Active tectonics in the Gulf of California and seismicity \((M > 3.0)\) for the period 2002–2014

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**Abstract**

We present a catalog of accurate epicenter coordinates of earthquakes located in the Gulf of California (GoC) in the period 2002–2014 that permits us to analyze the seismotectonics and to estimate the depth of the seismogenic zone of this region. For the period April 2002 to December 2014 we use body-wave arrival times from regional stations of the Broadband Seismological Network of the GoC (RESBAN) operated by CICESE to improve hypocenter locations reported by global catalogs. For the northern region of the GoC (30°N–32°N) we added relocated events from the 2011-Hauksson-Yang-Shearer, Waveform Relocated Earthquake Catalog for Southern California (Hauksson et al., 2012; Lin et al., 2007). From October 2005 to October 2006 we incorporated hypocenters located by Sumy et al. (2013) in the southern GoC combining an array of ocean-bottom seismographs, of the SCOOBA experiment, with onshore stations of the NARS-Baja array. This well constrained catalog of seismicity highlights zones of active tectonics and seismic deformation within the North America-Pacific plate boundary. We estimate that the minimum magnitude of completeness of this catalog is \(M_c = 3.3 \pm 0.1\) and the \(b = 0.92 \pm 0.04\) value of the Gutenberg-Richter relation. We find that most earthquakes in the southern GoC are generated by transform faults and this region is more active than the central GoC region. However, the northern region, where most deformation is generated by oblique faults is as active as the southern region. We used the ISC catalog to evaluate the size distribution of seismicity of these regions, and the \(b\) value of the Gutenberg-Richter relation and found that \(b = 0.86 \pm 0.02\) compared to the northern \(b = 1.14 \pm 0.04\) and the southern \(b = 1.11 \pm 0.04\) regions. We observed seismicity that occurs in the Stable Central Peninsular Province, despite the fact that significant active deformation has not been identified in this region.

**1. Introduction**

The Gulf of California (GoC) contains an active fault system that connects the San Andreas Fault to the north with the East Pacific Rise to the south. The seismicity in the GoC is mostly governed by large transform faults linked by extensional basins (Lonsdale, 1989; Stock and Hodges, 1989). Most earthquakes near these transform faults are right lateral strike-slip events, and normal fault events tend to occur on the spreading centers (Goff et al., 1987). The seismicity of the GoC has been previously studied using global catalogs of earthquakes (e.g. Sykes, 1968, 1970; Molnar, 1973; Goff et al., 1987) and a few with regional stations (Lomnitz et al., 1970; Thatcher and Brune, 1971; Reid et al., 1973; Reichle and Reid, 1977). More recently, Castro et al. (2011b) relocated small- to moderate-sized earthquakes in the GoC that occurred from April 2002 to August 2006. For the period from October 2005 to October 2006 Sumy et al. (2013) located the seismicity in the southern GoC using an array of ocean-bottom seismographs, of the SCOoba (Sea of Cortez Ocean-Bottom Array) experiment, combined with onshore stations of the NARS-Baja array (Network of Autonomous Recording Seismographs) (Trampert et al., 2002; Clayton et al., 2004). These earthquake catalogs of well-constrained epicenters have permitted a more detailed visualization of the shape of the Pacific-North America plate boundary and yield a better understanding of the kinematics of seaﬂoor spreading and continental extension within the GoC. The regional catalogs also provide new evidence for extensional deformation near the spreading centers and within the basins of the GoC (Sumy et al., 2013).

In this paper we compile a catalog of accurately located earthquakes of the GoC region for the period 2002–2014, including some of the previously mentioned studies as well as new work. We use body-wave arrival times from regional stations of the Broadband Seismological Network of the GoC (RESBAN) operated by CICESE (Centro de Investigación Científica y de Educación Superior de Ensenada, Baja California) to relocate 2850 events reported by the International Seismological
Centre (ISC) in the GoC. For the northern GoC (30°N–32°N) we include in the catalog earthquakes from the 2011-Hauksson-Yang-Shearer, Waveform Relocated Earthquake Catalog for Southern California (Hauksson et al., 2012; Lin et al., 2007). We used for the period October 2005 to October 2006 hypocenters located by Sumy et al. (2013) in the central-southern GoC from earthquakes recorded by the array of ocean-bottom seismographs, of the SCOOLA experiment, combined with onshore stations of the NARS-Baja array. The new catalog presented here is an improvement of hypocenter locations within the GoC reported by global catalogs. Note that the catalog does not include all events, because if an event did not pass our selection criteria for location accuracy, we did not include it. This provides us a clearer picture of the distribution of the seismicity than if we used all the events in this region from regional or global catalogs.

1.1. Geological setting

The Gulf of California is a trans-tensional rift system located between the Sierra Madre Occidental of continental Mexico and the narrow Peninsular Ranges of Baja California (Fig. 1). The peninsula of Baja California moves almost completely with the Pacific plate at about 48 mm/yr across the GoC (DeMets and Dixon, 1999; Dixon et al., 2000). Relative motion between the Baja California peninsula and the Pacific plate is suggested to be <3 mm/yr (DeMets et al., 2010) and modeling of geodetic data across the plate boundary, at the Ballenas Channel, gives a slip rate of 47.3 ± 0.8 mm/yr (Plattner et al., 2015). The Pacific-North America plate boundary has undergone a major reorganization, from oblique convergence with the Farallon plate to trans-tensional shearing, since ~12 Ma, after the southward migration of the

![Location of epicenters (circles) reported by the International Seismological Center (2013) catalog between 2002-04-01 and 2014-12-31. The triangles are the locations of the broadband seismic stations from the NARS-Baja (NE70 to NE83) and RESBAN (CHXB, BAHB, EVAR, PPXB, PLIB, NOVI, GUYB, NAVO, TOPB, SLGB, SFQB) arrays. The boxes indicate the zones we divided the GoC region for relocation purposes. The lines A-A’ and B-B’ indicate the cross-section profiles used in Fig. 4.](image-url)
Rivera triple junction (Atwater, 1970; Stock and Hodges, 1989). At the present time, the boundary between the Pacific and North America plates consists of short, nascent ridge centers connected by transform faults (Thatcher and Brune, 1971). Faulting in the GoC is dominated by right-lateral strike-slip motion on the transform faults that link spreading centers. In the southern GoC the spreading centers are well-developed ridge segments whereas in the northern GoC these are sedimentary pull-apart basins (Moore, 1973; Lonsdale, 1985).

### 1.2. Regional broadband arrays

The NARS-Baja array (Trampert et al., 2003; Clayton et al., 2004) operated from the spring of 2002 to the fall of 2008. This seismic network consisted of 14 broadband stations from Utrecht University (Fig. 1), with STS2 sensors, a 24-bit data logger and a global positioning system. This array was installed and operated in collaboration with the California Institute of Technology, Utrecht University and CICESE. The RESBAN network started in 1995 with installation of the first two stations (BAHB and GUYB); other stations were installed in later years (Rebollar et al., 2001). The seismographs of the RESBAN array are 24-bit Guralp digitizers with sensors Guralp CMG-40T or CMG-3ESP, a CMG-SAM2 acquisition module and GPS for time control. The stations of both arrays record at 20 samples per second, continuously. After the stations of the NARS-Baja array were removed in 2008, RESBAN installed seismographs at former NARS-Baja locations NE79, NE80, NE81 and NE82. At the present time RESBAN operates 13 stations in the GoC region.

The SCOOBA ocean-bottom array comprised 15 OBS seismographs that operated in the southern GoC from October 2005 to October 2006, but only eight stations provided usable data (Sumy et al., 2013). The stations of this array consist of four-component broadband instruments from the Scripps Institution of Oceanography that record at 32.25 samples per second.

### 2. The 2011-Hauksson-Yang-Shearer catalog for Southern California

This catalog consists of relocated earthquakes recorded by the Southern California Seismic Network (SCSN) from 1981 through June 2011 (Hauksson et al., 2012). The catalog contains events in the region extending from Owens Valley in the north and Baja California in the south, and the magnitudes of the earthquakes reported range from M 0.0 to 7.3.

Hauksson et al. (2012) used 1D and 3D velocity models from Hauksson (2000) to improve the locations reported in the SCSN catalog. Then, they relocated the hypocenters by clustering the events and using differential travel times to determine relative locations within each cluster (e.g. Lin et al., 2007). They included up to 150 nearest neighbors for the cross-correlation calculation and required that pairs of earthquakes be separated by no > 2.5 km.

They relocated the hypocenters using multithread central processing units by dividing the region into polygons. They used the clustering method by Shearer et al. (2005) and Lin et al. (2007) to identify clusters of earthquakes. Then, they used the cross-correlation differential times to relocate the events. The preferred hypocenter locations of this catalog are those determined with travel-time picks and differential travel times. If differential travel-times were not available, they reported hypocenters determined with the 3D velocity model. When these were not available, they included hypocenters determined with HIPOINVERSE-2000 (Klein, 2002) and a 1D velocity model.

Most events (75.3%) in this catalog were determined with differential travel-times and only 0.3% were relocated with a 1D model. The earthquake depths in this catalog extend from 0.8 km to about 20 km and only a few events have depths ~30 km. The 90% of the horizontal location errors are < 0.75 km and vertical errors are < 1.25 km.

### 3. The 2013-Sumy et al. catalog for the Southern Gulf of California

Sumy et al. (2013) used P-wave pick arrivals, automatically detected and manually inspected, to locate hypocenters in the southern Gulf of California with the HIPOINVERSE-2000 (Klein, 2002). The data set comes from 8 ocean-bottom seismographs deployed from October 2005 to October 2006 in the southern GoC and 16 broadband seismographs of the NARS-Baja array (Trampert et al., 2003; Clayton et al., 2004).

They initially located events with four or more P-wave picks using a 1D velocity model obtained through a simultaneous inversion using the VELEST algorithm (Kissling, 1988; Kissling et al., 1994). To improve the hypocenter locations, they formed seven geographically distinct clusters and relocated the events using the double-difference algorithm by Waldhauser and Ellsworth (2000) and Waldhauser (2001). The mean horizontal location errors, estimated from a bootstrap error analysis, are on the order of ~2 km.

### 4. The international seismological Centre (ISC) catalog

We searched in the ISC Bulletin for earthquakes located in the GoC region between 2002-04-01 and 2014-12-31. We found a total of 2850 events (Fig. 1). Most of the earthquakes seem to concentrate in the north and south ends of GoC, and in the Guaymas basin (27°N–28.5°N). The earthquakes in the southern end are typically generated by transform faults and this region is usually regarded as being more active than the northern GoC region, where most deformation is generated by oblique faults. We quantify the rate of seismicity of these regions, and the amount of seismic activity with the Gutenberg-Richter (G-R) relation.

We divided the GoC region into four zones (30°N–32°N, 28°N–30°N, 26°N–28°N and 23°N–26°N) and calculated the number of events and the cumulative number for the magnitude range 0.1–7.0, with magnitude increments of 0.1. Fig. 2 displays the frequency-magnitude distributions of the four zones. The distribution of non-cumulative number of events (circles in Fig. 2) is useful to identify the minimum magnitude of completeness (Mc) of the catalog (e.g. Wiemer and Wyss, 2000; Zúñiga and Castro, 2005). We found that Mc varies between 3.5 ± 0.1 and 3.6 ± 0.1, being 3.5 ± 0.1 for the central GoC and 3.6 ± 0.1 for the north and south zones. We also calculated the b value of the G-R law (solid lines in Fig. 2) for the four zones. The most northern zone (32°N–30°N) has the larger number of events (950), for the period analyzed, and similar b value (b = 1.14 ± 0.04) than the southern zone (26°N–23°N) (b = 1.11 ± 0.04). The north-central zone (30°N–28°N) has the smallest number of events (384) and the smallest b value (b = 0.86 ± 0.02) of the four zones.

### 5. Hypocentral locations from regional data

Earthquake locations based on regional body-wave arrivals usually provide better hypocentral coordinates than global catalogs. For instance, Castro et al. (2011b) found that earthquakes with mb magnitude 3.2–5.0 in the GoC reported by the Preliminary Determination of Epicenters (PDE) catalog differ on the average by as much as ~40 km from those located with regional data. They also found that the epicentral location discrepancies decrease for larger earthquakes (Mb > 5.6 to 6.7) to approximately 25 km but these differences are still important. Sumy et al. (2013) compared the epicentral locations of earthquakes in the southern GoC obtained with regional data with those in the ISC catalog and found that the epicenters differ by an average of ~50 km.

In this paper we estimated initial hypocentral locations using handpicked P and S wave arrival times, with an approximate accuracy of one tenth of a second, from the regional stations of RESBAN (Fig. 1) and the HIPOINVERSE computer code (Klein, 2002). We selected events in the GoC, from the global catalog, that occurred between 2002 and 2014 and were recorded by at least four stations of RESBAN.
We used a four layer velocity model determined by Lopez-Pineda et al. (2007) from surface-wave analysis. The $P$-wave velocity of this model varies from 4.6 to 7.9 km/s for the first 25 km, and has a velocity of 8.2 km/s for the upper mantle (dotted line in Fig. 3).

6. Relocated hypocenters

The hypocentral locations obtained with HYPOINVERSE were relocated using the Source Specific Station Term (SSST) method (Richards-Dinger and Shearer, 2000; Lin and Shearer, 2005) and the Double Difference (hypoDD) algorithm (Waldhauser and Ellsworth, 2000). The SSST method accounts for lateral heterogeneities of the velocity structure calculating specific station terms of each target event. In this technique each station has a correction function that varies with earthquake position. Lin and Shearer (2005) implemented the SSST technique in their COMPLOC earthquake location code. We used a version of this computer code that uses regional phases and weights the arrival times according to the hypocentral distance (e.g. Castro et al., 2010).

We divided the GoC region into nine boxes (Fig. 1) taking into account the distribution of epicenters located with HYPOINVERSE. We used arrival times from all the available stations but only earthquakes within the corresponding box of the target event to calculate the SSST correction. We tested the three models shown in Fig. 3 and compare the root mean square (RMS) of the residual travel times to select the best model. The velocity model of Gonzalez-Fernandez et al. (2005) (solid line in Fig. 3) was determined from a 280 km-long multi-channel seismic reflection line deployed in the northern GoC. This four-layer model includes an uppermost layer with $P$-wave velocities between 1.77 and 2.15 km/s that represent the sediments. The second velocity layer (4.11–5.09 km/s) corresponds to more deeply buried sedimentary
rocks. The middle crust has velocities of 5.37–5.67 km/s, the lower crust 6.58–6.73 km/s and the upper mantle a velocity of 7.9 km/s. In a previous study Castro et al. (2011b) tested this and other three models proposed for the GoC and found that the model obtained by Gonzalez-Fernandez et al. (2005) (Model GF2005 henceforth) gives the smallest residuals. Sumy et al. (2013) determined a velocity model (dashed line in Fig. 3) inverting arrival times from 228 earthquakes using the VELEST algorithm (Kissling, 1988; Kissling et al., 1994). This model is similar to the model of López-Pineda et al. (2007) (dotted line in Fig. 3). We also relocated the events with the Sumy et al. (2013) model and obtained similar results as with the GF2005 model. We decided to use the GF2005 model for the rest of the analysis.

We also used the hypoDD code (Waldhauser and Ellsworth, 2000) to relocate the earthquakes initially located with HYPOINVERSE. The Double Difference (DD) method uses pairs of nearby earthquakes with small hypocentral separation compared to the source-station distance and the expected scale length of the velocity heterogeneities. Thus, the difference in the observed travel times of the two events at a given station is attributed to the spatial offset between them and can be calculated accurately.

We first used the PHZDT code (Waldhauser and Ellsworth, 2000) to form travel time differences from P- and S wave picks and then hypoDD to relocate the initial epicenters. The maximum distance between source pair and stations was limited to 800 km, the maximum hypocentral separation to 20 km, and the maximum number of links per event to 150. We relocated the earthquakes by dividing the GoC region into the same nine boxes as before. A few events (Table 1) have a resulting focal depth > 20 km. We revised the hypocentral locations of these events and found that the focal depths obtained with the SSST method are shallower for many of those events and the vertical error, estimated with HYPOINVERSE, significant (erz > 10 km). We decided to keep these events in the catalog (Table S1) because the horizontal error is small but we did not use them to analyze the cross sections. Fig. 4 (left frame) shows the distribution of the hypocenters relocated with the DD algorithm, projected on a plane parallel to the axis of the GoC (NW-SE direction) using as origin the northernmost point of the Gulf (31.786°N,114.750°W) (profile A-A’ in Fig. 1). Most of the earthquakes have focal depths < 10 km and the deepest are located on the northwestern side of the GoC. We also projected the hypocenters on a plane perpendicular to the GoC axis (Fig. 4 right frame), in the SW-NE direction (profile B-B’ in Fig. 1). We observed in this projection that earthquakes located near the axis, near zero distance, tend to be shallower than more distant events from the origin, on both SW and NE directions. This variation of focal depth is likely related to the increase of crustal thickness and the temperature decrement towards the margins of the GoC.

Lin and Shearer (2005) compared these two relative hypocenter location algorithms with synthetic data and found that for regions with distributed seismicity, like the GoC region, the DD and SSST methods give relative locations of comparable accuracy. Fig. 5 shows the RMS travel time residuals obtained with the SSST (left frame) and with the DD (right frame) methods. The RMS is < 0.5 s for 62% of the events relocated with SSST and 68% with DD. For RMS < 0.2 s the percentage of earthquakes is higher with SSST (31%) than that with DD (9%). However, the percentage of events with RMS < 1.0 s is 96% with DD and 60% with SSST but the number of earthquakes that we were able to relocate with the SSST algorithm was greater because the number of pairs of events with small hypocentral separation is more limited.

7. Results and discussion

We formed a catalog of relocated hypocenters putting together earthquakes from: (a) 311 events relocated between 32°N and 30°N in the period 2002–2014 from the 2011-Hauksson-Yang-Shear, Waveform Relocated Earthquake Catalog for Southern California (Hauksson et al., 2012; Lin et al., 2007); For this catalog, 90% of the horizontal location errors are < 0.75 km and the vertical errors < 1.25 km; When hypocenter coordinates were not available in this catalog we reported our relocation hypocenters; (b) 652 earthquakes located between 29.5°N and 26°N by Sumy et al. (2013); The mean horizontal location errors of this catalog, estimated from a bootstrap error analysis, are on the order of ~2 km; When hypocenter coordinates were not available, and for the periods June 2002 to September 2005 and November 2006 to November 2014 we inserted our hypocenters relocations; and (c) 361 events from our relocations obtained using regional body-wave arrivals for events not located by the former two catalogs. The hypocenter location errors, calculated with Hipoinverse, have a RMS ~0.62 s and horizontal error of ~8.6 km. The RMS values of the relocated events were reduced considerably, as shown in Fig. 5. The median value is 0.53 s and the spatial error of the relocated hypocenters is approximately 2.4 km.

As we discuss in Sections 2 and 3, different methods were used to relocate the events of the three catalogs. However, the goal was the same, to determine the best possible hypocenter locations. We combine the three catalogs with the main purpose of understanding the kinematics of seafloor spreading and continental extension within the GoC, and the shape of the Pacific-North America plate boundary. Table S1 of the electronic supplement lists the hypocentral coordinates of the earthquakes compiled. We listed the hypocentral coordinates of earthquakes relocated with the DD algorithm when available, otherwise the coordinates were obtained with the SSST method. Fig. 6 shows the distribution of relocated earthquakes listed in Table S1, and we observe that most epicenters are on the Pacific-North America plate boundary.

We also calculated the minimum magnitude of completeness of the catalog $M_c = 3.3 \pm 0.1$ and $b = 0.92 \pm 0.04$ value of the Gutenberg-Richter relation. Fig. 7 shows the cumulative (triangles) and noncumulative (circles) number of events of the catalog of relocated earthquakes and the least-squares fit determined to estimate the $b$ value. The $b$ value of 0.92 is very similar to that obtained ($b = 0.86–1.14$) for the different regions of the GoC (Fig. 2).

The distribution of focal depths (Fig. 4) can be used to estimate the depth of the seismogenic zone in the GoC. Although most earthquakes have focal depths < 10 km, events located near the axis of the GoC tend to be shallower. There is a group of events on the southern part of the Baja California Peninsula, near NE78 (Fig. 6) with focal depths above 20 km (Table 1) and another between stations SLGB and BAHB in the vicinity of the Ballenas Transform Fault. These focal depths are beyond the expected bottom of the seismogenic thickness. The crustal thickness in the Baja California Peninsula varies from approximately 27 km on the western side to ~20 km on the GoC margin. The maximum

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depth of the Moho of ~42 km is beneath the Peninsular Ranges batholith, near the Sierra San Pedro Martir (Reyes et al., 2001 and Lewis et al., 2001).

7.1. The northern GoC

The northern region of the GoC is characterized by a complex system of faults that strike N-N30°E and are mainly oblique-normal with dips of 60°–80° and small offsets (Persaud et al., 2003). Fig. 8 shows the distribution of the relocated epicenters from the 2011-Hauksson-Yang-Shearer catalog (yellow circles) and other events, not present in that catalog that were relocated using the RESBAN arrival times (red circles). Most events inland (yellow circles) north of the shoreline are aftershocks of the 2010 El Mayor-Cucapah (Mw 7.2) earthquake. The focal mechanisms (Fig. 8), taken from the GCMT or the NEIC catalog, are from the bigger earthquakes (Mw 4.5–5.4) plotted in their relocated positions, and are generally consistent with the NW-SE orientation of the faults located SE of Consag basin. The strike of the fault planes, inferred from the focal mechanisms, are between 45°N and 49°N for events 1 and 2 (Table 2). A set of relocated events near the western margin of the GoC have normal fault mechanism, such as the one we show as event 3 (Fig. 8 and Table 2) which corresponds to an Mw 5.2 earthquake that occurred in September 2014. This mechanism is the result of the predominantly tensional stress regime of this region. All five of the events in this swarm have similar focal mechanisms, suggesting active extension along previously unmapped faults near the coastline of Baja California, within extended continental crust of the Gulf of California Extensional Province, west of the Upper Delfin Basin. Shallow fault arrays have been identified in this region by Aragón-Arreola and Martin-Barajas (2007) although these are mapped parallel to the coastline, not parallel to the nodal planes for the normal faulting focal mechanisms in this swarm. Because this active faulting is part of the overall plate boundary zone, both NE- and NW-striking faults are to be expected as part of the kinematic pattern here.

Based on a simple kinematic analysis Goff et al. (1987) suggested that the Delfin and Wagner basins may be part of a triangular pull-apart basin defined by a diffuse zones of extensional faulting previously identified by Henyey and Bischoff (1973). Near the upper Delfin basin (~30.5°N) the seismicity often occurs in the form of large earthquake swarms (e.g. Reichle and Reid, 1977). To the east of the upper Delfin basin the faults change direction, striking predominantly NE-SW. The epicenters coincide with the distribution of the faults and tend to...
group on the ends of the fractures where it is likely that the tectonic stress tends to concentrate.

7.2. The north-central region of the GoC

This region contains the lower Delfin Basin (~30°N) and the Canal de Ballenas (~29°N) (Fig. 9). Many of the bigger ($M_s > 6$) plate boundary earthquakes occur on the transform faults south of Delfin Basin (Goff et al., 1987). Important earthquakes have occurred on the Canal de Ballenas Transform Fault. These include, for instance, the earthquakes of 8 July 1975 ($M_s 6.5$) and 3 August 2009 ($M_w 6.9$), that occurred west of the island Angel de la Guarda. Fig. 9 shows that most of the relocated epicenters are located along the Canal de Ballenas. The bathymetric relief in this zone indicates that a high rate of tectonic activity is currently taking place. The focal mechanisms, taken from the GCMT catalog, are mostly strike-slip with the strike of the fault plane varying between N33°W and N47°W (Table 2) paralleling the strike direction of the Canal de Ballenas fault. The epicenters in black color are the main event (big star) and the aftershocks of the 2009 earthquake sequence located by Castro et al. (2011a) using the SSST technique. Three important aftershocks (smaller stars) with magnitudes $m_b 4.9, M_w 6.2$ and $M_w 5.7$ occurred during the first 48 h after the main event. Castro et al.
(2011a) estimated that this earthquake sequence had a rupture area of ~600 km² and an average slip of 1.3 m. There are several epicenters located on the Stable Central Peninsula Province (SCPP) where significant deformation related to the extension of the gulf has not been identified (Stock et al., 1991). These earthquakes are intraplate events probably generated by the stress transferred when the plate boundary ruptures along the Canal de Ballenas Transform fault (Castro et al., 2011a). It is possible that these events are reactivating earlier faults, such as the N-S normal faults that bound Bahía de Los Angeles and control topographic steps in the terrain near station BAHB (Fig. 9).

East of Angel de la Guarda Island the seismicity is absent. Based on a seismic line that crosses the upper Tiburon basin, offshore of station PLIB, Aragón-Arreola and Martin-Barajas (2007) concluded that that basin is structurally inactive. South of Canal de Ballenas, where en echelon transform zones define the plate boundary, the focal mechanisms of the earthquakes are a combination of strike-slip and normal fault events, and this is another seismically active zone of the GoC (Fig. 9).

Gutenberg and Richter (1954) reported an earthquake $M = 7.5$ in this region (28°N, 112.5°W), on the Guaymas Transform fault, that occurred on 16 October 1907.

### 7.3. The south-central region of the GoC

The Guaymas and Carmen basins (Fig. 10) are connected by transform faults, where big earthquakes tend to occur, like the 12 March 2003 $M_w$ 6.3 event (26.5°N, 110.8°W). The Guaymas basin is considered a narrow and very active magmatic rift (Lizarralde et al., 2007). The magmatism in this basin is anomalous with respect to global mid-ocean ridge production (White et al., 1992). Based on wide-angle and multi-channel seismic data, Lizarralde et al. (2007) estimated that the continent-ocean transition is located in this basin. Goff et al. (1987) found that this transition is also marked by a broader zone of crustal deformation in the north and a ~10° change in the strike of the principal faults on the northern GoC compared with the strike of the main faults.
in the southern GoC. The earthquakes in this region are distributed in the NW-SE direction along the Guaymas Transform fault. The focal mechanisms show that the strike of the fault plane varies between 35° and 38° (events 9 and 10 in Fig. 10 and Table 2). To the south the seismicity changes direction to SW-NE, migrates southeast and connects with the Carmen Transform fault, where the epicenters are distributed again in the NW-SE direction. Gutenberg and Richter (1954) located an $M = 7.0$ earthquake on the Carmen Transform fault (27°N, 111°W) that occurred on 27 June 1945. It is interesting to note in Fig. 10 that the number of earthquakes is greater on the NW (~27°N) and SE (~26°10′N) extremes of the Carmen Transform fault, where tectonic stress is presumably higher. We also observed swarms of intraplate events outside of these en echelon structures, on the Peninsula NE of station NE75 and near station NE76, and in the gulf between the step-over of the transform faults. Some of these earthquake swarms in the GoC may be related with magmatic activity that in some cases occur near volcanic seamounts, such as the swarm near (27° N 25′, 111° W 50′) in Fig. 10. Another set of events, found on land to the NE of station NE75, likely is related to the slab remnant and the dynamics of the upper mantle. Receiver function results by Persaud et al. (2007) near ~27°N, below station NE75 (Fig. 1), suggest a possible slab top close to the Moho, making the upper mantle more rigid than expected. This can explain why some earthquakes may occur below the crust in this region.

7.4. The south region of the GoC

The transform faults south of Carmen basin have also generated important earthquakes in the past, like the 7 January 1901, $M_w 7.0$ (Pacheco and Sykes, 1992). Earthquakes on the Farallon Transform fault follow the NW-SE direction of the strike (Fig. 12), and the distribution of epicenters becomes more diffuse on the southern end, near the rift that connects with the Pescadero Transform fault. This is one of the more seismically active regions in the GoC and the focal mechanisms are predominantly strike-slip as shown in Fig. 12. The strike of the fault planes varies between N37°W and N45°W (Table 2).

The Alarcon basin, located at the southern end of the GoC, is a wide rift that went through approximately 350 km of continental extension, before seafloor spreading started in this rift segment 2–3 Myr ago (Lizarralde et al., 2007). The earthquakes here align NW-SE along the Alarcon Transform fault (~24°N) and SW-NE at the southern end (Fig. 12). We also observe a swarm of events SW of the transform fault (~23°N 30′), near seamounts, that
Fig. 10. Epicenters relocated in the south-central zone of the GoC, for the period 2002–2014. The red circles are earthquakes relocated with hypoDD (Waldhauser and Ellsworth, 2000) and the yellow circles are events located by Sumy et al. (2013). The focal mechanisms were taken from the GCMT catalog. The topography and bathymetry are from GeoMap App.

Fig. 11. East-west profiles showing the average shear wave velocities (top), modified from Di Luccio et al. (2014), and hypocenters relocated in this study between 26.9°N and 26.7°N.
could be associated with volcanism, and a few intraplate earthquakes NE of the main fault. These events align in the N-S direction (~108°W 15′) and could be related to the bathymetric feature that runs in the same direction.

Fig. 13 shows average S-wave velocities along an east-west profile at 25.8°N determined by Di Luccio et al. (2014) and a seismicity cross-section that includes our hypocenters relocated between 25.7°N and 25.9°N. Most of these earthquakes are within the GoC, above the high-velocity region imaged by Di Luccio et al. (2014), but there are a few events towards the west, under the Stable Central Peninsula Province, where the shear velocity in the upper mantle decreases to ~4.1 km/s. This moderate low-velocity zone may be related to upwelling of asthenospheric material in the upper mantle as suggested by Lizzaralde et al. (2007) and can be associated with a slab window (Di Luccio et al., 2014). The earthquakes in this region may be the result of stress accumulated during these processes. There are a few active faults documented in shallow water of the western margin of the Gulf of California in this region, in the continental crust (Nava-Sánchez et al., 2001) but these do not appear to be associated with any significant seismicity during the time interval that we examined in compiling this catalog.

8. Conclusions

We provide a seismotectonic interpretation of a new catalog of seismicity with well constrained hypocenters located in the GoC. This catalog permits us to identify regions of active tectonics within the Pacific-North America plate boundary. We estimate that the minimum magnitude of completeness of this catalog is $M_c = 3.3$ and the overall $b$ value of the Gutenberg-Richter equals 0.92 ± 0.04. We found that the $b$ value of 1.14 and the number of events of the southern region of the GoC is larger than other regions, indicating that this region is the most seismically active of the gulf. Although most events in the catalog are located on the plate boundary, stress transfer outside the boundary caused by geometrical irregularities and/or reactivation of preexisting faults, generates clustered swarms of intraplate earthquakes. Such seismicity occurred in the Stable Central Peninsula Province (Figs. 9 and 10) despite the fact that significant active deformation related to the
extension of the GoC has not been identified in that province (Stock et al., 1991).

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