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Active Crustal Deformation in the Area of San Carlos, Baja California Sur, Mexico as Shown by Data of Local Earthquake Sequences

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Abstract—We analyzed earthquakes of sequences that occurred at different times near San Carlos, a town of approximately 5000 inhabitants. The seismic sequences happened during March–April 1989, October 2000–June 2001, and 5–15 February 2004 at about 200 km west of the Pacific-North America plate boundary. The strong shaking from initial earthquakes of the first two sequences prompted the installation of temporary seismic stations in the area. With data recorded by these stations, we found an earthquake distribution that is consistent with the northwest segment of the Santa Margarita fault. Both the focal depth, that seemed to increase in E–NE direction, and a composite fault-plane solution, obtained from polarity data of the small earthquakes, were also consistent with the main characteristics of that fault. We also found that our normal-faulting mechanism (east side down) was quite similar to centroid moment tensor solutions for earthquakes with M_w 5.4 and 5.3 that occurred in the area in February 2004. It is likely, then, that these larger earthquakes also occurred along the Santa Margarita Fault. To get some insight into the regional stress pattern, we compared the above mechanisms with mechanisms reported for other earthquakes of the Pacific margin of Baja California Sur and the Gulf of California regions. We observed that focal mechanisms of the two regions have T axes of stress that plunge sub horizontally in E–NE average direction. The corresponding P axes have N–NW average trend, but for the Pacific earthquakes these axes plunge at angles that are $\sim 35°$ larger than those for the Gulf earthquakes. These more vertically inclined P axes of compressive stress mean substantial oblique fault motions. The mixture of oblique and strike-slip components of fault motions, as the focal mechanisms show, confirms a transtensional stress regime for the region. Before this research, we knew little about the seismicity and styles of faulting in the area. Now we know that earthquakes can occur along the coastline of Baja California, at 60 km east of the Tosco-Abreojos fault system. We conclude that transtensional deformation is taking place across a wide zone of the Pacific margin of Baja California. Finally, we point out that although the studied earthquakes were of small magnitude, they might serve as a reminder of the danger that future larger events pose to San Carlos.

Key words: Pacific margin of Baja California, seismic activity, transtensional stress regime.

1. Introduction

The region of this study is located along the Pacific coast of Baja California Sur, at the central part of the Magdalena Shelf (Fig. 1). This zone includes San Carlos, a town of approximately 5000 inhabitants. In the past 25 years, several earthquakes rocked this small town and caused minor damage to houses and alarm among residents. The inflicted damage consisted of ground fissures, cracking in plaster covering masonry, and books and other objects thrown down from shelves. The earthquake effects and distribution of damage were only noticeable at short distances from the sources.

In this paper, we present the results of analyses of small-magnitude earthquake sequences recorded instrumentally for the first time in the neighborhood of San Carlos. These sequences occurred during March–April 1989, October 2000–June 2001, and 5–15 February 2004. Before this study, the seismicity of the area was unknown mostly due to a lack of local seismic stations. Some earthquakes of the first two sequences produced intense ground motions at San Carlos, and that prompted the installation of small temporary seismic networks in the area. The 2004 events, on the other hand, occurred far from San Carlos. In spite that two of those events were of M_w 5.4 and 5.3, no one in town felt their motions.

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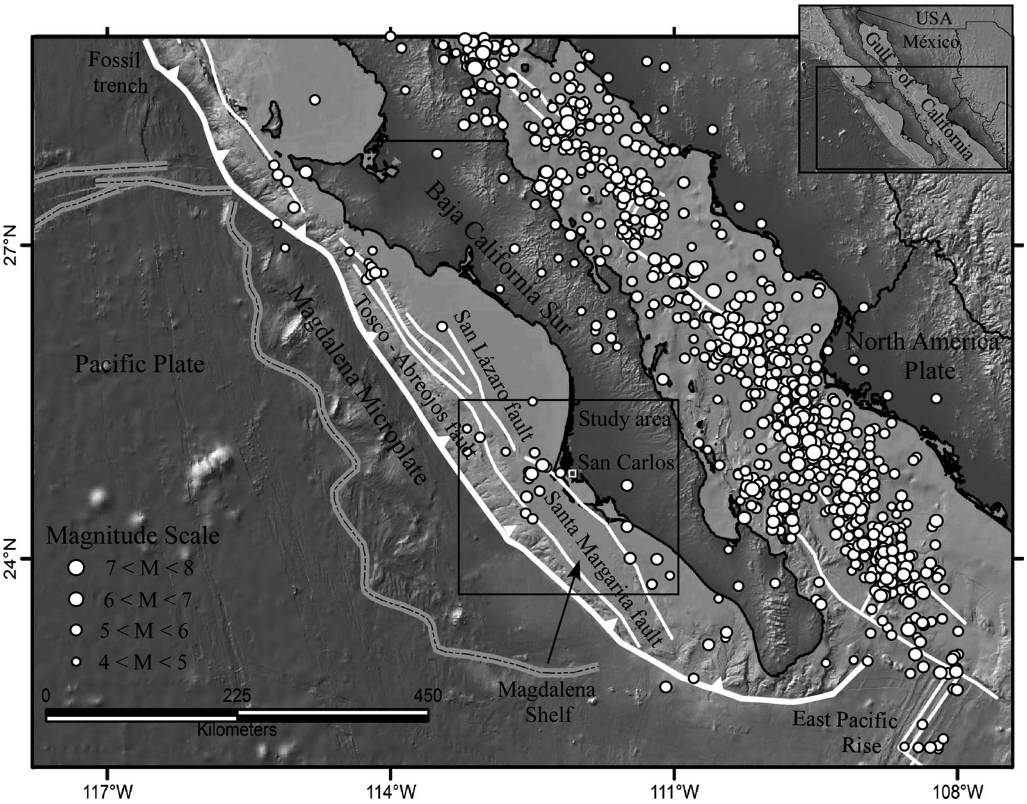

Figure 1
Seismicity of the Baja California Sur-Gulf of California region for the period from 1960 to 2014, as reported in the Northern California Earthquake Data Center (NCEDC)

Because of this, we did not install temporary stations in the area. Nonetheless, stations of the NARS-Baja seismic network (Clayton *et al.* 2004) recorded the two larger events of the sequence at distances between 150 and 600 km. With data from those stations, we relocated the epicenters of the 2004 earthquakes.

We present the results of our study in terms of earthquake locations and their correlation with a known fault of the study area. In addition, we describe how a composite focal mechanism obtained for the recorded small earthquakes and two mechanisms of previous larger events of the area are indicative of a transtensional stress regime for the region. We investigated the condition of regional stress by comparing these focal mechanisms with mechanisms for earthquakes of the Pacific margin and the Gulf of California region. The results also provide insights about a zone of concentration/release of stresses near San Carlos, with potential seismic hazard of unknown level to this town.

2. *Tectonic Setting and Regional Seismicity*

Prior to ~29 Ma, the Farallon and several microplates were subducting along the western margin of the American continent (Atwater 1970). About 12 million years ago, the western North America subduction process ceased and the plate-margin slip concentrated mostly in the Gulf of California (Lonsdale 1991). At that time, the Pacific plate began the capture of the Baja California microplate (Atwater 1989; Bohannon and Parsons 1995). Since then, most of the relative slip between the Pacific and North American plates has taken place along the transform fault system that runs through the Gulf of California. There is, however, the hypothesis that faults of the coastal and offshore zones west of Baja California accommodate a fraction of the relative plate motion (e.g., Humphreys and Weldon 1991; DeMets *et al.* 1995; Dixon *et al.* 2000; Fletcher and Munguía 2000; Michaud *et al.* 2005; Munguía *et al.* 2006; Fletcher *et al.* 2007). If we accept this hypothesis, then the assumption that the Baja California peninsula transferred completely to the Pacific plate by 3.6 Ma might not be valid (DeMets 1995; Stock and Hodges 1989; Michaud *et al.* 2004).

The major tectonic features that cut through the study area are the Tosco-Abreojos and San Lázaro-Santa Margarita fault systems (Fig. 1). These faults trend approximately north-northwest, dip to the east, and control the position and geometry of two asymmetric transtensional basins. Detailed reviews of the tectonics and fault systems of the region can be found in papers by Spencer and Normark (1979), Normark *et al.* (1987), Michaud *et al.* (2005, 2011); Fletcher *et al.* (2007), Brothers *et al.* (2012) and Salazar (2014) among others.

Figure 1 also shows the seismicity of Baja California Sur and the Gulf of California regions for the period from 1960 to 2014. The data plotted include earthquakes in the 3–7 magnitude range obtained from the Northern California Earthquake Data Center (NCEDC) catalog. As the figure shows, the faults in the Gulf of California produce the highest rate of seismicity. Yet, some events reaching magnitudes of up to 5.4 had occurred off the west coast of Baja California. Though these earthquakes are rather small in number, they give clear evidence of tectonic activity along the western margin of the Baja California peninsula.

In the 54-year period of seismicity considered in Fig. 1, 24 events with magnitudes between 3.5 and 5.4 occurred along the offshore faults of our study area (inner rectangle in the figure). All of these events were located with data from stations in North America and it thus seems natural to expect some bias in the epicenters. Results of previous studies have demonstrated that this has been the case for other earthquakes of the region. When near-source data were available for an earthquake location, the locally and teleseismically determined epicenters differed by up to ~ 50 km (Reichle *et al.* 1976; Munguía *et al.* 1977; Goff *et al.* 1987; Fletcher and Munguía 2000; Castro *et al.* 2011).

Figure 2 is a plan view of the regional faults of the area and the epicenters of the larger earthquakes that occurred there in the 1960–2014 period (NCEDC catalog). In that period, the more relevant earthquakes of the region had magnitudes 5.3, 5.4, and 5.3. The numerals 3, 13, and 16 identify the locations of these events on the map of Fig. 2. The first of those events occurred on 26 January 1968; the other two occurred on 9 February 2004. Figure 3 shows graphically the chronological order of occurrence of the 24 events of the study area. From that figure, we note that nine earthquakes occurred in 2004, seven of which had magnitudes 4.0 or larger.

3. *Micro Earthquake Data Collection*

3.1. *1989 Fieldwork Procedure*

On 30 March and 4 April 1989, people in San Carlos felt two earthquakes of moderate intensity. Although these earthquakes produced only light damage in the town, they were the cause of much concern among the population. Due to the lack of seismic stations, there were no local instrumental recordings of those earthquakes. In addition, none of these 1989 earthquakes appeared in the listings of global earthquake catalogs. Based only on the information provided by some local inhabitants, we speculate here that those events had magnitudes between 3 and 3.5. Our reasoning for this conjecture is as follows. First, we noted that global catalogs of distant seismic stations usually report earthquakes of the region with $M > 3.5$. However, none of the 1989 earthquakes under study appeared in the listings of such catalogs. Second, we propose the lower magnitude bound on the basis that people start feeling local earthquakes with magnitudes 3.0, or slightly lower, depending upon distance.

After the first 15 days of seismicity, we installed six temporary stations in the area of the epicenters. The stations were equipped with 1-s natural period seismometers (Kinemetrics, model Ranger SS-1) connected to smoked-paper seismographs

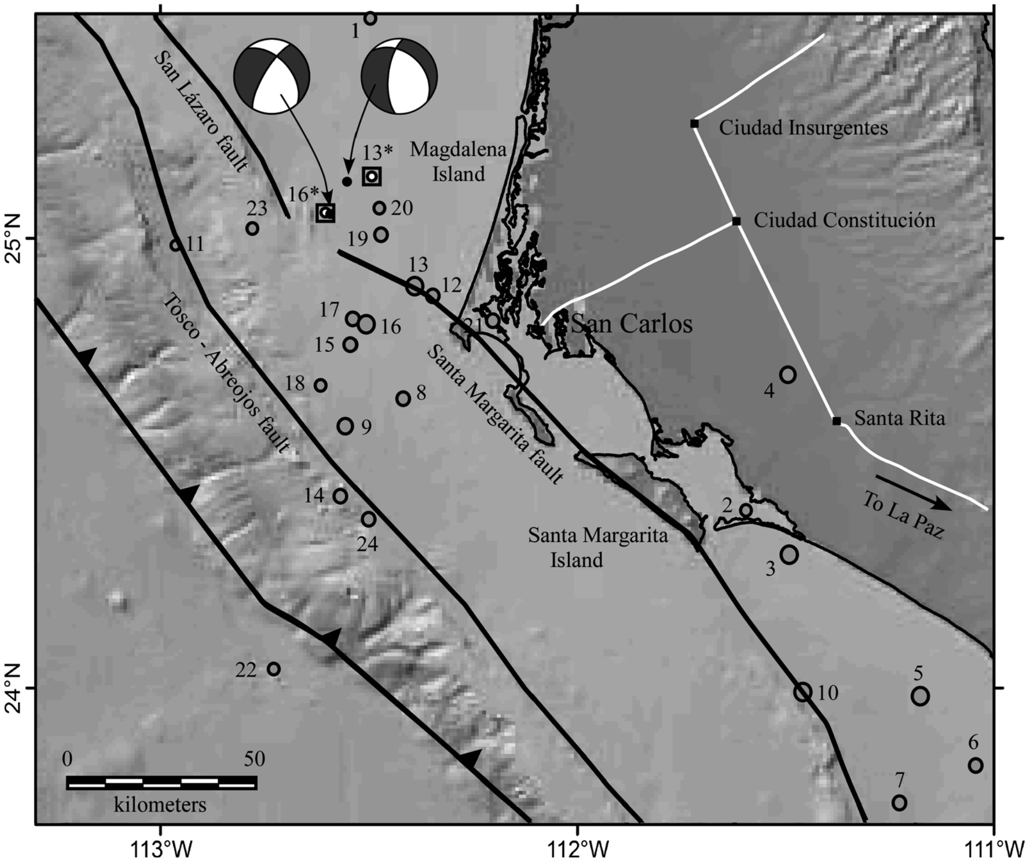

Figure 2
Zoom of the study area to show the epicenters of earthquakes that occurred in the 1960–2014 period (*circles*), as reported in the NCEDC catalog. All of these events had magnitudes between 3.5 and 5.4. The three earthquakes with the larger magnitudes (5.3, 5.4 and 5.3) have the numbers 3, 13 and 16, respectively. The first of these three events occurred on 26 January 1968; the other two occurred on 9 February 2004 (see Fig. 3). *White circles* inside *squares* indicate relocated epicenters for the 2004 events. *Black dots* and beach balls represent the epicenters and double-couple fault plane solutions reported in the CMT catalog for these events

(Sprengnether, model MEQ 800). The triangles in Fig. 4 mark the sites occupied by these analog stations. In a 29-day period of operation, the network recorded 21 earthquakes with magnitudes of up to 3.2. We describe the epicenter location process in a later section of this paper.

3.2. 2000–2001 Fieldwork Procedure

The second period of earthquake activity started on October 2000 and ceased by June 2001. On the 27 and 28 of October 2000, two earthquakes produced intense ground shaking at San Carlos. On that occasion, a seismic station located at a distance of 190 km south of San Carlos recorded those initial events. Based on data from that station and on the magnitude relationship of Lee *et al.* (1972), we calculated duration magnitudes of 3.5 for both earthquakes. As in the 1989 earthquake series, those initial earthquakes produced only small cracks and fissures on some local constructions.

Residents of the cities of Constitución and Insurgentes, located at 50- and 60-km distances from downtown San Carlos (see Fig. 2), respectively, did not feel the earthquakes. Due to scarceness of people living between San Carlos and those cities, there was no information on the earthquake effects at intermediate distances. However, a few people living or

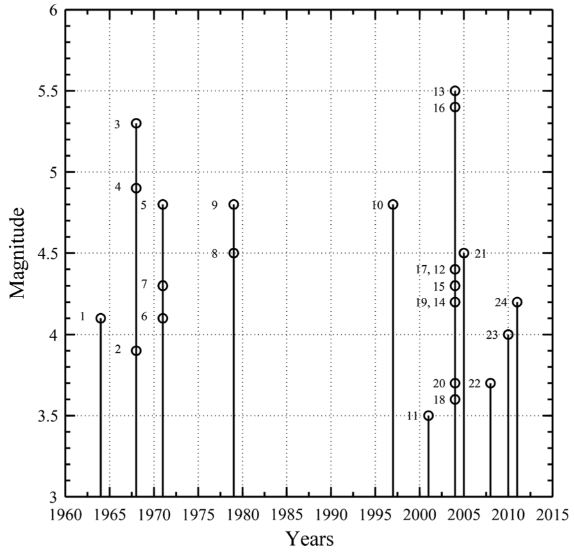

Figure 3
Chronological order of occurrence of the earthquakes plotted in Fig. 2. Earthquakes with the numbers 13 and 16 occurred on 9 February 2004

working north and southeast of San Carlos, but at distances larger than 15 km from downtown, did not perceive the motions from those events. Our conclusion was that the earthquakes caused alarm and minor damage only at distances of less than 15 km from downtown San Carlos.

At 2 weeks from the first two events, we had installed eight digital seismic recorders (white outlined pentagons in Fig. 4) and four analog stations (white squares in Fig. 4) in the area. The digital instruments consisted of three-axial K2 accelerographs or K2 recorders with external Episensor accelerometers (all from Kinemetrics). These digital stations recorded the seismic signals at a rate of 200 samples per second. The four analog stations used were of the same type as those in the 1989 fieldwork. This combined network recorded for a period of 8 months.

4. *Data Analysis and Results*

4.1. Hypocenter Locations

The earthquake hypocenters were determined with the program Hypocenter (Lienert and Havskov 1995), a program that is part of the Seisan software package (Havskov and Ottemöller 2001). We used this location program with the crustal velocity model of Fletcher and Munguía (2000), which consists of four layers over a half space with the following P-wave velocity and thickness characteristics, respectively: 4.0 km/s, 2 km; 6.0 km/s, 5 km; 6.4 km/s, 7 km; and 6.9 km/s, 10 km. The lower infinite half-space had a P-wave velocity of 7.6 km/s.

In Fig. 4, circles with a plus sign inside represent the locations of fourteen of the 1989 earthquakes. The epicenters of those earthquakes do not correlate with any of the borderland faults that lie to the west of Baja California. Rather, they spread out perpendicular to the trend of those regional faults. However, we must be cautious on this, because it could be, in part, a result of the sparseness of our seismic stations. Only the epicenters that fall closer to downtown San Carlos had good station coverage and so they were more reliably located. For those events, the estimated focal depths are between 1 and 8 km. Micro earthquakes located at larger distances from San Carlos have depths that increase eastward from 10 to 16 km. In short, not all of these 1989 events were located with good precision, but still they are seismic evidence of tectonic activity in the area of our study.

In the 2000–2001 fieldwork, we recorded many earthquakes in digital and analog format. This time, we took advantage of the high-quality digital recordings to make accurate readings of the P- and S-wave arrival times. These times, combined with time readings from recordings of the analog stations, were the basis for our hypocenter location process. Figure 4 shows the epicenters of 31 earthquakes (white circles) that could be well located. These locations resulted from the use of 5–14 arrival times (with median of eight readings) from well-distributed stations around the epicenters. It is worth noting here that all digital stations recorded within 25 km of the epicenters. Because of this, the horizontal and vertical location errors were quite small. Median values of the location errors are rms of 0.07 s, horizontal error (erH) of 0.6 km, and depth error (erZ) of 0.6 km. Table 1 contains the results of the location process for the earthquakes of this sequence.

An interesting feature of these 2000–2001 earthquakes is that, even though they occurred evenly

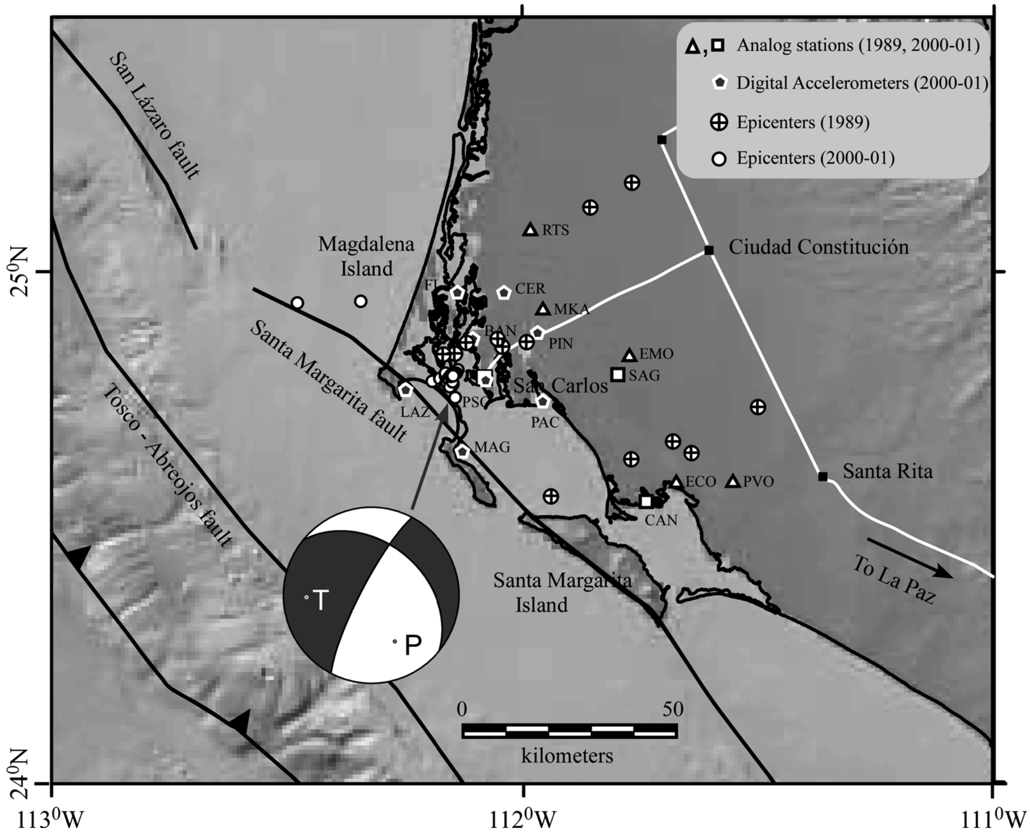

Figure 4
Map that shows the sites of the recording seismic stations together with the epicenters of earthquakes recorded in the 1989 and 2000–2001 field surveys

distributed in time along a 7-month period, their sources occurred tightly clustered in a zone of 5-km radius. Only two micro earthquakes of M_w 2.3 and 2.5 occurred offshore of the Magdalena Island, at distances of 35 and 45 km from downtown San Carlos. Earthquakes of this zone of concentrated activity occurred at 5–10 km from San Carlos.

4.2. Relocation of the M_w 5.4 and 5.3 Earthquakes of February 2004

Although the 2004 earthquake sequence developed during the period 5–15 February, the two stronger events of the series occurred on 9 February. The NCEDC teleseismic locations for these particular events are marked with the numbers 13 and 16 in Fig. 2. In San Carlos, people did not feel these earthquakes, and that is why we did not install temporary instruments on that occasion. Nevertheless, seismic stations of the NARS-Baja array recorded the two larger events at epicentral distances of 150 to 600 km. These distances are rather large, but the azimuthal coverage provided by these stations was better than that of the teleseismic stations. Using the data from NARS stations we attempted to refine the global epicenter determinations of the NCEDC listings. For the M_w 5.4 and 5.3 earthquakes, the newly located epicenters are shown in Fig. 2 with white circles inside squares (numbers 13* and 16*). We note that the relocated epicenters are ~30 km NNW of the epicenters reported in the NCEDC catalog and that the distances from these earthquakes to San Carlos are larger than originally reported. This explains why the residents of San Carlos did not feel these earthquakes. It is also worth noting from Fig. 2 that the new epicenters lie close to the global

Table 1

Epicenter locations of 31 events of the 2000–2001 earthquake series

Date yr mo day	Time hr min	Lat. (°)	Long. (°)	Depth (km)	M_w	NR	Az (°)	CD (km)	rms (s)	erH (km)	erZ (km)
2000 11 24	22 41	24.78	−112.16	5.71	1.3	6	303	7.0	0.02	0.30	0.40
2000 11 28	20 21	24.77	−112.16	7.86	1.5	7	283	7.3	0.07	0.90	0.90
2000 12 04	15 13	24.78	−112.19	6.64	1.8	7	297	10.4	0.08	0.90	0.60
2000 12 04	19 34	24.78	−112.18	6.84	1.6	7	293	9.3	0.07	0.80	0.40
2000 12 08	08 22	24.78	−112.18	6.95	1.8	7	295	9.6	0.08	0.90	0.50
2000 12 09	16 29	24.79	−112.17	9.62	1.9	6	288	10.9	0.02	0.30	0.40
2000 12 11	20 37	24.80	−112.16	10.14	1.8	5	284	9.2	0.01	0.20	0.20
2000 12 31	23 59	24.77	−112.17	6.90	1.5	7	287	8.2	0.07	0.80	0.50
2001 01 02	22 07	24.77	−112.16	6.91	1.5	5	285	7.7	0.03	0.50	0.60
2001 01 18	01 27	24.94	−112.35	5.63	2.5	6	337	23.7	0.09	0.50	0.30
2001 01 26	04 48	24.80	−112.13	9.49	1.8	7	263	4.7	0.08	0.90	0.80
2001 03 01	01 05	24.78	−112.15	6.43	1.6	14	117	6.4	0.11	0.30	0.90
2001 03 16	05 05	24.94	−112.48	6.00	2.2	8	299	15.2	0.12	1.90	1.50
2001 03 18	17 50	24.78	−112.15	7.05	1.9	10	206	6.7	0.07	0.60	0.60
2001 03 23	02 39	24.77	−112.17	5.56	1.4	7	288	8.3	0.04	0.60	0.90
2001 03 23	03 13	24.78	−112.15	7.00	1.7	14	108	6.1	0.08	0.20	0.30
2001 04 22	09 28	24.78	−112.18	5.88	1.5	6	291	8.9	0.05	0.90	1.40
2001 04 29	07 02	24.80	−112.14	6.44	2.3	8	200	8.7	0.07	0.70	1.20
2001 05 12	21 42	24.79	−112.14	6.76	1.9	11	114	5.6	0.08	0.30	0.70
2001 05 13	00 36	24.78	−112.14	7.83	2.2	12	107	5.6	0.07	0.20	0.50
2001 05 25	14 35	24.78	−112.16	6.40	1.7	8	303	7.0	0.07	0.80	0.90
2001 05 25	18 17	24.77	−112.16	6.96	1.5	8	307	7.4	0.09	1.00	0.40
2001 05 31	11 07	24.78	−112.15	7.11	1.7	11	109	6.3	0.09	0.30	0.60
2001 06 03	20 54	24.77	−112.15	6.63	1.7	10	111	6.3	0.08	0.30	0.70
2001 06 04	06 37	24.78	−112.15	8.15	1.3	6	188	6.0	0.02	0.30	0.40
2001 06 07	23 59	24.79	−112.14	8.47	2.1	10	168	5.2	0.08	0.50	0.60
2001 06 08	00 01	24.79	−112.14	8.45	1.7	10	172	5.3	0.06	0.40	0.50
2001 06 08	02 53	24.80	−112.15	6.55	1.4	8	289	6.4	0.07	0.80	0.80
2001 06 08	03 03	24.79	−112.14	7.57	1.8	10	165	4.7	0.06	0.40	0.50
2001 06 11	21 49	24.79	−112.15	7.87	1.7	8	291	6.2	0.07	0.70	0.60
2001 07 01	01 31	24.79	−112.14	5.46	1.4	10	114	5.6	0.12	0.50	1.10

NR is the number of arrival times used in the earthquake locations; CD is distance to the closest station, rms is the root mean square value and erH and erZ are horizontal and vertical location errors, respectively

Centroid Moment Tensor locations (CMT) (black dots) (Dziewonski *et al.* 1981; Ekström *et al.* 2012).

4.3. Moment Magnitude of the 2000–2001 Micro Earthquakes

The ground accelerations recorded from the 2000–2001 earthquakes were of small amplitude and of little interest from the engineering point of view. Such low accelerations did not warrant a detailed analysis in this study. We only used the acceleration data to estimate the size of the micro earthquakes. For that, we first calculated the seismic moment, Mo, of the earthquakes first, via standard spectral analysis of the recorded shear waves (Brune 1970). We then used the moments to obtain the moment magnitude, M_w, by using the formula of Hanks and Kanamori (1979). The magnitudes estimated for the recorded micro earthquakes were in the 1.3–2.5 range. For such small events, the recorded peak ground accelerations were up to 8.4 cm/s^2 at distances of 5–10 km from the sources.

4.4. Focal Depth and Composite Fault Plane Solution for the 2000–2001 Earthquakes

Figure 5a shows an enlarged view of the zone of earthquakes that occurred to the west of San Carlos

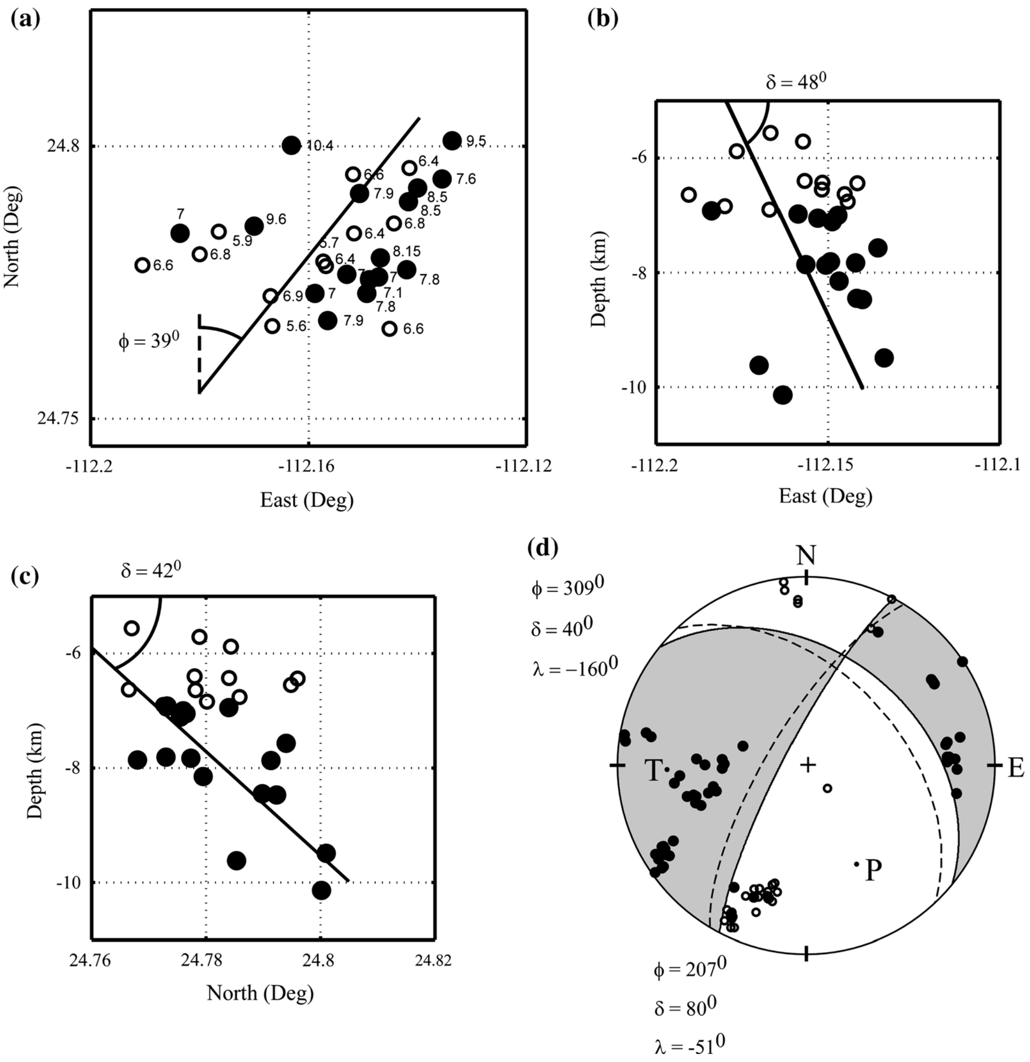

Figure 5

a Enlarged view of the area of clustered earthquakes that occurred during the 2000–2001 interval. The *number* located to one side of each epicenter indicates the focal depth of the correspondent event. *Solid circles* stand for earthquakes with depths equal to 7.0 or larger. The line plotted with azimuth of 39° shows an apparent trend of the epicenters. In **b** and **c**, we show plots of focal depth versus the east and north geographic coordinates, respectively. The *straight line* on these plots corresponds to the line drawn in the map of Fig. 5a projected from 5 to 10 km depth. **d** Composite fault plane solution determined with P-wave polarity data from the same group of earthquakes. The *dashed lines* in **d** represent the CMT double-couple solution for the M_w 5.4 event of 9 February 2004, at 01:24 h (UTC)

during the 2000–2001 interval. Numbers located to one side of the epicenters indicate the focal depth of the earthquake sources, which vary from 5.6 to 10.4 km. Those earthquakes for which the focal depths were equal to 7.0 km or larger are marked with black circles in the figure. Although the epicenters were located within a small area, it appears that they follow NE trend, as indicated by the straight line plotted at an azimuth of 39°.

Figure 5b and c shows plots of focal depth versus the east and north geographic coordinates, respectively. The straight line on these plots corresponds to the line drawn in the map of Fig. 5a, projected from 5 to 10 km depth. These two figures show that the focal depth increased in E–NE direction, at an angle from the surface that is between 42° and 48°. This might not be strongly convincing, due to the limited number of events and the small volume that contains the hypocenters. Nevertheless, if this trend in the focal depth is true, then the data would be consistent with the composite fault plane solution of Fig. 5d, as is described next.

The fault plane solution of an earthquake is a useful tool to describe the style of faulting in a given region. In this study, however, due to the small size of the analyzed earthquakes we could not obtain fault plane solutions for individual events. Nonetheless, using the P-wave polarity data from 21 of the closely spaced events, we determined the composite fault plane solution of Fig. 5d. The assumption here was that all of these events occurred on the same fault plane and with the same focal mechanism, which seemed to be a valid assumption given the closely spaced sources.

It is worth noting that our composite fault plane solution is quite similar to the global CMT double-couple solutions for the M_w 5.4 and 5.3 events of 9 February 2004 (see Fig. 2; Table 2). For comparison, we drew the CMT mechanism of the M_w 5.4 event of 9 February 2004 (at 01:24 h) (dashed lines) on top of the fault plane solution of Fig. 5d. One may see that the two mechanisms are nearly equal, even though the stronger earthquake occurred 3 years later and at ~60 km northwest of the San Carlos events (event 13* in Fig. 2). Such strong similarity between the focal mechanisms tells us that the two earthquake sequences occurred along the same active fault, but at different times.

Our fault plane solution has a plane that strikes in SE–NW direction and dips to NE, consistent with the San Lázaro-Santa Margarita and the Tosco-Abreojos faults systems that cut through the area of study (e.g., Normark *et al.* 1987; Spencer and Normark 1979; Fletcher *et al.* 2007; Brothers *et al.* 2012; Salazar 2014). The seismicity analyzed here, however, was located 5 km east of the northwest segment of the Santa Margarita Fault and ~50 km east of the Tosco-Abreojos Fault. It is more likely, then, that the earthquakes had occurred in association with the Santa Margarita Fault. The apparent depth-increasing E-NE trend of the earthquakes plus features of the focal mechanisms seems to support this conclusion.

Based on the spatial location of the analyzed earthquakes, we confirm the existence of active faults east of the Tosco-Abreojos fault system. As shown here, such faults have the potential to generate earthquakes of low to intermediate magnitudes. This also implies that transtensional deformation is taking place in a wide zone along the Pacific margin of Baja California Sur, and it is not limited to the Tosco-Abreojos fault system. More seismic data are required to improve the present understanding of the geometry and kinematics of the active faults of the region.

4.5. *Examination of the Current State of Stress in the Region*

In this section, our goal is to get some insights into the state of the tectonic stress that prevails in the region. For this, we will compare the focal mechanisms considered in this study with the focal

Table 2

Global CMT fault plane solution data for two earthquakes that occurred on February 2004 and for the composite fault plane solution determined in this study

Date yr mo day	Time hr mn	Latitude (°)	Longitude (°)	Depth (km)	M_w	Strike (°)	Dip (°)	Rake (°)
CMT fault plane solutions								
2004 02 09	01 24	25.06	−112.60	12	5.4	317	49	−157
						211	73	−43
2004/02/09	09 03	25.13	−112.56	12	5.3	312	37	−138
						186	66	−60
Composite fault plane solution for the 2000–2001 earthquakes								
Fault plane 1						309	40	−160
Fault plane 2						207	80	−51

mechanisms for other earthquakes of the region. To begin that, Table 3 summarizes the azimuth and plunge angles of *P* and *T* stress axes from the mechanisms of this study and from other regional earthquakes. The first earthquakes to consider are two *M* 5.3 events reported by Molnar (1973). These earthquakes occurred in August 1969 southwest of Todos Santos, at 240 km southeast of San Carlos; Figure 6a shows their fault-plane solutions. Figure 6b shows projections, onto the equatorial plane, of the *P* axes (continuous lines) and the *T* axes (discontinuous lines) from Molnar's mechanisms and from the mechanism of this study. Concentric circles were drawn to serve as scale for the plunging angles. With this scale, the longer the projection lines, the more horizontal the *P* or *T* axes are.

Figure 6b also includes global average orientations of the *P* and *T* axes of stress from mechanisms for earthquakes of La Paz–Los Cabos and of the Gulf of California regions (Munguía *et al.* 2006). We indicate those regional stress orientations with the arrows labeled P_{LPC}, P_{GC}, T_{LPC}, and T_{GC}. Munguía *et al.* (2006) determined the P_{GC} and T_{GC} stress orientations from highly consistent directions of *P* and *T* axes on mechanisms for 13 representative events of the Gulf of California fault system studied by Goff *et al.* (1987). These earthquakes had their epicenters distributed along the Gulf fault system, from the Delfin Basin zone (29°N) to the Tamayo Fracture Zone (23°N). Thus, the calculated trends for P_{GC} and T_{GC} are close approximations to the orientations of the regional stresses that drive the Gulf of California fault system. For these Gulf earthquakes, Munguía *et al.* (2006) estimated average plunge angles of $\sim 9°$ and $\sim 12°$ for the P_{GC} and T_{GC} axes, respectively. Such near horizontal axes of stress are clear indication of predominant strike-slip faulting within the Gulf region.

The P_{LPC} and T_{LPC}, on the other side, are average trends of the stress axes calculated from earthquakes of La Paz–Los Cabos region (Munguía *et al.* 2006). At the southern part of that region, the analyzed earthquakes had mechanisms that showed predominant strike-slip motions. The mechanisms reported by Molnar (1973) (Fig. 6a, b) are additional examples of earthquakes with predominant strike-slip faulting at the southern part of La Paz–Los Cabos region. At the northern part of this region (24°–24.5°N), including the eastern margin of Baja California Sur, the earthquakes were of the normal-fault type. In this case, the *P* axes had a mean plunge angle of 55° at an azimuth of 168°, whereas the *T* axes were nearly horizontal, with a 61° average trend (see Table 3).

According to information from Table 3, the *T* axes on focal mechanisms for earthquakes of the Gulf of California and of the northern La Paz–Los Cabos region are nearly horizontal. In addition, we see that the orientation of those axes varies only within 36°. These variations in the orientation of the axes of stress are probably due to motions of Baja

Table 3

Azimuth and plunge angles of P and T axes determined from focal mechanisms for the earthquakes studied herein and from earthquakes of previous studies

Events	*P* axes		*T* axes	
	Azimuth (°)	Plunge (°)	Azimuth (°)	Plunge (°)
2004	Event 1: 166	44	88	14
	Event 2: 136	58	76	12
2006	154	40	88	26
Average of 2004 and 2006 data:	152	44	84	17
Northern La Paz–Los Cabos region	169	57	65	8
Entire La Paz–Los Cabos region	158	41	61	7
Gulf of California	170	9	84	12
Molnar (1973)	Event 1: 156	40	55	12
	Event 2: 142	32	51	0

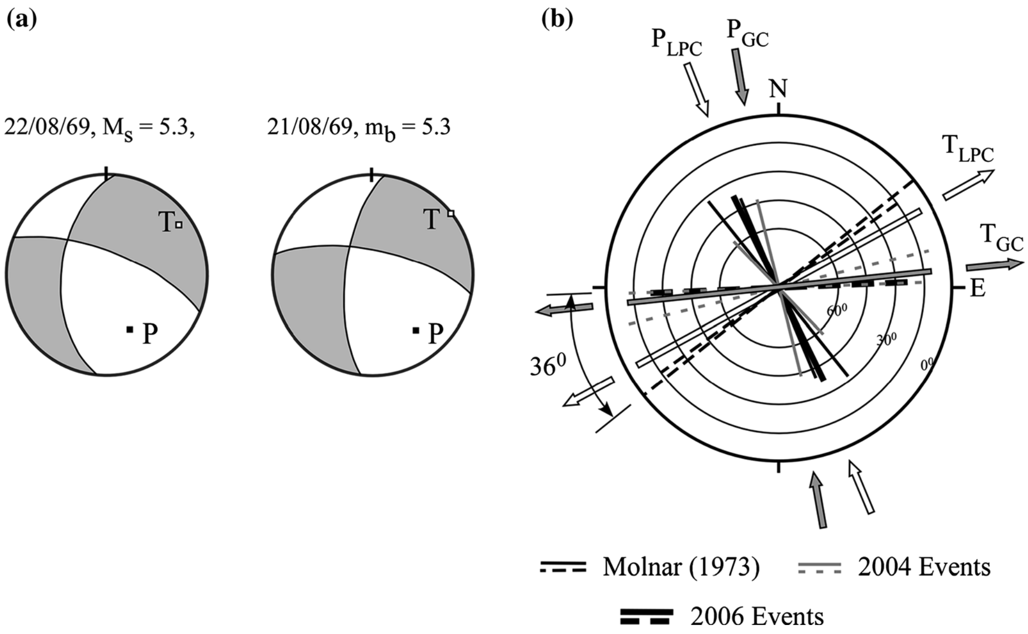

Figure 6

a Fault plane solutions for earthquakes of the Pacific margin of Baja California Sur, as reported in the study of Molnar (1973). **b** *P* and *T* axes from the focal mechanisms in **a** and from the mechanisms obtained in this study projected onto the equatorial plane. The concentric circles are a scale for the plunge angles. With this scale, the longer the lines of projection, the more horizontal the *P* or *T* axes are. *Arrows* with the P_{LPC}, P_{GC}, T_{LPC}, and T_{GC} labels are the global average stress orientations for the La Paz–Los Cabos (LPC) and for the Gulf of California (GC) regions, as taken from Munguía *et al.* (2006)

California as a micro plate. We envisage a complex tectonic situation for the region since Baja California is loosely coupled with the North America plate and its transfer to the Pacific plate is not yet complete (e.g., Fletcher and Munguía 2000; Michaud *et al.* 2004; Plattner *et al.* 2009; among others). Under this situation, the seismicity occurs in response to a combination of local and regional tectonic stresses.

In contrast to the *T* axis, the *P* axes from mechanisms of the La Paz–Los Cabos region earthquakes plunge at an average angle that is higher (55°) than that for the Gulf earthquakes (9°). In this study, we found a similar result for the case of the 2004 and 2006 earthquakes. In this case, since the mechanisms of these events and our composite mechanism were all similar, we averaged the plunge and azimuth of the *P* and *T* axes. For the *P* axis, the results showed an average plunge angle that is about 35° larger than the plunge angle of mechanisms of the Gulf earthquakes. Such higher plunge angle reflects an important component of oblique fault motion. Thus, the mixture of oblique- and strike-slip faulting is clear evidence of a transtensional stress regime in the region of study. In a study of the 2006 earthquake swarm of Bahía Asunción, Munguía *et al.* (2015) reported closely spaced hypocenters for earthquakes with normal and strike-slip fault mechanisms. This swarm occurred 350 km northwest of San Carlos and ~35 m to the east of the Tosco-Abreojos fault. The seismicity of Bahía Asunción and San Carlos areas is thus evidence of wide zones of transtensional deformation along the western margin of Baja California Sur. According to this, the western margin of Baja California Sur is a region characterized by active tectonism, with faults that accommodate part of the relative plate motion, as proposed in many other studies (e.g., Humphreys and Weldon 1991; Dixon *et al.* 2000; Fletcher and Munguía 2000; Michaud *et al.* 2005; Munguía *et al.* 2006; Fletcher *et al.* 2007).

5. *Summary and Conclusions*

We studied earthquakes that occurred along the western margin of Baja California Sur, at 200 km from the Gulf of California fault system. Their study is important for a better understanding of the seismotectonic framework and of the hazard potential of future earthquakes in the region. Our results show that most of the located epicenters correlate well with the northwest segment of the Santa Margarita fault. This normal fault extends parallel to the coastline and forms part of a group of W-NW striking faults that isolate Baja California from the Pacific plate (e.g., Fletcher and Munguía 2000). We inferred that the source depths for the well-located micro earthquakes deepen to northeast. Such apparent direction of increasing depth was in agreement with a composite fault plane solution determined with data from these small events. This mechanism showed that in the study area the mode of faulting is primarily of the normal faulting type (east side down). Further, we found that the CMT mechanisms for two M_w 5.4 and 5.3 earthquakes that occurred in the area on 9 February 2004 had nearly the same mechanism. This fact suggested to us that the larger size earthquakes occurred also along the Santa Margarita Fault. It seems then that the Santa Margarita fault is one of the most active faults to the west of Baja California Sur. At least in the period of historic seismicity considered here, this fault, and possibly other faults of the Tosco-Abreojos fault zone, accommodated some of the total Pacific–North American slip rate. Other earthquakes of intermediate magnitude that have occurred to the south and north of our study area also had focal mechanisms showing substantial components of normal faulting (Molnar 1973; Fletcher and Munguía 2000; Michaud *et al.* 2005, 2011; Munguía *et al.* 2006, Munguía 2015). Then, these overall results support the hypothesis of plate motion partitioning between the Gulf of California and the Pacific margin of Baja California (e.g., Humphreys and Weldon 1991; DeMets 1995; Dixon *et al.* 2000; Fletcher and Munguía 2000; Michaud *et al.* 2005, Munguía *et al.* 2006; Fletcher *et al.* 2007; Munguía *et al.* 2015).

Another important feature of this study deals with the size of the analyzed earthquakes. The earthquakes seem to be of little relevance due to their low magnitudes. However, accurate location of their sources revealed a zone in which stresses accumulate and release more often in the region. The earthquakes of that zone occur at 6- to 10-km distance of San Carlos. With magnitudes of slightly over 3.0, some of those earthquakes already caused minor damage and some alarm in town. As for the Bahía Asunción area, it is likely that the slight damage caused in San Carlos was due to a combined effect of the near-source distances and the amplification of the earthquake motions by poor soil conditions (Munguía *et al.* 2015). The presence of shallow soft sediments below a given site is a ground condition that plays an important role on the amplitudes of the earthquake ground motions (e.g., Hartzell *et al.* 2003; Munguía and González 2012). This, however, is an issue that deserves detailed future study with more and better seismic data.

Up to now, earthquake damage in San Carlos has been minimal because of the small size of the occurred earthquakes. In the past decades, the activity of the Santa Margarita and other possible faults resulted only in earthquakes of low-to-intermediate magnitudes. However, the possible occurrence of future stronger earthquakes near San Carlos is something that we cannot discard. This is a possibility that poses a seismic hazard of unknown level to the town. Hence, the earthquakes analyzed in this study should serve as a remainder to San Carlos residents of the danger upon occurrence of stronger events.

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