to conduct a reliable assessment.

Another alternative is to compare the PGA of this particular event with appropriate empirical GMPE's for the region. After considering the above, we conclude that the best option to evaluate the intensities of our event in study is to compare the observed PGA of the 13 August 2006 earthquake with those calculated from four empirical GMPE's applicable for the region: namely, those of (i) Ordaz et al. (1989), (ii) Youngs et al. (1997), (iii) Arroyo et al. (2010) and (iv) Tejeda-Jácome and Chávez-García (2007). We propose that such a method is viable in that comparisons between a single event and an empirical GMPE have routinely been performed after an event happened and these four empirical GMPE's were constructed by using events with magnitudes within the range of the event studied herein.

2. TECTONIC SETTING OF THE REGION WHERE THIS EVENT OCCUR

According to Astiz et al. (1988) events similar to the one studied herein occur where the trench axis bends sharply, causing horizontal (parallel to the trench strike) extensional or compressional intraplate stress. The event in study occurred in a tectonically complex area of the Mexican subduction zone near to a major plate triple junction formed by the Rivera, Cocos and North American plates, the triple junction being located along the Middle America Trench (MAT) offshore of Manzanillo, México. The tectonic regime may be even more complicated as the interactions between these plates appears to have fragmented (1) the overriding North American plate into two kinematically independent crustal blocks, the Jalisco and Michoacán blocks, separated by the Colima Rift (e.g., Luhr et al., 1985; Johnson and Harrison, 1990; DeMets and Stein, 1990) and (2) the Cocos plate forming a kinematically distinct plate, the northern Cocos plate, situated between the Orozco and Rivera transforms (Bandy, 1992; Stock and Lee, 1994; Bandy et al., 2000; Dougherty et al., 2012). These fragmentations may be important as the epicenter of the 13 August 2006 earthquake is located along that part of the MAT where the northern Cocos plate is subducting beneath the Michoacán block and it is also possible that the 13 August 2006 earthquake is a reactivation of a pre-existing fault originally formed in response to this crustal fragmentation. Unfortunately, the motions of these blocks relative to their parent plates are not well established, but are most likely less than 1 cm/year (Bandy, 1992; Bandy and Pardo, 1994; Ferrari et al., 1994; Selvans et al., 2011; Kostoglodov et al., 2012). Thus, we ignore these blocks in our discussion. The hypocentral depth estimated by the National Earthquake Information Center (NEIC) (21.4 km), and the centroid depth (23.5 km) estimated by the Global CMT project are all roughly consistent with an event occurring on the main plate interface (20 km according to Pardo and Suárez, 1995); however, the focal mechanism is clearly not that of an event occurring along the plate interface with slip in the direction of plate convergence. For unusual event, in this study we estimated a depth of 16 km, given the close proximity (25 km) of the event to the southern Colima Graben it is also possible that this event was a reactivation of one of the faults associated with the southern Colima Rift. This rift is a major NE-SW oriented tectonic boundary: to the NW the Rivera plate subducts beneath the North American plate,

Table 1. The 24 local acceleration stations where the August 13 2006 earthquake was recorded

No	Station	*R*, km	Soil type	PGA, cm/s^2	Quadratic mean acceleration observed, cm/s^2					
					T 0.1 s	T 0.3 s	T 0.5 s	T 1 s	T 2 s	T 3 s
1	[1]SJAL	42.22	Rock	145.42	341.53	97.15	23.61	9.30	2.28	1.37
2	*CEOR	62.06	Rock	34.69	82.73	52.65	19.94	15.79	7.86	2.11
3	*BA5	85.91	Rock	60.61	85.99	117.84	29.79	13.31	3.92	1.28
4	[1]COJU	91.67	Rock	36.72	128.07	18.92	10.67	2.39	0.74	0.38
5	[1]MARU	19.81	Rock	58.73	179.94	47.37	33.96	6.43	1.65	0.84
7	*TAPE	121.68	Rock	14.45	30.75	8.20	3.08	0.91	0.25	0.14
6	"R15	115.05	Rock	10.30	19.26	20.75	8.19	4.71	0.69	0.25
8	[1]MANZ	122.43	Rock	19.07	74.75	12.82	4.35	1.04	0.26	0.17
9	*CAM	130.55	Rock	15.20	49.11	19.77	4.05	1.13	0.33	0.16
10	*NAR	135.41	Rock	16.35	35.01	72.78	12.00	1.63	0.46	0.22
11	*CEN	138.75	Rock	5.77	15.51	12.86	2.63	1.31	0.28	0.13
12	[1]COMA	124.3	Rock	6.66	19.03	13.81	9.45	4.00	1.50	0.76
13	*EZA	147.63	Rock	12.28	26.08	23.83	5.58	0.98	0.33	0.15
14	*CIHU	155.56	Rock	9.71	20.18	26.51	6.89	1.50	0.32	0.13
15	"EZ5	139.23	Rock	15.83	37.64	35.62	19.15	6.64	2.26	0.76
16	[1]COLL	161.83	Rock	4.95	13.54	6.58	2.25	0.69	0.19	0.09
17	[1]CALE	83.7	Rock	21.36	46.63	55.49	22.40	5.16	0.96	0.30
18	[1]CDGU	163.59	Rock	12.05	25.22	12.50	4.75	1.43	0.51	0.28
19	WILE	142.06	Rock	3.20	4.23	13.05	7.34	1.64	0.36	0.12
20	[1]NITA	175.92	Rock	7.93	18.61	15.85	9.01	2.96	0.45	0.22
21	[1]CANA	168.15	Rock	5.98	16.05	10.35	5.00	1.70	0.26	0.13
22	[1]URUA	202.72	Rock	2.90	3.97	10.49	3.49	1.21	0.39	0.18
23	[1]GDLC	273.48	Soil							
24	[1]CUP	474.03	Rock	0.31	0.33	0.80	0.70	0.49	0.35	0.19

[1] Stations from IINGEN.
* Stations from temporary network parallel to subduction.
" Stations for RESCO.
In this study only the 23 stations in rock were considered.

whereas, to the SE the Cocos plate subducts beneath the North American plate. Earthquake studies indicate active east-southeast extension within the rift (Pacheco et al., 2003; Global CMT project).

It is also worth noting that young lithosphere is beginning to enter the trench west of the southern Colima rift (Bandy, 1992; Bandy et al., 2000; Michaud et al., 2000, 2001; Peláez-Gaviria et al., 2013). Young lithosphere provides more resistance to subduction (England and Wortel, 1980) and therefore may affect the local stress regime in this area.

3. DATA AND RESOURCES

To relocate this event we use a total of 21 records. 14 records were provided for broadband stations of the SSN, all of them are permanent seismic stations equipped with Streckeisen STS-2 broadband sensors and Quanterra Q680 and Quaterra Q330 digitizers, recording at 100 samples per second; 3 records from permanent acceleration station of the Instituto de Ingenieria of the UNAM (IINGEN) all of them are Etna Episensor wideband accelerographs (from d.c. to 200 Hz, recording at 200 samples per second); and 4 records from temporary acceleration stations close to the source installed by us in the area in 2006 all of them Altus Etna wideband accelerographs (from d.c. to 100 Hz, recording at 100 samples per second). Figure 3 shows the locations of the 21 regional and local stations used in this study for the estimation of location and focal mechanism.

To evaluate ground motions of moderate events we use 23 observed records of the 13 August 2006 earthquake provided from three different data sources (Fig. 2).

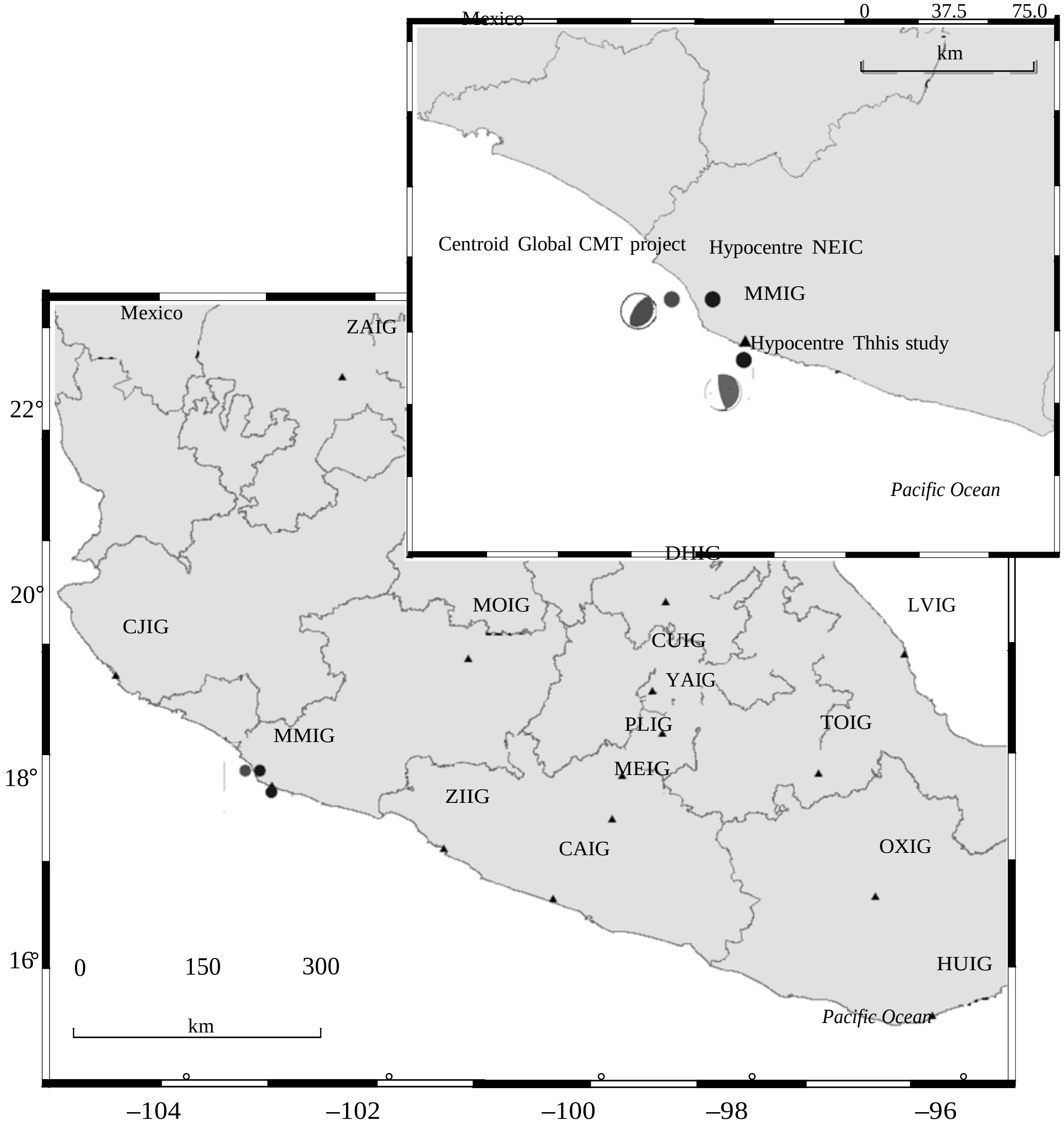

Fig. 3. Regional broadband stations (black triangles) used in the present study. Red filled circle of the inset figure marks the centroid location of the 13 August 2006 earthquake provided by the Global CMT project. Blue filled circles mark the location of the hypocenter provided by NEIC and those estimated in this study. Beach balls represent the focal mechanism determined by the Global CMT project and those estimated in this study. Beach ball reported by NEIC is the same focal mechanism provided by Global CMT project.

Table 1 describes the settings and observations at the 24 stations of permanent and temporal networks that recorded the event. However, because one of these stations locates in soft soil, we remove this station from the analysis. Two of the sources are permanent seismic networks which consist of 14 Etna Episensor wideband accelerographs (from d.c. to 200 Hz, recording at 200 samples per second) which are part of the national accelerations network of the Instituto de Ingeniería (IINGEN) of Universidad Nacional Autónoma de México (UNAM) and two Guralp CMG40T-DM24 flat response wideband velocity type seismographs (from 0.5 to 100 Hz, recording at 100 samples per second) which are part of the network Red Sísmica del Estado de Colima (RESCO). The third source of data was the temporal networks installed in the region as part of this project; the instruments used were: (i) four Altus Etna wideband accelerographs (from d.c. to 100 Hz, recording at 100 samples per second), and (ii) four model 18, Geosig strong-motion recorders, with analogue-digital converter, wideband accelerometers (from d.c. to 100 Hz, recording at 100 samples per second). Because 2 of the 24 records used in this study were velocity records, it was necessary to transform them to acceleration. Derived

Table 2. Velocity model used for the calculation of the epicenter using data of the Broadband Network of Servicio Sismologico Nacional (SSN) of Mexico

P-Wave Velocity (km/s)	Depth (km)
6.0	0.0
7.76	16.0
7.95	33.0
8.26	100.0
8.58	200.0
8.97	413.0

uncertainties of this transformation are negligible. Also, the instrumental response of each of the different instruments was removed.

4. CONFIRMATION OF LOCATION AND FOCAL MECHANISM

Logically, before starting with any task to evaluate ground motions of this unusual event, the first action is to confirm the location and focal mechanism provided by the Global CMT project for this unusual earthquake. To reach this objective we made use of a different methodology and different type of data than those used by the Global CMT Catalog and NEIC. The use of a different methodology and data could give more validity in the confirmation of such an unusual result. In our work we use regional and local broadband records whereas the Global CMT catalog uses teleseismic records. We estimated the epicenter of the 13 August 2006 earthquake by using 14 broadband stations of SSN and additionally data from 7 near-field strong motion stations (less of 100 km of the epicenter). Three of records were provided by the acceleration network of IINGEN, stations: MACE, MARU, SJAL and 4 acceleration records were provided by the temporary acceleration network installed by us in 2006 in the region, stations: BA5, CAM, CEN, EZA. The implication of the use of local data in our study should be the increase accuracy of the relocation and re-estimation of the focal mechanism. The location was estimated by using the Seisan program for earthquake analysis of Lienert and Havskov (1995). The crustal structure used (Table 2) was that obtained by Campillo et al. (1996). The estimated location derived in this study (Fig. 3 and Table 3) places this event offshore at 18.21° N, 103.35° W at a depth of 16 km. The hypocenter reported in the NEIC is located onshore at 18.284° N, 103.527° W at a depth of 23.6 km. The centroid reported for the Global CMT project is located offshore at 18.45° N, 103.63° W at a depth of 23.5 km. All locations (CMT, NEIC and this study) place the earthquake in a complex tectonic region where 3 lithospheric plates converge.

We estimated the fault plane solution by conducting a detailed review of the computational process in which we started with a thorough revision of the quality of the data. We removed three regional stations from the records available because we found some problems related with quality of data, specifically the first arrival was unclear or had too small a signal to noise ratio. In the end we kept 14 records provided by the broadband stations: ZIIG, CAIG, MMIG, OXXI, MEIG, PPIG, YAIG, PPIG, CUIG, DHIG, MOIG, ZAIG, CJIG, and LVIG, stations belonging to SSN. Additionally we kept the 7 records provided by IINGEN and one temporary regional net installed in the area, stations: MARU, SJAL, MACE, CEN, EZA, BA5, and CAM. In this way we kept a total of 21 reliable records to estimate the fault plane solutions by using the regional distribution of P-wave polarities by using the program for focal mechanism solutions FOCMEC developed by Huerfano et al. (2005). Figure 4 shows our new estimation of the beach ball diagram of the focal mechanism solution for the unusual event (strike,

Table 3. Location and focal mechanism reported by the global CMT project and that calculated by using regional and local stations

Centroid				
Institution	Date/Hour	Centroid location (Latitude, Longitude, Depth)	Focal Mechanism (Strike, Rake, Dip)	M_w
CMT	2006-08-13 15:14:28	18.450°, –103.630°, 23.5 km	211, 87, 67	5.3
Hypocenter				
Institution	Date/Hour	Hypocenter location (Latitude, Longitude, Depth)	Focal Mechanism (Strike, Rake, Dip)	M_w
NEIC	2006-08-13 15:14:25	18.284°, –103.527°, 23.6 km	211, 87, 67 (same as reported by Global CMT project)	5.3
This study	2006-08-13 15:14:25	18.21°, –103.35°, 16.00 km	162, 79, 82	—

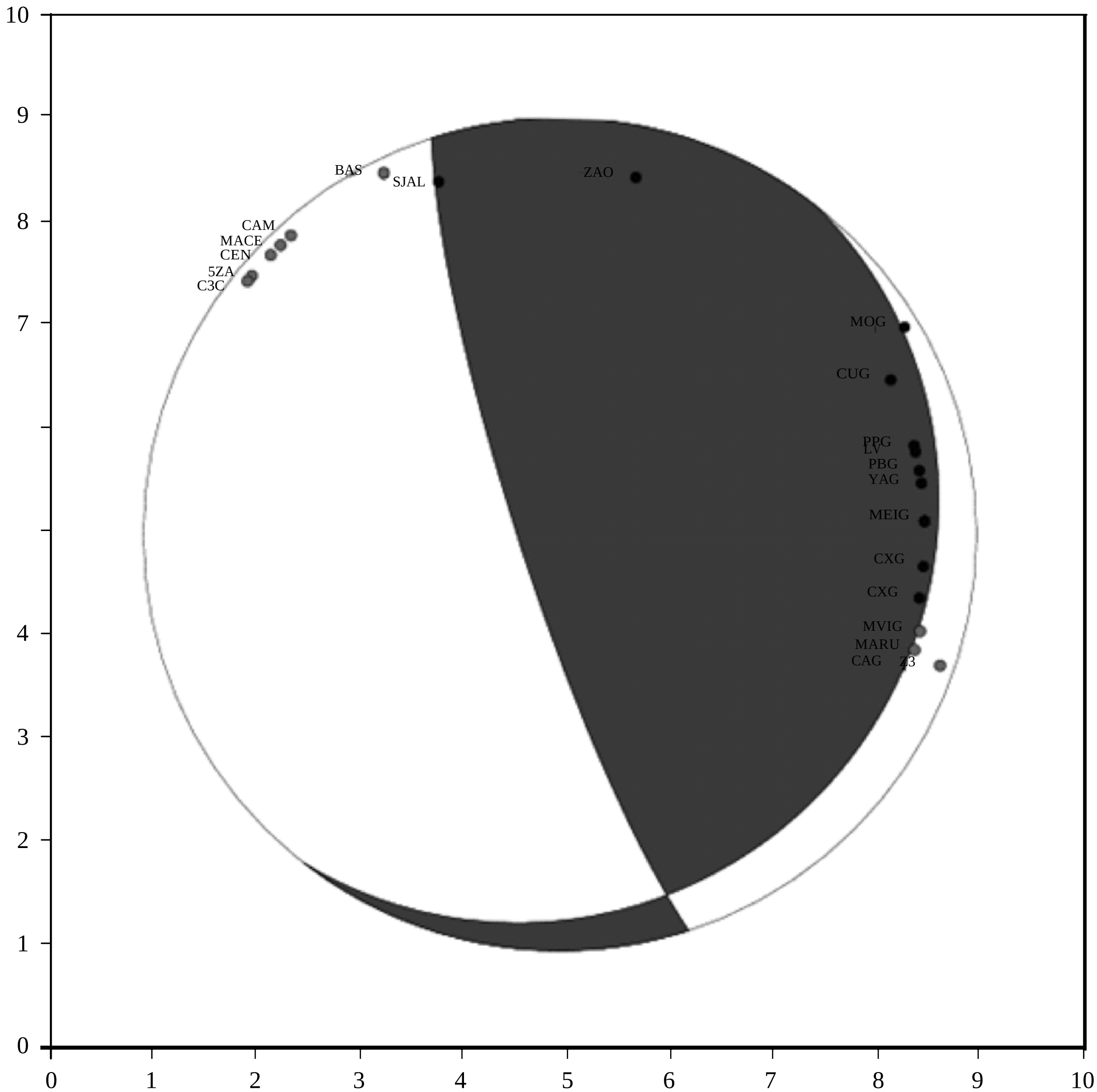

Fig. 4. Focal mechanism solution for the unusual event estimated in this study. Fault plane solution was estimated by using the regional distribution of P-wave polarities of 21 regional and local records. 14 records were provided by the broadband stations: ZIIG, CAIG, MMTG, OXXI, MEIG, PPIG, YAIG, PPIG, CUIG, DHIG, MOIG, ZAIG, CJIG, and LVIG, stations belonging to SSN. Additionally we kept the 7 records provided by IINGEN and one temporary regional net, stations: MARU, SJAL, MACE, CEN, EZA, BA5, and CAM.

dip, rake) for fault or auxiliary planes = (162°, 79°, 82° and 38°, 145°, 13°). The solution shows a resemblance with those obtained for CMT (strike, dip, rake) for fault or auxiliary planes (211°, 87°, 67°, and 38°, 96°, 23°), and NEIC (strike, dip, rake) for fault or auxiliary planes (211°, 87°, 67°, and 38°, 96°, 23°), in the sense that it is a reverse solution with strike nearly parallel to the convergence direction (i.e. roughly perpendicular to the trench).

For the focal mechanism of the 13 August 2006 earthquake estimated in this study and those provided by Global CMT project, there is no tectonic evidence to define which of the two nodal planes indicated in both focal mechanisms corresponds to the fault plane. However, in both cases the nodal planes are oriented practically parallel to the direction of the plate convergence and perpendicular to the fault planes of the great majority of the earthquakes in the region. The borders of Colima Graben exhibit a similar orientation as those provided by both focal mechanisms and also there are several submarine canyons located just NW of the epicenter of this event which also show an orientation similar to both nodal planes (Fig. 5). However, these alignments are insufficient

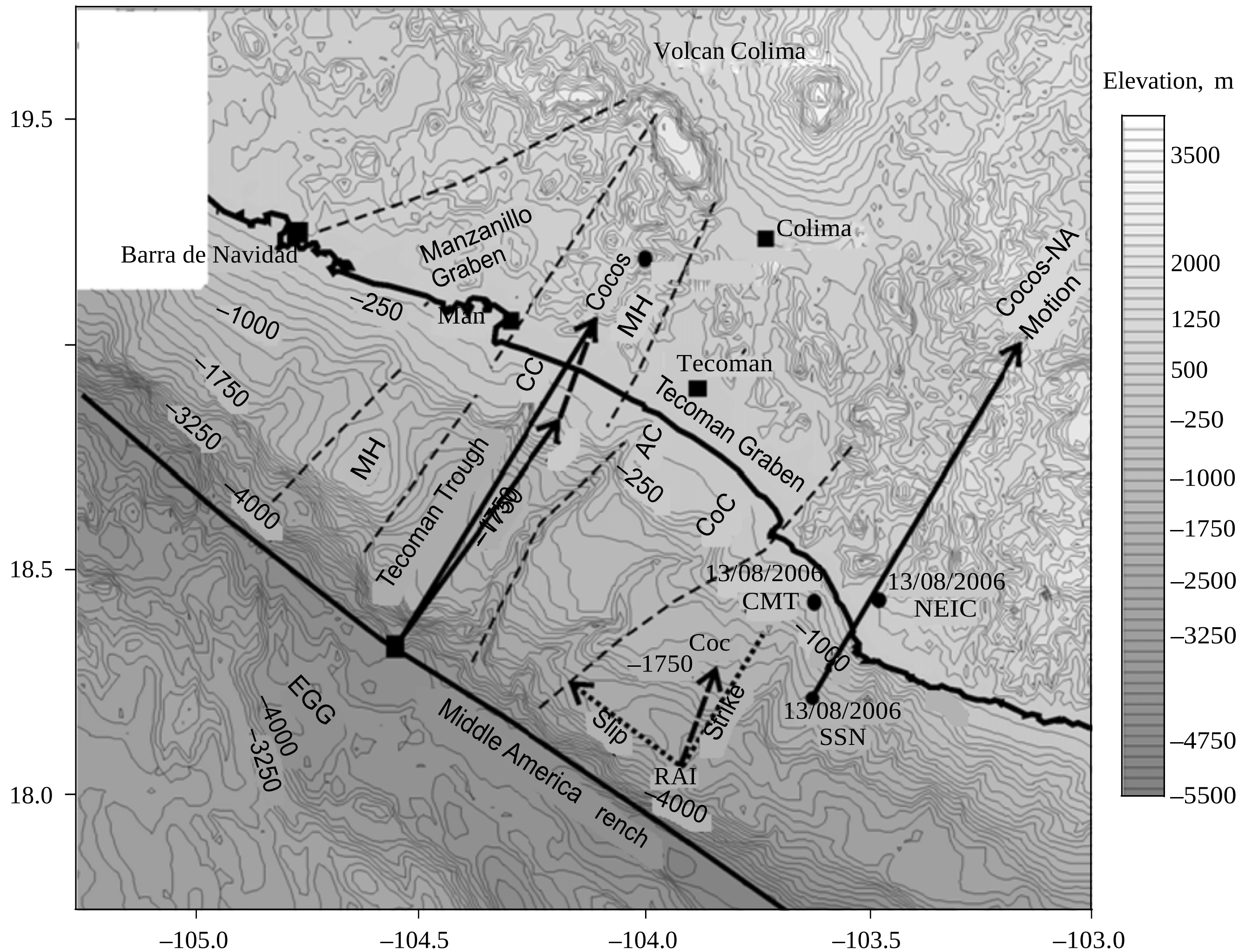

Fig. 5. Topographic/bathymetric contour map illustrating the main morphologic elements of the southern Colima rift. Also shown are the locations (solid circles) of the 13 August 2006 earthquake as reported by the CMT, NEIC and SSN as well as the epicenter of the March 7, 2000 normal event. The triangle at the intersection of the EGG and MAT is the velocity vector diagram illustrating.the relative motions between the Rivera, Cocos and North American plates at this plate triple junction. The Cocos-NA motion is also plotted at the SSN reported epicenter of the 13 August 2006 earthquake. The Rivera-Cocos relative motion vector (dashed arrow) is also illustrated in the epicentral area of the 13 August event along with the slip direction (dotted arrow) and the strike of the fault plane (dotted line) of this event. Note that the strike of the fault plane is parallel to a major submarine canyon in the offshore area near the epicenters. Abbreviations are: EGG = El Gordo Graben; MH = Manzanillo Horst; Coc = Cocos Plate; Riv = Rivera Plate; Man = Manzanillo; AC = Armeria Canyon; CC = Cuyutlan Canyon; CoC = Coahuayana Canyon. (Modified from Bandy et al., 2005).

to define which of the nodal planes corresponds to the fault plane.

5. EVALUATIONS OF THE UNUSUAL EVENT

Historical earthquakes from the Mexican subduction zone typically present focal mechanisms whose strikes are oriented parallel to that of the trench axis. The four local empirical GMPE's considered in this study were derived using earthquakes with this type of mechanism. However, we observed that some earthquakes (the oldest) used in the derivations of the empirical GMPE's used herein, are not reported by Global CMT project and it was not possible to define the orientation of the strike. But, in general, given the orientations of the focal mechanisms of data considered in these empirical GMPE's the energy radiates mostly landward in the direction of plate convergence. This is reflected in the respective curves of empirical GMPE's that characterize the attenuation. In the case of the 13 August 2006 earthquake, as discussed above, there is no tectonic evidence to define which of the two strikes indicated by the focal mechanism corresponds to the fault plane. However, both planes are oriented practically parallel to the direction of the plate convergence and perpendicular to the fault planes of the great majority of the earthquakes in the region. Usually, these kinds of faults have a lateral slip motion since this accounts for the differences in slip between the two adjacent subducting plate sections. Thus, the strike slip component should be larger.

To compare the values of the PGA and pseudo-acceleration spectra of the 13 August 2006 event we use the magnitude reported by the SSN (M_w = 5.2). This magnitude had been published since 2006 on the web site of the CMT Mexican Project (which is presently being renovated). For the purpose of our study, we made use of the magnitude reported by SSN (M_w = 5.2) for the following reasons: (i) The implication of the use of regional data of SSN should be the increase accuracy estimation of the magnitude of this event and (ii) because it allows us to apply the recent empirical GMPE published by Tejeda-Jácome and Chávez-García (2007) which considers earthquakes in the range between 3.3 M_w to 5.2 M_w. The importance to apply this empirical GMPE in our study is because this empirical GMPE is derived from earthquakes recorded in the same area where the unusual event occurred and propagated.

Four different empirical GMPE's that consider earthquake data from subduction tectonic environments are used in this work to make the comparison, namely: (1) the empirical GMPE of Ordaz et al. (1989) who used subduction earthquakes from the Mexican Pacific coast; (2) the empirical GMPE of Youngs et al. (1997) which considers subduction earthquakes from around the world; (3) the empirical GMPE of Arroyo et al. (2010) which considers Mexican interplate earthquakes; and (4) the empirical GMPE of Tejeda-Jácome and Chávez-García (2007) which considers 26 earthquakes recorded in the same region where the event in study occurred, events with $3.3 < M < 5.2$ and $5 <$ depth < 76 km.

A response spectrum is another, more meaningful way to characterize earthquake ground motions. The response spectrum is a good indicator of the level of response that may be induced by a particular ground motion in a set of different structures. Therefore, pseudo-acceleration spectra were also computed from observed records for 30 linearly elastic systems for viscous damping of 5% between 0.1 and 3 s (0.3–10 Hz). Then, the geometric mean of the 5% damping response spectral ordinates of the two horizontal components at each station were computed in agreement with the procedure followed in each empirical GMPE compared herein (Fig. 6).

Before proceeding with the comparison it is necessary to clarify that empirical GMPE's are usually developed using recorded ground motion data from several earthquakes and expressed statistically by its mean and standard deviation (usually in natural logarithm units). The standard deviation represents mainly the influence of the uncertainty or scatter in the ground motion prediction equation; in very simple terms, this uncertainty is due to the choice of a model (epistemic uncertainty that is systematic) and the random fluctuations (aleatory uncertainty that is statistical). When the recorded ground motion at each station of an individual earthquake is compared with an empirical GMPE it naturally would fall above or below the mean because of the intrinsic variability of an individual event. This comparison represents a first overview of the ground motion and is not enough to arrive at a final conclusion as to the level of its ground motion relative to the empirical GMPE. For this reason in order to conduct an adequate and quantitative comparison we include a statistical analysis by considering the standard deviation. Also we calculate the residuals of the 13 August 2006 earthquake relative to each empirical GMPE used herein.

5.1. Residuals for Observed PGA and Response Ordinates

Figure 7 shows the observed residuals for the PGA and response ordinates at three structural periods (T = 0.3, 0.5 and 1 s) of the moderate 13 August 2006 earthquake with that predicted by the empirical GMPE's in terms of distance. The residual is defined as the logarithmic difference between observations, yobs, and estimations, ypre, for each empirical GMPE compared herein; note that a positive or negative residual implies, respectively, under or overestimation of the observed data set. As seen in Fig. 7, there are no significant bias trends associated with the empirical GMPE's of Youngs et al. (1997) and Tejeda-Jácome and Chávez-García (2007) in terms of distance (squares and crosses respectively) for PGA and spectral ordinates of T = 0.3, 0.5 and 1 s; therefore, we consider that the empirical GMPE's of Youngs et al. (1997) and Tejeda-Jácome and Chávez-García (2007) fit well the observed data set for this type of earthquake and, consequently, both empirical GMPE's provide a reliable estimate for PGA and all spectral ordinates. On the other hand, as seen in Fig. 7, there are significant bias trends associated with the empirical GMPE of Arroyo et al. (2010) in terms of distance (triangles) for the PGA and spectral ordinates of T = 0.3, 0.5 and 1 s; the residuals show an underestimation of the observed data set that decreases with increasing structural period. In contrast, as seen in Fig. 7, there are no significant bias trends associated with the empirical GMPE of Ordaz et al. (1989) in terms of distance (circles) for PGA and spectral ordinates of T = 0.3 s; however, there are significant bias trends for spectral ordinates of T = 0.5 and 1 s (the residuals show an overestimation of the observed data set).

5.2. Evaluation of Intensities of the Unusual Event

Figure 6 presents the comparison of the four above mentioned GMPE's with the observed PGA and with the response spectral ordinates at the structural periods of T = 0.3 s, T = 0.5 s, T = 1 s of the unusual event for the 23 sta-

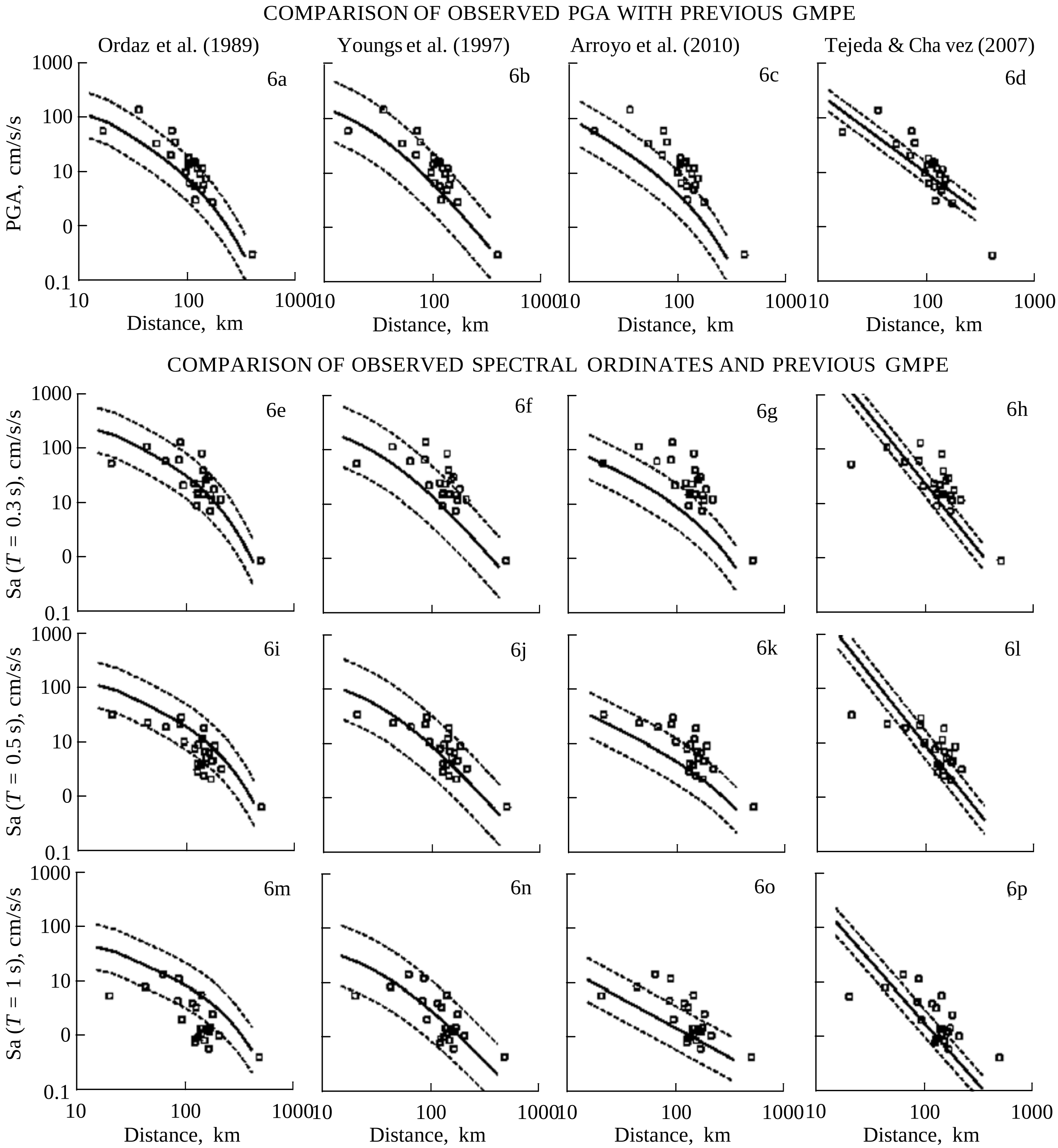

Fig. 6. Comparison of four different GMPE's versus PGA (Figs. 6a, 6b, 6c and 6d) and response spectral ordinates at the structural periods of T = 0.3 s, T = 0.5 s, T = 1 s (Figs. 6e–6p) the moderate (M_w 5.2) 13 August 2006 earthquake. Observed PGA and 5% damping response spectral ordinates are indicated by the squares (also see Table 1). The thick black lines correspond to the horizontal component of the response spectra of earthquake predicted by the GMPE and the region between the dotted lines represents the prediction interval to a 90% confidence interval for each GMPE used.

tions located on hard soil. The compared values (squares) correspond to the geometric mean of the two horizontal components at each station in agreement with the procedure followed in each of the four empirical GMPE's. In all plots, the region between the dashed red lines corresponds to the mean ± standard deviation that represents the prediction interval for each GMPE (Table 4). For the sake of clarity, the numeric values and percentages result-

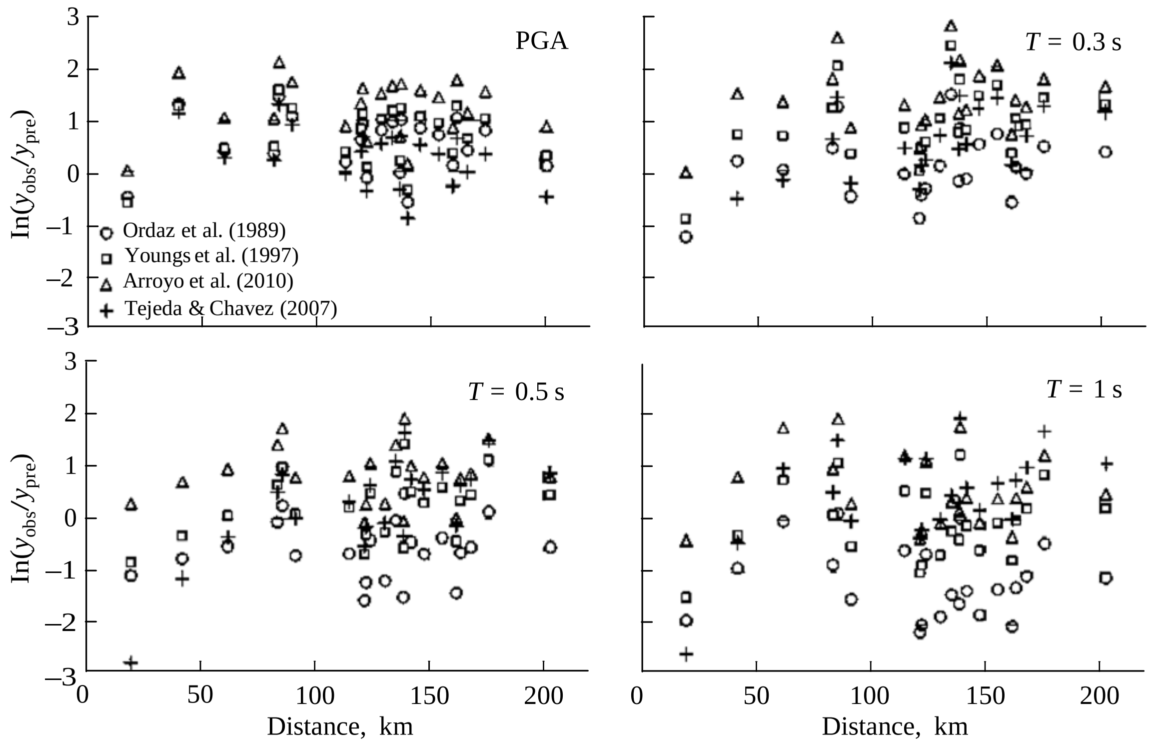

Fig. 7. Residual of PGA and response spectral ordinates at three structural periods (T = 0.3 s, T = 0.5 s, T = 1 s) of the moderate (M_w 5.2) 13 August 2006 earthquake with predicted GMPE's in terms of distance.

ing from the comparison are summarized in Table 5. In this table the gray filled cells highlight the region (above, inside or below respect to the curve) where the observed PGA and spectral ordinates mostly concentrate. The next comparison takes into account the 90% confidence interval (region between the dotted lines of Fig. 6).

Before proceeding with the analysis of the results of the comparisons it is necessary to keep in mind that it is expected that the respective curves of the four predicted empirical GMPE's locate above the observed PGA and spectral ordinates of this particular event. This behavior is expected because the fault plane of the focal mechanism of the moderate event is perpendicular to the direction of the axis of the MAT. Therefore we expected that the maximum intensities of this particular event in the specific area evaluated, spread mainly parallel to the axis of the MAT in comparison with four predicted empirical GMPE's where the maximum intensities spreads mostly landward perpendicular to the axis of MAT (in the direction of the subduction).

5.2.1. Comparison of empirical GMPE with observed PGA. Figures 6a to 6d and row 1 of Table 5 show that, contrary to what is expected for the unusual event, in none of the 4 cases of comparison does the observed PGA concentrate below the prediction interval. Instead, in one case (Arroyo et al., 2010) the observed PGA are concentrated mostly above the prediction interval while in the other three comparisons the observed PGA are concentrated mostly inside the prediction interval. This result (observed PGA concentrated mostly inside or above the predicted interval) attests to the unexpected behavior of the unusual event.

Table 4. Standard deviation (in natural logarithm units) of predicted empirical GMPE's for earthquake with M_w = 5.2

Reference	PGA	T = 0.3 s	T = 0.5 s	T = 1 s
Ordaz et al. (1989)	0.58	±0.58	*0.58	*0.58
Youngs et al. (1997)	0.92	0.92	0.92	0.92
Arroyo et al. (2010)	0.75	0.72	0.72	0.68
Tejeda-Jácome and Chávez-García (2007)	0.28	0.33	0.36	0.35

± This value was assumed similar to value of PGA.

Table 5. Percentage of points of the unusual event that locate above, inside or below the limits of the prediction interval (90% confidence interval) of the empirical GMPE's for earthquake with M_w = 5.2 (data summarized from Fig. 6)

No.		Ordaz et al. (1989)			Youngs et al. (1997)			Arroyo et al. (2010)			Tejeda-Jácome and Chavez-García (2007)		
		above	inside	below	above	inside	below	above	inside	below	above	inside	below
PGA													
1	PGA	8.7	91.3	0.0	4.3	95.7	0	73.92	26.08	0	34.78	52.17	13.04
Spectral ordinates													
2	*t* = 0.3	8.7	86.96	4.34	26.04	73.96	0	82.61	17.39	0	52.19	43.47	4.34
3	*t* = 0.5	0	73.92	26.08	4.3	95.7	0	34.78	62.22	0	52.17	39.13	8.7
4	*t* = 1.0	0	39.14	60.86	0	95.7	4.3	26.08	73.92	0	52.19	43.47	4.34

5.2.2. Comparison of empirical GMPE with spectral ordinates. Figures 6e to 6p and rows 2, 3, and 4 of Table 5 show that from the comparison of the four empirical GMPE's with observed spectral ordinates (T = 0.3, 0.5 and 1 s), only one case (Fig. 6m, Ordaz et al., 1989, T = 1 s) shows the expected behavior where the spectral ordinates concentrate mostly below the prediction interval. For all other cases of comparison, the spectral ordinates concentrate mostly inside or above the prediction interval. Similar to the comparison with observed PGA, this result (spectral ordinates concentrated mostly inside or above of predicted interval) also attests to the unexpected behavior of the unusual event.

In addition to the results presented above, in Table 5 it is possible to observe that: (i) All spectral ordinates considered in this study locate mostly above the prediction interval of the empirical GMPE of Tejeda-Jácome and Chávez-García (2007), again suggesting an unexpected behavior of the unusual event. This is of particular importance because the empirical GMPE's of Tejeda-Jácome and Chávez-García (2007) was derived using data from the same region (Jalisco, Colima and Michoacán) where the unusual event was recorded. The other three empirical GMPE's used herein were constructed using data from other regions of México and the world; (ii) All spectral ordinates and observed PGA locate mostly inside the prediction interval of the empirical GMPE's of Youngs et al. (1997). Although there is no evidence of the inclusion of this type of unusual earthquakes in the empirical GMPE of Youngs et al. (1997) a possible inclusion of this type of events could explain this behavior. The possibility of the inclusion of such events in the empirical GMPE of Youngs et al. (1997) may be due to the fact that it takes into account a large database consisting of more than 164 earthquakes, many of these events date from 1945. For these older events, focal mechanisms are not available in the Global CMT Project, also some of the earthquakes listed in their database recorded after 1964 are not listed in Global CMT Project and consequently focal mechanisms are not available.

5.3. *Isoseismal Map*

Figure 8 shows the contour maps of the quadratic mean of both horizontal components of the 13 August 2006 earthquake for peak ground acceleration (Fig. 8a) and a structural period of T = 1 s (Fig. 8b). In Fig. 8a it can be seen that the region with the highest PGA (contours of 50, 60, 70, 80 and 90 cm/s^2) covers the cities of Tecomán and Manzanillo, these urban areas locate at distances less than 130 Ion from epicenter. Also, it can be seen that contours of the PGA of 50, 60, 70, 80 and 90 cm/s^2, curiously, elongate markedly perpendicular to the direction of fault plane of the event and parallel to the axis of MAT. Additionally can be seen that the elongation starts in the epicentral location of the event and drastically decreases in the opposite direction; this behavior is similar to the phenomena of directivity so perhaps this could be an indication of source directivity of this earthquake, although there is no other data to support it. However, another explanation could be that the elongation of these contours indicates the direction of the convergence of the microplates where this event was recorded, i.e. perpendicular to the axis of MAT; this would be consistent with the fault plane of the focal mechanism reported by Global CMT project. Alternatively, this could be explained in the sense that this thrust fault could have an S-wave radiation pattern which would be expected to produce an intensification of the seismic effects perpendicular to the fault plane. There are several factors that can cause higher PGA than those expected by empirical GMPE, such as rupture propagation, directivity, local site effects or higher stress drop. However, the causes of this behavior are not clear and it is necessary to keep in mind that the intensities given in these maps corresponds to a rough average of intensities using 24 observed records at the zone.

(a)

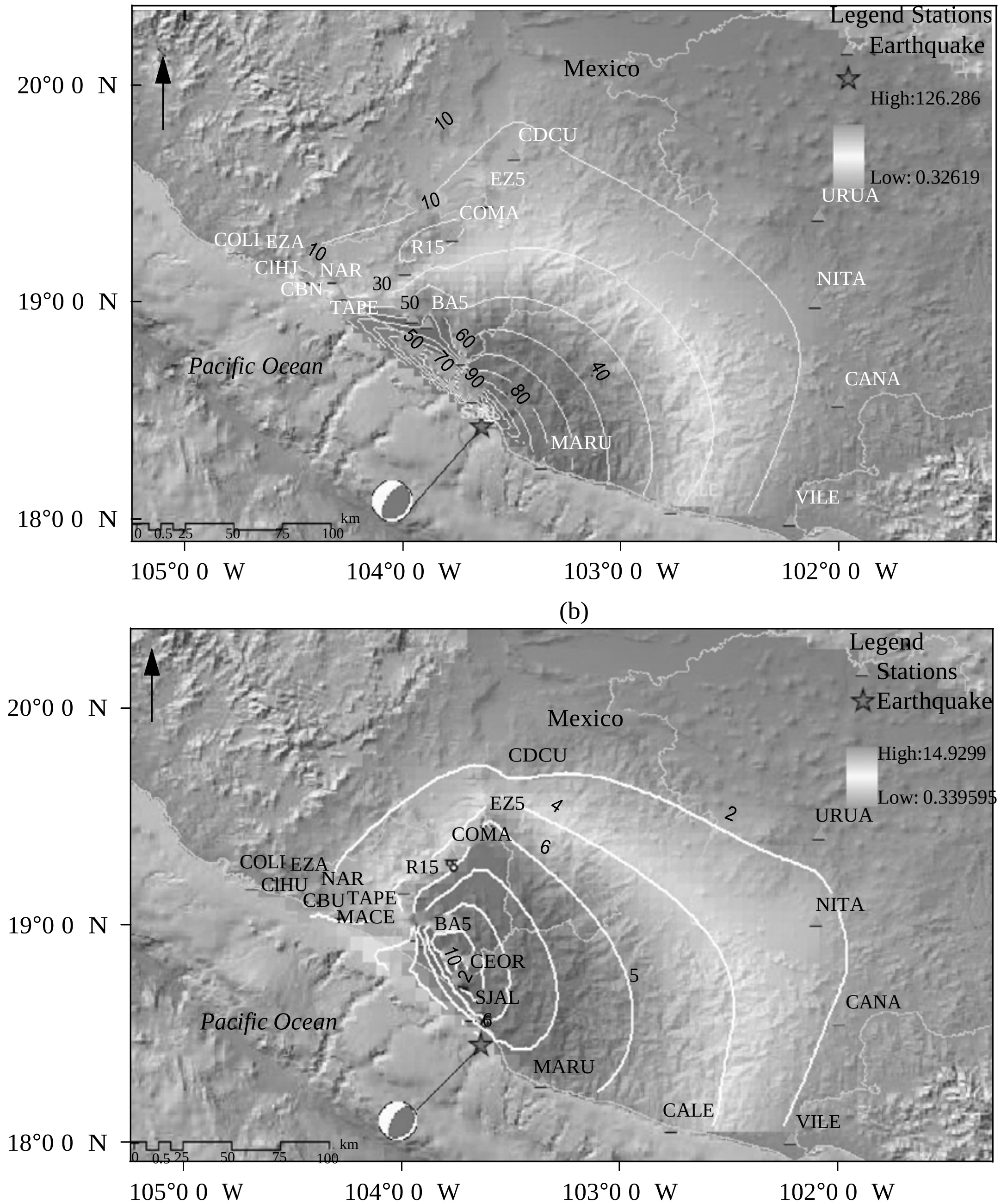

Fig. 8. Contour maps of the quadratic mean of both horizontal components of the moderate (M_w 5.2) 13 August 2006 earthquake: (a) peak ground acceleration and (b) structural period of T = 1 s.

6. PUZZLE OF THE 13 AUGUST 2006 EARTHQUAKE

The 13 August 2006 earthquake is puzzling. Although the reported epicenter and hypocentral depths are consistent with an event occurring along the main thrust contact between the Cocos and North American plates, its focal mechanism (Global CMT project) solution is clearly atypical. Its location close to a plate triple junction raises the possibility that the event could also result from stresses arising from the interaction of the Rivera and Cocos plates along their mutual boundary located beneath the Tecomán Graben. Other possible causes include geometric or structural complexities (e.g., Lahr et al., 1988; Wolf et al., 1993), especially near the intersections of boundaries, or a reactivation of a pre-existing fault. Such reactivations are common (e.g., Bonini et al., 2012), and several trench perpendicular normal faults forming the southern

Colima Rift (and perhaps within the underlying Rivera-Cocos plate boundary) are likely candidates for such a reactivation.

Bathymetric maps show that there are no major bends in the trend of the axis of the MAT in the area of the event. However, since the bathymetric map is a somewhat smoothed representation of the actual geometry, we cannot entirely rule out geometric complexities as the cause of this unusual event. Also, plate motion directions (Fig. 5) for this area suggest that this event was not directly related to Cocos-NA relative motion, however, there might be some kind of structural anomaly present along the plate interface in this area. If so the event might be indirectly related to Cocos-NA motion. Another possibility, which we favor, is that the event may be a reactivation of a major fault associated with either the southern Colima Rift or the underlying boundary separating the Rivera and Cocos plates due to the interaction between the Rivera and Cocos plates as they subduct. The recent MORVEL plate motion model (DeMets et al., 2010) predicts that near the triple junction the Cocos plate converges with the Rivera plate at a rate of 1.8 cm/year in the direction N17° E (Fig. 5). A N17° E oriented compression could reactivate pre-existing faults whose orientations are similar to those comprising the rift and underlying boundary (i.e. N31° E; the strike of the fault plane of the 13 August 2006 earthquake) and could yield the characteristics observed for the 13 August 2006 earthquake. A reactivation of a pre-existing fault may also explain why this event generated ground accelerations that are different from those predicted for "typical" subduction thrust events of this area.

7. CONCLUSIONS

We present a study of the moderate 13 August 2006 earthquake that has a focal mechanism with nodal planes oriented practically perpendicular to those of the great majority of the earthquakes occurring on the subduction zone of the Mexican Pacific Coast.

To confirm the location and focal mechanism provided by the Global CMT project for this unusual earthquake, we relocate this event and re-estimate the focal mechanism by applying a different methodology and use different types of data than those used by the Global CMT project. In general we use regional and local broadband records unlike the Global CMT project, which uses only teleseismic records. The implication of the use of local and regional data in our study should be the increased precision in the re-location and re-estimation of focal mechanism. The estimated hypocentral location derived in this study by using 14 broadband stations of SSN and 7 acceleration stations closest to source is near to the hypocenter estimated by the NEIC and centroid estimated by Global CMT project. The focal mechanism solution obtained in this study is similar to that reported by Global CMT project; however, our solution has a larger component of strike-slip motion than that reported by the Global CMT project. The hypocentral location of this study and those provide by NEIC agree in that the event occurred in a complex tectonic region near the triple junction formed between the Cocos, Rivera and North American.

A kinematic assessment of the cause of the 13 August 2006 earthquake suggests that this event was most likely caused by (1) geometric complexities, (2) some kind of local structural anomaly present along the plate interface in this area, or (3) a reactivation of a preexisting fault due to forces arising from the interaction of the Rivera and Cocos plates beneath the Tecomán Graben. Each possibility may explain why this event generated ground accelerations that are different from that predicted for subduction thrust events of this area.

The contour maps of the quadratic mean of both horizontal components of this event show that the region with highest PGA covers the cities of Tecomán and Manzanillo. These contours, curiously, elongate markedly in the direction normal to the fault plane of the event and parallel to the axis of MAT. Additionally it can be seen that the elongation starts in the epicentral location of the event and drastically decreases in opposite direction, this behavior could be an indication of the rupture propagation.

We compare peak ground accelerations and spectral ordinates (T = 0.3, 0.5 and 1 s) of observed records of this event with four empirical GMPE's appropriate for the region (Ordaz et al., 1989; Youngs et al., 1997; Arroyo et al., 2010 and Tejeda-Jácome and Chávez-García 2007). In order to conduct an adequate and quantitative comparison we include a statistical analysis by considering the residuals and standard deviation associated with the empirical GMPE's. Because the fault plane of the focal mechanism of the moderate event is perpendicular to the direction of the axis of the MAT, we expected that the maximum intensities of this particular event in the specific area evaluated would spread mainly parallel to the axis of the MAT in comparison with four predicted empirical GMPE's where the maximum intensities spreads mostly landward perpendicular to the axis of MAT (in the direction of the plate convergence). Usually, these kinds of faults have a lateral slip motion, since this accounts for the differences in slip between the two adjacent subducting plate sections. Then, the strike slip component should be larger. For this reason we expected that the respective curves of the four predicted empirical GMPE's should locate above the observed PGA and 5% damping response spectral ordinates at all structural periods of this particular event. The comparison of empirical GMPE's with observed PGA and spectral ordinates shows that the observed values concentrate mostly inside or above the predicted interval. These results attest to the unexpected behavior of the unusual event.

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