Original paper

Active segment of the 12 November 2003 Mw 5.6 earthquake at Salsipuedes oceanic basin, Gulf of California. Mexico

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Resumen

Analizamos el registro de ocho estaciones autónomas con sismógrafos de banda ancha de la red conjunta entre la Universidad de Utrecht, Instituto Tecnológico de California y Centro de Investigación Científica y de Educación Superior de Ensenada, del sismo Mw. 5.6, que ocurrió el 12 de noviembre de 2003, en la cuenca oceánica *Salsipuedes* en la parte media del Golfo de California, a 2 km al oeste de la isla Ángel de la Guarda. Este evento se localizó en las coordenadas geográficas 29.16ºN y 113.37ºO a 30 kilómetros al noreste de Bahía de los Ángeles, además un precursor y cientos de réplicas se registraron en las 48 horas siguientes de su tiempo origen. Con la localización de 29 sismos identificamos el segmento activo, perpendicular a la principal falla tranformante NW-SE del *Canal de Ballenas* que representa el límite transtensional entre las placas del Pacífico y Norte América. La dirección de la falla activa descrita es congruente con el mecanismo de falla normal propuesto por el NEIC dependiente del United States Geological Survey, cuyos valores indican un rumbo de 39º, echado de 34º y deslizamiento de -44º.
Con el análisis de la magnitud de duración de 456 réplicas, calculamos un valor de b=1.14±0.28. Además determinamos un momento sísmico de (3.5 ±3.3)$X10^{17}$Nm, el radio de la fuente fue de 3.7 ± 2.63 km y la caída de esfuerzos estática fue de 3.94 ± 1.15 MPa (39.4 ± 11.5 bar.).

Palabras clave: parámetros de fuente, sismotectónica, Golfo de California.

Abstract

We analyzed records of eight seismic stations of the autonomous broadband seismograph network of a joint project between Utrecht University (the Netherlands), California Institute of Technology, and *Centro de Investigación Científica y de Estudios Superiores de Ensenada* (CICESE). These stations recorded the Mw 5.6 earthquake that occurred on 12 November 2003 at *Salsipuedes* basin in the middle of the Gulf of California 2 km west of the island *Angel de la Guarda*. This event was located at 29.16º N and 113.37º W, 30 km northeast of *Bahia de los Angeles*. A foreshock and hundreds of aftershocks were recorded in the 48 hours after its origin time. With the location of 29 earthquakes we identified the active segment, perpendicular to the main transform fault NW–SE of *Canal de Ballenas*, representing the transtensional boundary between the Pacific and North American plates. The direction of the active fault described is consistent with the normal fault mechanism reported by the National Earthquake Information Center (strike=39º, dip=34º, slip=−44º).
From the duration magnitude of 456 aftershocks, we calculated a *b*-value of 1.14±0.28; furthermore, we calculated a seismic moment of (3.5 ±3.3) $X10^{17}$Nm, a source radius of 3.7 ± 2.63 km, and a static stress drop of 3.94 ± 1.15 MPa (39.4 ± 11.5 bar.).

Key words: source parameters, seismotectonics, Gulf of California.

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Introduction

Since the Miocene, the Gulf of California has been continuously affected by a slow rifting with NW-SE displacement between the North American and the Pacific plates. This process generates a high seismicity rate, volcanism, seafloor spreading, thinning of the continental crust and geothermal processes (Lomnitz *et al.*, 1970).

The *Centro de Investigación Científica y de Educación Superior de Ensenada* (CICESE), in a joint project with Utrecht University (the Netherlands) and the California Institute of Technology (Trampert *et al*., 2003) deployed 22 broadband digital seismic stations of continuous recording, more than one year prior the occurrence of the studied earthquake, as part of the Network of Autonomously Recording Seismographs, (NARS-Baja) array.

The stations were deployed all along the 1200 km of the *Baja California* peninsula, Sonora, and Sinaloa states around the Gulf of California. The purpose of this network was to study local and regional seismicity and the crust and upper-mantle structure.

In this study, we relocated the 12 November 2003 Mw 5.6 earthquake. We examined the source parameters of the mainshock using the local seismic network. We also estimated source displacement spectra, $\dot{M}o(f)$ and, through the analysis of seismicity we identified the alignment of rupture and estimated the b- value.

Tectonics and seismicity

In the middle of the Gulf of California the *Salsipuedes* basin is bounded by the *Baja California* peninsula to the west and the *Angel de la Guarda* Island to the east. Frequent earthquake swarms are well documented to occur in the northern end of this zone (Rebollar *et al*., 2001). Eventhough there is a transform fault connecting the *Salsipuedes* with *Tiburon* and *Delfin* basins (at the southeast and northwest ends, respectively), serious doubts arise to the plate boundary position due to the complexity of the structures interpreted, and by the bathymetric information showing faults at both sides of the island. In addition, Vaquier and Whiteman (1973) in an experiment conducted between 1970-1971 determined 4 mm/year of relative displacement between *Angel de la Guarda* Island and the peninsula of *Baja California*. Kasser *et al*. (1987) using laser geodimeter measurements between stations located on elevated points of *Baja California* and Sonora, estimated a right lateral shear motion direction (N46ºW and 8 mm/year) in the *Salsipuedes* basin. Lonsdale (1989) indicated the existence of grabens and horsts structures at the Gulf of California, nearby to *Angel de la Guarda* Island with azimuth of 312°, which is the same direction of the transform fault. From 1973 until 2003, the reported seismicity includes few earthquakes of magnitude greater than 5; all of them with right-lateral strike slip fault mechanism (Goff *et al*., (1987), GCMT catalog, www.globalcmt.org). In Table 1 relevant information of the earthquakes mentioned above is provided. Among them in 1975, an Ms=6.5 earthquake is of particular interest because it was associated with the structure of *Salsipuedes* basin, as well as its aftershocks (Munguía *et al*., 1977).

Data recording and earthquake location

On 12 November 2003, an earthquake occurred in the *Salsipuedes* basin and was recorded by

Table 1. Earthquakes with magnitude greater than 5 that have occurred in the neighbourhood of *Salsipuedes basin* and *Canal de Ballenas*.

Zone	Date	Latitude °	Longitude °	Seismic Moment Nm	Magnitude Mw
Canal de Ballenas north	1973/10/13[1]	29.58	-113.64		5.2
	1975/07/08[3]	29.49	-113.40	$1.6X10^{18}$	6.5
	1980/08/30[2]	29.7	-113.73	$2.23X10^{17}$	5.5
	1991/02/14[2]	30.12	-113.70	$1.64X10^{17}$	5.4
Canal de Ballenas south	1977/11/14[1]	29.27	-112.97		5.6
Salsipuedes basin	1977/11/21[2]	29.07	-113.10	$1.23X10^{18}$	6.0
	1980/09/21[2]	29.34	-113.73	$2.49X10^{17}$	5.5
	1982/02/07[2]	29.03	-113.03	$2.86X10^{17}$	5.6
	1993/03/05[2]	29.25	-113.43	$4.15X10^{17}$	5.7
	1997/11/26[2]	29.38	-113.80	$1.4X10^{17}$	5.4
	2003/11/12 4	29.0	-113.24	$(3.5±3.3)X10^{17}$	5.6±0.2

[1] NEIC. [2] Global CMT catalog. [3] Goff *et al*. (1987). 4 This study.

the NARS-Baja network as well as its associated foreshock, and 456 aftershocks occurred during the following two days.

The NARS-Baja seismic stations, NE74, NE75, NE80, NE81, and NE82, consisted of a Streckeisen STS-2 broadband sensor with a generator constant of 1500 V*s/m and a bandwidth response between corners 0.0083 Hz (120 sec) and 50 Hz, a Global Positioning System (GPS), and a laptop for data acquisition and timing (Trampert *et al*., 2003). The RESBAN station network consists of a Guralp CMG-40T or CMG-3ESP broadband sensor. All seismic stations recorded continuously with a rate of 20 samples per second (See Figure 1).

Using the closest stations of the NARS-Baja network (NE74, NE75, NE80, NE81, NE82), and the ones of RESBAN network (BAHB, IAGU, PLIB) to the epicenter, we relocate the mainshock using the HYPOCENTER code (Lienert *et al*., 1988; Lienert and Havskov, 1995) and a velocity model that includes a thin continental crust with a Moho depth in the range from 20 to 24 km. This model was used by Rebollar *et al*. (2001) and it is displayed in Table 3. The records with the best signal-to-noise ratio correspond to the stations shown in Figure 2. The mainshock was located at 29.16ºN and 113.37°W. This event had a Mw 4.4 foreshock, with epicentral location at 29.17ºN and 113.356ºW. Table 2 and Figure 3 show the location of the mainshock, the foreshock and 27 aftershocks at the rupture area and post-event seismic activity. You can see the rupture area marked by a white star and a set of aftershocks that identify it, also showed the post-event seismicity, and associated with an existing structure in the oceanic floor. Note the perfect partnership between the structures and seismicity.

We constructed a vertical section perpendicular to the strike of the fault and plot the position of the mainshock, foreshock and aftershocks with respect to depth; this vertical section is shown in Figure 4. We note that the seismogenic zone reaches a depth of 12 km, suggesting a brittle crust of similar thickness.

b-value

The statistical Gutenberg-Richter (1942) *b*-value was estimated for the aftershock sequence in order to identify a seismotectonic pattern of the *Salsipuedes* basin. The duration magnitude (M_d) of 476 aftershocks recorded at seismic station BAHB, was calculated using the equation (1):

$$M_d = 2.24 logT\text{-}0.85, \qquad (1)$$

where T is the duration of the signal. This relationship has been used by Rebollar and Reichle (1987), López-Pineda and Rebollar (2005).

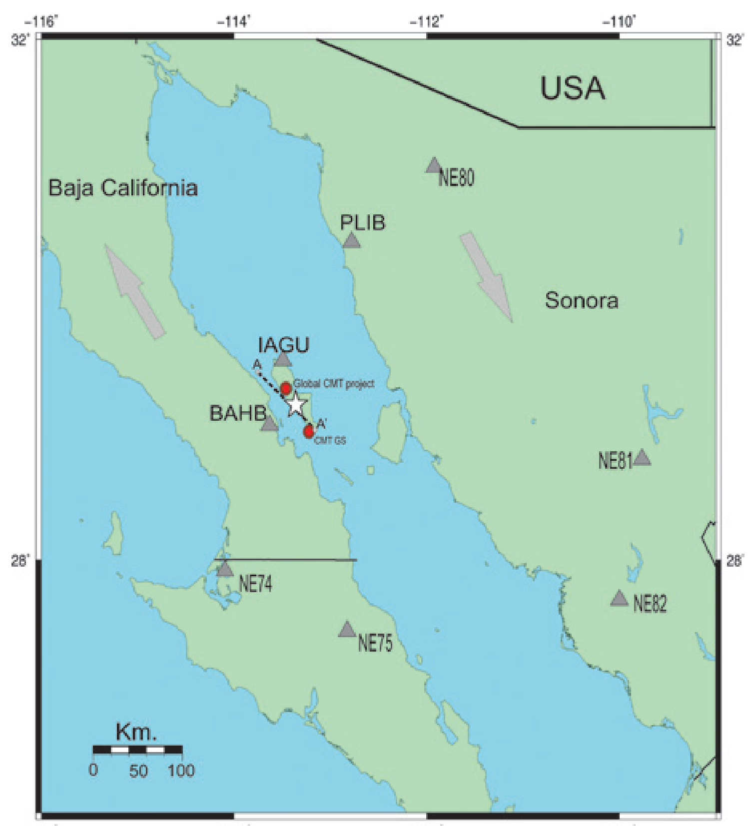


Figure 1. Location of broadband seismic stations (filled triangles) and the 12 November 2003 Mw 5.6 earthquake (white star). The location of the centroid proposed by Global CMT Project and CMT GS are indicated by red circles. Dashed line indicate section AA' to which the seismicity was projected. The relative motion of tectonic plates is indicated with large arrows.

Table 2. Location: ‘Foreshock, ² mainshock, and aftershocks using HYPOCENTER code.

Date	Hour	Latitude°	Longitude°	Depth (km)	Error Lon °	Error Lat °	Error Depth (km)
20031112’	04:47	29.171	-113.357	8.2	0.7	0.5	4.3
20031112²	04:54	29.160	-113.370	3.6	0.2	0.1	1.2
20031112	05:16	29.167	-113.363	8.2	0.3	0.2	0.1
20031112	06:03	29.174	-113.356	6.8	0.0	0.0	0.0
20031112	06:45	29.120	-113.405	5.5	0.0	0.0	0.0
20031112	06:51	29.160	-113.370	8.1	0.2	0.1	0.0
20031112	07:40	29.227	-113.467	12.5	0.2	0.1	0.1
20031112	07:43	29.162	-113.483	11.6	0.3	0.1	0.1
20031112	07:50	29.124	-113.403	4.5	0.0	0.0	0.0
20031112	07:57	29.123	-113.403	4.0	0.0	0.0	0.0
20031112	08:08	29.113	-113.413	5.8	0.0	0.0	0.0
20031112	08:16	29.132	-113.395	8.2	0.6	0.4	0.0
20031112	08:24	29.137	-113.039	8.0	0.6	0.4	0.0
20031112	08:31	29.160	-113.370	4.1	0.0	0.0	0.0
20031112	08:41	29.125	-113.397	1.9	0.0	0.0	0.0
20031112	08:59	29.114	-113.408	8.1	0.1	0.1	0.0
20031112	09:56	29.083	-113.402	0.0	0.1	0.1	0.0
20031112	10:01	29.108	-113.417	6.0	0.1	0.1	0.0
20031112	11:32	29.118	-113.408	4.6	0.0	0.0	0.0
20031112	11:51	29.159	-113.375	8.2	0.1	0.1	0.0
20031112	12:51	29.092	-113.408	0.0	0.1	0.1	0.1
20031112	13:01	29.105	-113.410	0.0	0.1	0.1	0.0
20031112	14:04	29.113	-113.413	0.0	0.1	0.1	0.0
20031112	15:07	29.151	-113.367	1.4	0.0	0.0	0.0
20031112	16:26	29.162	-113.368	8.3	0.0	0.0	0.0
20031112	16:49	29.164	-113.365	3.0	0.0	0.0	0.0
20031112	18:48	29.162	-113.367	8.1	0.1	0.1	0.1
20031112	19:04	29.161	-113.368	3.8	0.0	0.0	0.0
20031112	19:16	29.095	-113.427	0.0	0.0	0.0	0.0

Table 3. Crustal velocity model used to locate the 12 November 2003 earthquake Mw 5.6 and its associated foreshocks and aftershock (Rebollar *et al*., 2001).

Layer Thickness (km)	P-wave velocity (km/sec)	S-wave velocity (km/sec)	Density (g/cm³)	Q_α	Q_β
4.0	4.0	2.6	2.3	400	200
4.0	5.7	3.3	2.5	2000	2000
16.0	6.7	3.8	3.0	2000	2000
0.0	7.8	4.0	3.4	2000	2000

Duration magnitudes of the located earthquakes range from 2.3 to 3.5. The *b*-value from the Gutenberg-Richter relationship was calculated and the estimated *b*-value was 1.14 ± 0.28 using a least-squares approach (Figure 5).

This *b*-value contrasts with that obtained for Loreto earthquake of 12 March 2003 using 333 aftershocks. López-Pineda and Rebollar (2005) obtained a *b*-value of 0.68. This difference suggests larger heterogeneous concentration of stresses at *Salsipuedes* basin than *Carmen* basin (Scholz, 1968).

Regarding the moment tensor solution, there are two proposed mechanisms for the earthquake fault of 12 November 2003 Mw 5.55 ± 0.05; these solutions are shown in Table 4. As it is noted in Figure 3, the seismicity location agrees with a trend perpendicular to the main transform NW-SE fault. A strike of 39º is therefore more consistent with the tectonics of the area.

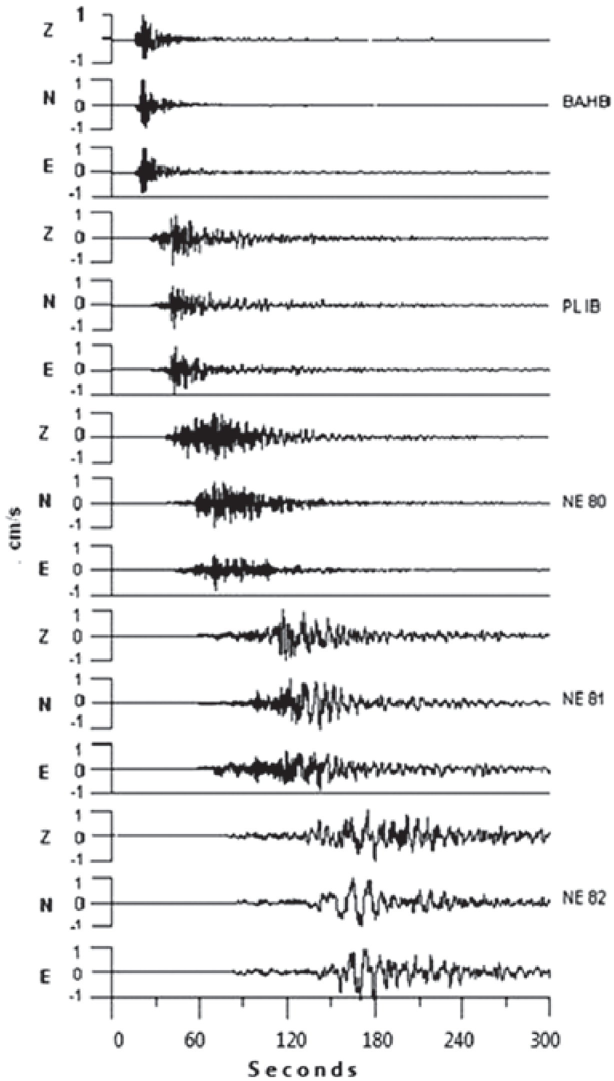


Figure 2. Normalized velocity seismograms recorded by the BAHB, PLIB, NE80, NE81, and NE82 seismic stations in their Z, N, and E components.

Source spectrum and stress drop

We estimated the average displacement spectra, $\dot{M}o\,(f)$, of the mainshock from the analysis of the *S*-wave group recorded at horizontal components of 5 stations within a hypocentral distance of 475 km. Following Singh *et al*. (1999), the Fourier acceleration spectral amplitude of the intense part of the ground motion at a station, under far-field, point-source approximation, may be written as

$$A(f,R) = Cf^2\,\dot{M}o(f)G(R)e^{-\pi fR/\beta Q(f)}, \quad (2)$$

where

$$C = FPR_{\theta\varphi}(2\pi)^2/(4\pi\rho\beta^3), \quad (3)$$

In the equations above, $\dot{M}o\,(f)$ is the moment rate spectrum so that $\dot{M}o\,(f) \rightarrow M_0$ as $f \rightarrow 0$, R = hypocentral distance, $R_{\theta\varphi}$ = average radiation pattern (0.55), F = free surface amplification (2.0), P takes into account the partitioning of energy in the two horizontal components $\left(\frac{1}{\sqrt{2}}\right)$, β = shear-wave velocity at the source (3.00 km/s), ρ = density in the focal region (2.65 kg/m3), and $Q(f)$ = quality factor, which includes both anelastic absorption and scattering. The appropriate geometrical spreading term, $G(R)$, is R^{-1} for $R \leq R_0$ and $(RR_0)^{-1/2}$ for $R > R_0$. The form of $G(R)$ implies dominance of body waves for $R \leq R_0$ and of surface waves for $R > R_0$. For this earthquake, we took $Q(f) = 213f^{\,0.72}$ (Rebollar *et al*., 1995) and R_0 = 100 km. Taking logarithms of equation 2 we obtain

$$\log\left[A(f,R)\right] = \log C + \log\left[G(R)\right] + \log\left[f^2\,\dot{M}o(f)\right] - \frac{1.36 fR}{\beta Q(f)}\,. \quad (4)$$

We solved equation (4) in the least-squares sense to obtain log [$f^2\,\dot{M}o\,(f)$] and so $\dot{M}o\,(f)$.

The source displacement spectra of the mainshock for the 5 stations are shown in Figure 6. We interpret these spectra within the framework of a ω^2-source model and obtain an estimation of the seismic moment (M_0) and corner frequency (f_c). The stress drop ($\Delta\sigma$) is computed using the Brune (1970) model. The source spectra can be fit by M_0, f_c and $\Delta\sigma$ values indicated in these figures.

The Brune model consists in a circular fault plane with finite radius on which a shear stress pulse is applied instantaneously on the whole fault

Table 4. Earthquake location and fault geometry calculated by CMT GS, http://earthquake.usgs.gov/earthquakes/eqarchives/sopar/ and Global CMT Project, www.globalcmt.org.

Source	Lat.	Long.	Depth	Mw	Plane 1			Plane 2		
					Strike	Dip	Rake	Strike	Dip	Rake
NEIC	29.11	−113.35	7	5.6	168	67	−116	39	34	-44
GCMT	29.34	-113.45	15	5.5	168	55	-109	19	39	-65

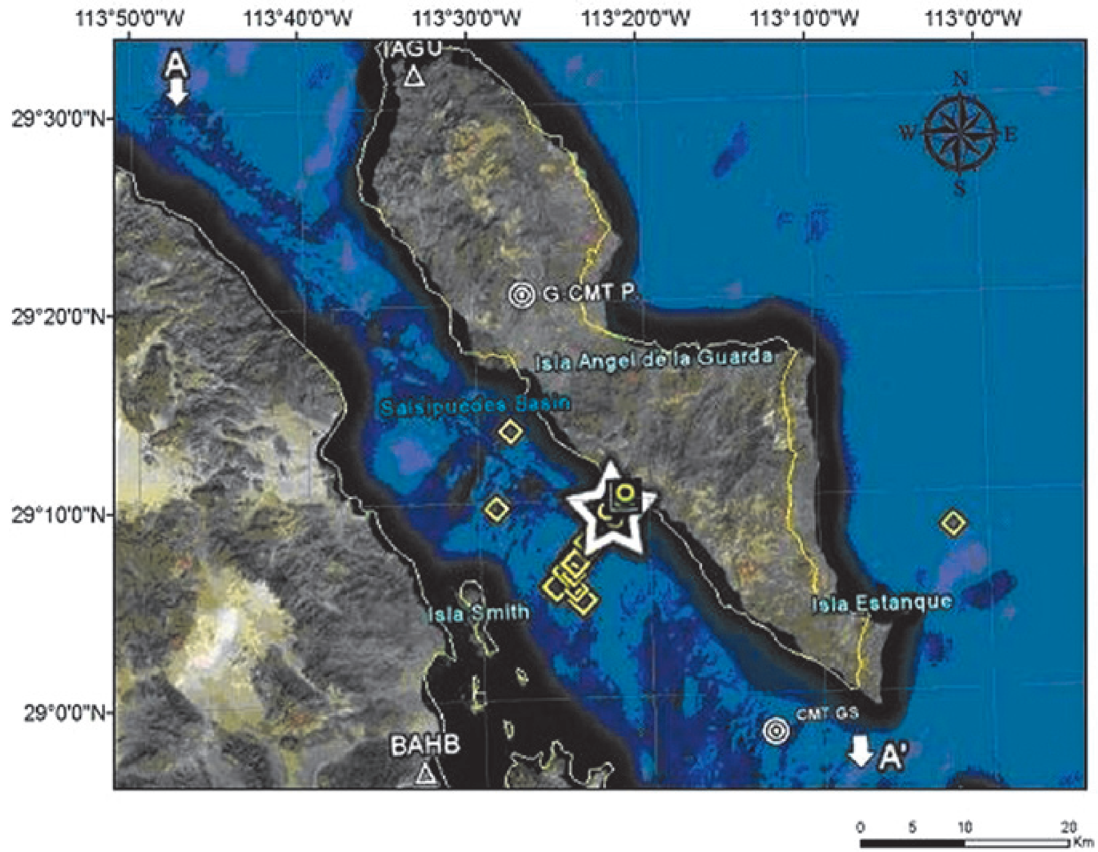


Figure 3. Seismicity of the study area, the star shows the location of the 12 November 2003 Mw 5.6 earthquake at *Salsipuedes* basin, the square shows the foreshock. The size of the star indicates the extent of aftershock area (open circles). The diamonds indicate the post-event activity which covers a pre-existing alignment (Observed structures on the ocean floor). White open triangles indicate stations and concentric white circles denote the location of the centroid according to GCMT and CMT GS.

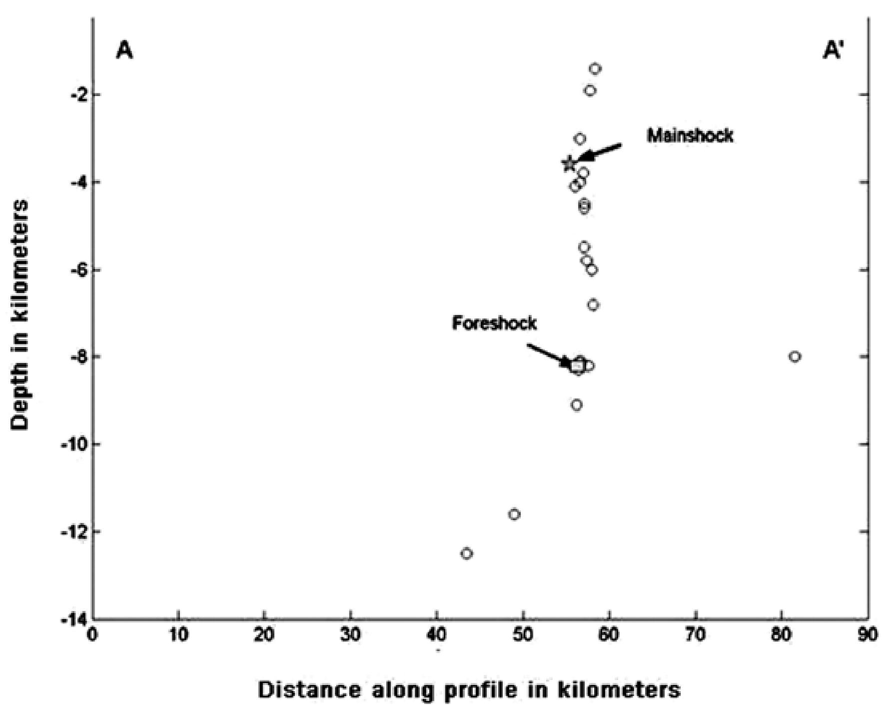


Figure 4. Vertical section of the recorded seismicity projected along the line AA' shown in Figure 1. The foreshock and mainshock are indicated by a square and a star respectively.

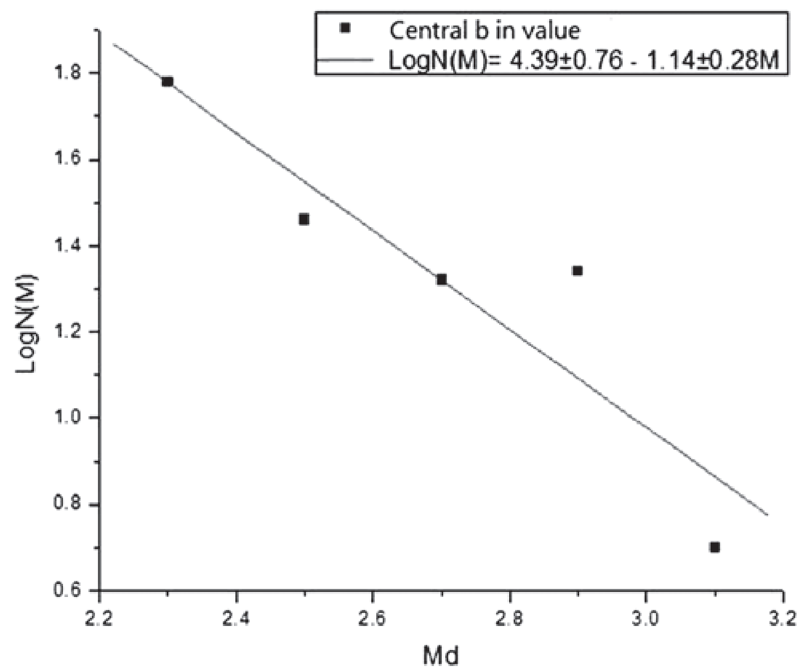


Figure 5. Frequency-magnitude plot of 476 aftershocks of the 12 November 2003 earthquake in Salsipuedes basin. A *b*-value of 1.14 ± 0.28 was calculated for duration magnitudes in the range at 2.3 ≤ *M* ≤ 3.1 using a least-squares fit.

area and there is no fracture propagation. This model is commonly used to obtain fault dimensions from spectra of S waves for earthquakes of small-to-moderate size (M < 6), for which the circular fault is a good approximation. Under this hypothesis, the source radius is given by:

$$r = 0.3724\beta/f_c. \quad (5)$$

The moment magnitude was calculated by Equation (6), proposed by Hanks and Kanamori (1979)

$$Mw = \frac{2}{3}\log M_0 - 10.7 \,. \quad (6)$$

Taking the average value for these parameters, we obtain finally M_0 =(3.5 ± 3.3)*X*10[17]Nm, fc = 0.36 ± 0.15 Hz, r = 3.7 ± 2.6 km and $\Delta\sigma$= 3.9 ± 1.15 MPa (39± 11.5 bar.).

Discussion and Conclusions

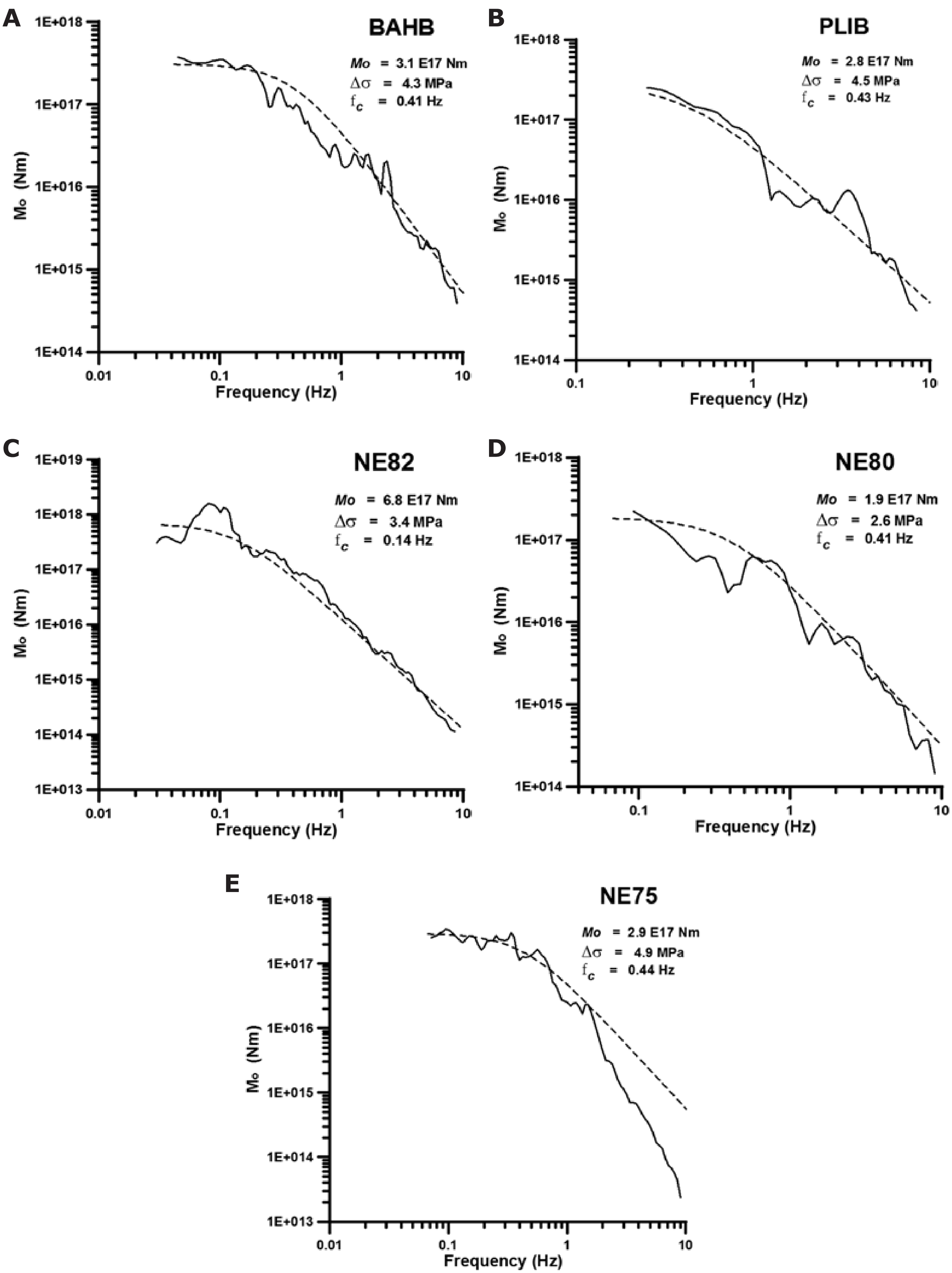
According to results of seismic reflection studies conducted in the upper part of the Gulf of California by Lonsdale (1989) and González-Fernández *et al*. (2005), the *Salsipuedes* basin is in its early stage of development. In this region the basins are aligned in an en echelon trend linking the pull-apart basin by NW-SE transform faults*. Canal de Ballenas* transform fault connects the *Salsipuedes* basin at SE with the *Delfin* basin at the NW. In this zone, six earthquakes with magnitude larger than 5 have occurred during the last thirty years. The focal mechanisms of the great majority of these earthquakes were strike-slip. The earthquake studied here is the first one with a dip-slip mechanism in this part of the Gulf of California, which was located off the west coast of *Angel de la Guarda* Island. Other earthquakes with normal faulting mechanisms have been reported by Rebollar *et al*. (1995) at *Bahia de las Animas* (30 km south of the epicenter of study) and Reichle and Reid (1977) following a seismic swarm pattern at *Delfin* basin, (60 km northwest of the epicenter of study). Castro *et al*. (2011) associates this type of faulting in the Gulf of California to spreading centers.

The distribution of earthquakes with magnitude larger than 5 during the last thirty years suggests a seismic activity migration from north to south.

Table 5. Calculated source parameters. r is the source radii, M_0 is the seismic moment calculated from the displacement spectra, Δσ is the static stress drop calculated with the displacement spectra.

Δ	r (km)	fc Hz	M_0 (Nm)	Δσ MPa
BAHB	2.72	0.41	$3.1X10^{17}$	4.3
PLI	2.60	0.43	$2.8X10^{17}$	4.5
NE80	2.72	0.41	$1.9X10^{17}$	2.6
NE75	2.54	0.44	$2.9X10^{17}$	4.9
NE82	7.98	0.14	$6.8X10^{17}$	3.4

Figure 6. S-wave average source displacement spectra of horizontal components at A) BAHB, B)PLIB, C)NE82, D) NE80, E)NE75 seismic stations. Continuous line is the observed spectrum and dashed line is the theoretical, assuming a w^2 source model.



Considering that the elastic energy stored in rocks in the form of deformation stress is released when the rocks reach their rupture, part of the energy propagates as vibrational energy producing seismic waves and another part of the energy remains in the rock as residual energy, this energy is transmitted to other parts of the same stress axis increasing the stress level of the adjacent regions (Husseini *et al*., 1975). So the seismic energy released by fracturing and sliding at the northern edge of the *Canal de Ballenas* transform fault, triggered off significant seismicity at the southern edge of the transform. Examples of these sequences are: (i) the 1973-1975-1977 earthquakes, (ii) the 1980-1982 earthquakes, and (iii) the 1997-2003 earthquakes. All of these shocks were presumably seismically associated (see their latitudes shown in Table 1).

The earthquake studied here represents an example of active extensional faults at north of Gulf of California. Eventhough Sumy *et al*. (2013) propose that much of the extension across the plate boundary is accommodated aseismically, this activity shows that, at least in this zone, normal faulting plays an important role.

A Mw 4.4 foreshock occurred seven minutes before the 12 November 2003 Mw 5.6 earthquake. Both events were located on a dip slip fault perpendicular to the main *Canal de Ballenas* transform fault according their locations indicated on Figure 3.

The b value represent properties of the seismic medium in some respect, like stress or material conditions in the focal region Scholz (1968) and we expect an inverse correlation between the b value and the level of stresses accumulated in the seismic region. Others like Mogi (1962) have associated high b-values with the material heterogeneity. Through a comparative analysis of *b*-values estimations at north of Gulf of California between 1.5 (Reichle and Reid, 1977; Rebollar and Reichle, 1987), 0.68 for *Loreto's* earthquake of 12 March 2003 at *Carmen* basin (López-Pineda and Rebollar, 2005) and the b value of 1.14±0.28 for this *Salsipuedes* basin earthquake at the middle of Gulf of California, we can infer that there is a transition of stress distribution from north, where the stresses are more heterogeneous, to south where concentration of stresses are more homogeneous, as well as in the central region of the Gulf of California.

From spectral analysis and assuming a Brune model of circular fault, we obtain the following source parameters:

$M_0 = (3.5 \pm 3.3) X 10^{17}$ Nm

Corner frequency fc = 0.36 ± 0.15 Hz

$r = 3.7 \pm 2.6$ km

$\Delta\sigma = 3.9 \pm 1.15$ MPa (39 ± 11.5 bar.)

In agreement with the magnitude of 5.6 previously reported by NEIC; the calculated static stress drop is typical of this tectonic region ranging between 2 and 49 bars (López-Pineda and Rebollar, 2005) and the rupture radius is consistent with the magnitude of a moderate earthquake.

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