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SHALLOW SEISMICITY AND FLUID EXPLOITATION IN THE NORTHERN BURGOS BASIN (NUEVO LEÓN, MÉXICO)

Juan M. Rodríguez-Martínez[1*], Eduardo A. Rossello[2] , Arquímedes Cruz López[3] , Lilia E.Arriaga-Díaz de León[4], Javier Eugenio Bermúdez-Cerda[5]
*[*1,4,5]Universidad Autónoma de Nuevo León. Depto. De Geohidrología y Geofísica, Facultad de Ingeniería Civil. Monterrey, México.*
[2]CONICET-Universidad de Buenos Aires, FCEN, Depto.Ciencias Geológicas. Buenos Aires, Argentina.
[3]Universidad Autónoma de Nuevo León. Facultad de Ingeniería Civil.

***Corresponding Author:-**
Email:lampazos54e94@yahoo.com

Abstract:-
This paper examines the relationships between recent shallow seismicity and exploitation of fluids in the northern Burgos Basin where cumulative seismic events recorded in the State of Nuevo Leon reach a total of 304 earthquakes between 2006 and 2016. In detail, 2 to 5 yearly events occurred from 2006 to 2011; but a later remarkable increase was evident as follows: 89 in 2012, 69 in 2013, 75 in 2014, 31 in 2015 and 27 in 2016. This behavior doesn't match the random fluctuations from natural seismicity rates. A statistical analysis allowed us to determine that the sequence of earthquakes after 2011 could be related to the activity of exploratory wells in the Burgos Basin, which were drilled down to the Pimienta (Upper Jurassic) and Agua Nueva (Upper Cretaceous) shale gas plays. The epicenters located in the State of Nuevo Leon, in the municipalities of China, General Terán, Montemorelos and Los Ramones, were associated with the Upper Jurassic Pimienta and Upper Cretaceous Agua Nueva shale gas fields. Only 17 earthquakes had magnitudes ranging from 4.0 - 4.5 Richter magnitude and those were associated with the exploratory wells Anhelido-1, Arbolero 1, Batial-1, Durian-1, Kernel-1, Mosquete-1, Neritas-1, Nuncio-1, Serbal-1 and Tangram-1. The hypocenters correspond to the depth at which the Pimienta and Agua Nueva Formations lie; hence, sharp changes in the minor shock frequencies were considered as indicators of induced seismicity related to hydraulic fracturing for fluid extraction. The scatterplot of the frequency and magnitude of events for 2009-2014 shows slopes between -7.0963 to -1.1538 that were considerably more negative than the natural seismicity values which span from 0.75 to 0.9. The slopes for 2012, 2013 and 2014 are negatives (-7.0963, -0.3656 and -0.1333), respectively. These dramatic changes in increasing of the minor shock sequences in the Burgos Basin allow us to be considered as indicators of induced seismicity due to fluid exploitation. This interpretation is based on the frequency and magnitude of shocks which achieve values of hydraulic fracturing-induced earthquakes associated with anthropogenic fracking, similar to other seismicity data obtained in different parts of the world where this Technique is applied.

Keywords: - *induced seismicity, hydraulic fracturing, epicentre, anthropogenic activity, Burgos basin, Mexico.*

1. INTRODUCTION

In regions where underground reservoir fluid extraction occurs, either of hydrocarbons or groundwater especially from shallow to medium deeps in extensional sedimentary basins, there may have been some increases in the seismicity records. This activity becomes important can affect the safety and functionality of the settlements and buildings located in the area. This is why the human-induced seismicity issue has been progressively studied with the goals of forecasting and, in the best cases, mitigating their effects through the development of new techniques (Nicholson and Wesson[59] 1990, Marone[51] 1998, Scholz[77][78] 1998, 2003, Ikari[44] et al. 2013, McGarr[54][55] et al. 2002, 2015; Committee on Induced Seismicity Potential in Energy Technologies[10] 2012, Brodsky and Lajoie[5] 2013, Ellsworth[21] et al. 2015, among many others).

This work was designed to demonstrate the correspondence of some damage to buildings in settlements in the northern portion of the Burgos Basin, northeast Mexico, with seismic events recently recorded that spatially overlap with underground fluid extraction activities. In this regard, unequivocal relationships were established between the distinctive characteristics of seismicity prior to the onset of fracking activities and the current frequencies, magnitudes and locations (epicenters and hypocenters) of earthquakes.

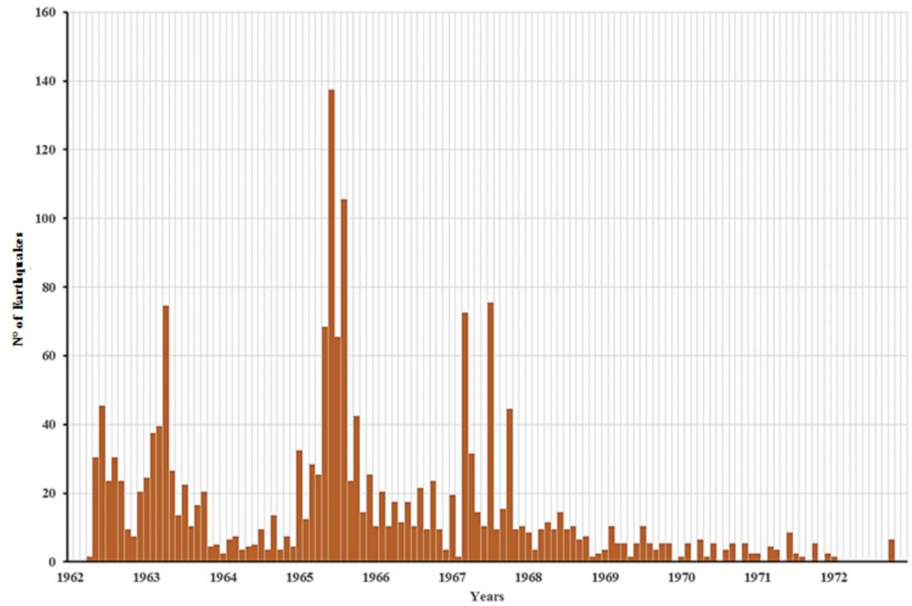
On the other hand, it is necessary to take actions intended to mitigate the effects on the local populations and infrastructure from increased exploration and exploitation of the unconventional hydrocarbon deposits and groundwater resources of the Burgos Basin; this would enable us to control in a rational- and sustainable way the impacts that would be generated by the use of their associated technologies.

2. Induced seismicity background

The term "induced seismicity" refers to the seismicity produced by anthropogenic activities in addition to the natural seismicity, both of them being the triggers for it (Avouac[4] 2012; Committee on Induced Seismicity Potential in Energy Technologies[10] 2012). The difficulty in establishing that trigger in its initial stage, represents also a difficulty in understanding the behavior of the stress field and its relationship with preexisting deformations.

Hydrocarbon and formation water extraction as well as groundwater overexploitation, causes terrain subsidence and differential reorganizations of the rocky massif as a result of the alteration of the geomechanical properties of the rocks, modifying the stresses and the fluid pressures (Schlumberger [74] 1984; Adushkin[1] et al. 2000; Murray and Hitzman[58] 2013; Rodríguez-Martínez[70] 2016).

The first fracturing or cracking (fracking) made with the aim to increase hydrocarbon production from low reservoir quality lithologies, was performed in Kansas, USA in a marginal well in the late 1940s (Rex [66] et al. 2014). Starting in the 1950s, this treatment had a major impact on reservoirs containing oil and gas hosted in source rocks (organic pelites or schists), mobilizing the remaining hydrocarbons trapped in their micropores. Since the late 1960s, it has been well known that the injection of fluids underground at high pressures may initiate small earthquakes (Shapiro and Dinske [81] 2009). In 1961, The United States Army introduced some waste into a well under its arsenal in the Rocky Mountains, which triggered earthquakes felt in Denver, several kilometers away (Ellsworth [20] 2013). By 1970, the pressure in depleted oil wells in Colorado was reestablished (**Fig. 1**), which clearly proved that the seismic activity increased with small earthquakes when water was injected, but that the pressure was reduced and the seismographs quieted upon its removal (Healy[37] et al. 1968; Herrmann and Park[39] 1981; Wei and Froehlich[87] 2013; Holland[41] 2013; Rubinstein and Ellsworth[72] 2013; Petersen[62] et al. 2015, Hornbach[40] et al. 2015).



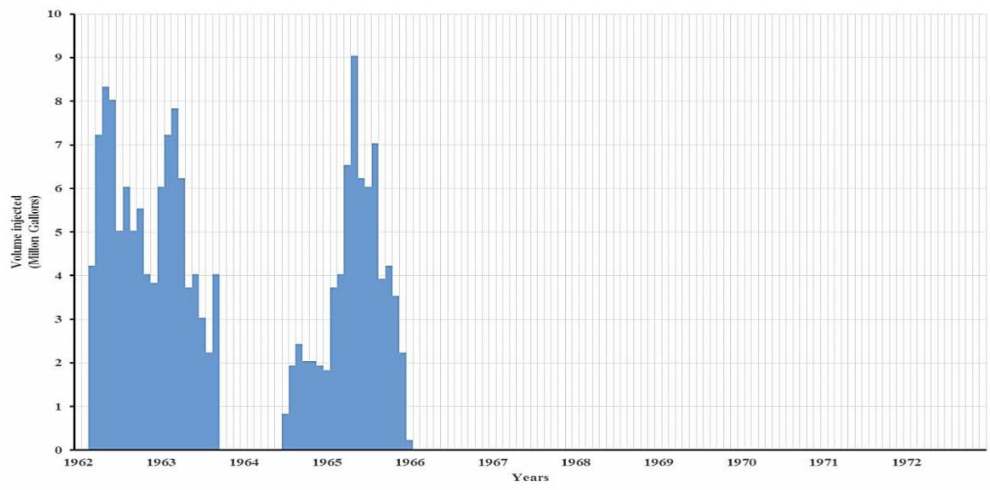


Figure 1. Earthquake yearly events (top) and the peak of fluid injections in deep wells (below) in Denver, Colorado (From Healy [37] et al. 1968 and modified by Rodríguez-Martínez [70] et al. 2016).

Studies conducted by Adushkin[1] et al. (2000), Froehlich and Davis[27] (2002), Mazzotti[52] (2007), Andrea and Andrews[3] (2013), Keranen[46][47][48] et al. (2013a, 2013b, 2014), Wei and Froehlich[87] (2013), among others, are the key scientific references for associations between earthquakes and petroleum exploitation, as in the cases of the oil fields in Texas (Cogdell) or Colorado (Davis and Pennington[12] 1989). Moreover, in some other places in the United States, there is some evidence of increased tectonic activity in areas with a high density of wells for shale gas extraction (Folger and Tiemann[25] 2016), including the productive regions: i) Barnett Shale, with approximately 15,000 active wells in the middle of 2011 (Frohlich[26] 2012), ii) TexasHaynesville Shale, with 390 wells, and iii) Eagle Ford Shale, with 1,040 wells (Eagle Ford Consortium[22] 2014). In addition, Shelly [76] et al. (2015) describe equivalent situations in the state of California.
The injection of fluids or wastewater into different types of hydrocarbon reservoirs (Kim[50] 2013; Ake and Mahrer[2] 2005; Horton[42] 2012; Kerenan[46][47] et al. 2013a, 2013b; van der Elst[85] et al. 2013; Kim[50] 2013) as well as the exploitation of geothermal fields, have also triggered induced seismicity (Deichmann and Giardini[14] 2009; Evans[23] et al. 2012; Gupta[34] 2002; González[32] et al. 2012).

3. Geological setting of the burgos basin.

The Burgos Basin is located in the northeastern portion of Mexico, approximately between 25°00´ - 28° 00´ N and 98°30´ y 100° 00´ W (**Fig. 2**). During more than 60 years of hydrocarbon exploitation in this basin, it has produced more than 8 x 10^{12} cubic feet of dry gas and subordinate condensate, from more than 220 terrestrial fields in Cenozoic and Cretaceous rocks (Eguiluz de Antuñano[18][19] 2011).

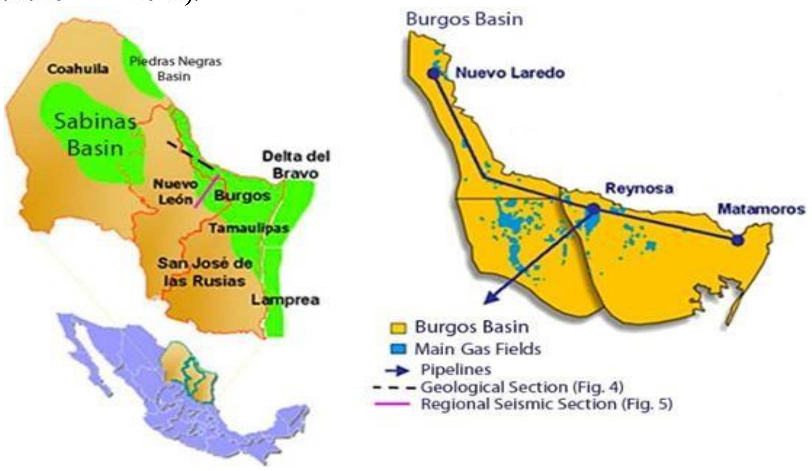


Figure 2. Burgos Basin in the northeastern corner of Mexico (From Echánove[16] 1976).

This depocenter forms part of the Coastal Plain of the Gulf of Mexico and is constituted by a sequence of sediments with thicknesses of approximately 5,000 m of a cenozoic siliciclastic succession and 3,000 m of carbonates, evaporites and mesozoic siliciclastics (**Fig. 3**), overlaying a basement of metamorphic and igneous rocks with extensional faults with vergences toward the east associated with the opening of the Gulf of Mexico (Eguiluz de Antuñano[18][19] 2011).

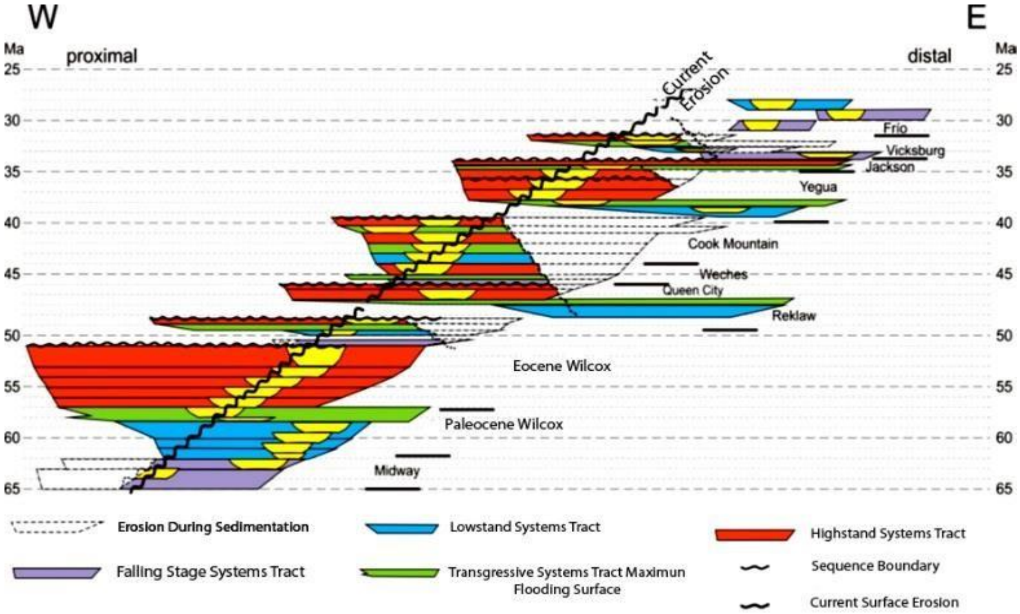


Figure 3. Diagram that represents the stratigraphic sequences in the Burgos Basin where from the west to the east the deposits vary from proximal to distal, respectively. The colors show the type of tract of the deposit systems. The horizontal cut lines indicate time lines, in millions of years (Ma) of the formations and the main tracts (From Eguiluz de Antuñano [18][19] 2011 and modified from Coe and Church[8] 2002).

The main sandy bodies conform to strips oriented north to south and bending toward the east; and represent deltaic front bar systems associated with growth extensional faults, mostly listric-normal type (Davison[13] 1986), which gave rise to tilting blocks with horsts and grabens (Echánove[16] 1976).

The sedimentary record of the basin exhibits several tectonic events of cortical subsidence with accumulation of pretectonic and syntectonic marine infill sequences, mainly spanning from the Late Jurassic to the Eocene (Echánove[17] 1986). The Laramide deformation is represented by gravitational slides with soft folds, growth faults and areas of deep erosion bounded between 48.5 and 39.5 Ma (Chávez-Cabello [11] et al. 2004; Eguiluz de Antuñano [18][19] 2011).

A vertical uplift of the crust occurred during the Oligocene and was associated with extensional faulting, land sliding and decoupling of the sedimentary cover upon the Jurassic evaporites, resulting in major unconformities (Chávez-Cabello [11] et al. 2004). Finally, during from the Late Oligocene to recent time, thick sequences of siliciclastites prograded toward the Gulf of Mexico, favored by growth faults and the diapirism of Jurassic muds and salt levels (**Fig. 4**).

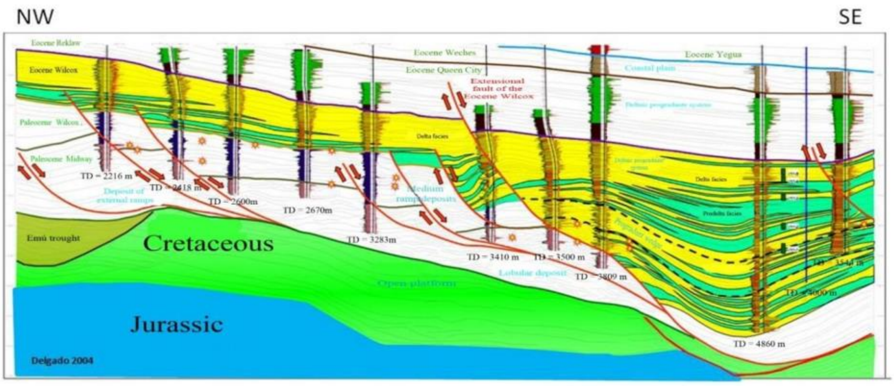


Figure 4. Regional geological section through the Burgos Basin in northeastern Mexico and indicative producing wells from Late Oligocene sequences on the southernmost portion (From Pemex[60] 2012). Location of this profile can be found in Figure 2.

The exploitation of hydrocarbons in the Burgos basin on both sides of the MexicoUnited States border has been associated with bird's foot type prograding deltas and loading of stratigraphic and structural traps related with growth failures (RodríguezMartínez [68] 1985). The sedimentary model for the Tertiary sequences corresponds to delta deposits prograding towards the Gulf of Mexico, deposits that consist of bar systems, channels or delta front sands, Sequences are associated with the presence of gravitational gliding favored by sinsedimentary growth faults (**Fig. 5**). As mentioned above, the sandstone bodies define stratigraphic and structural traps, forming a series of compounded horst and graben type blocks (Sadovsky and Pissarenko[73] 1991; Hernández-Mendoza[38] et al. 2008).

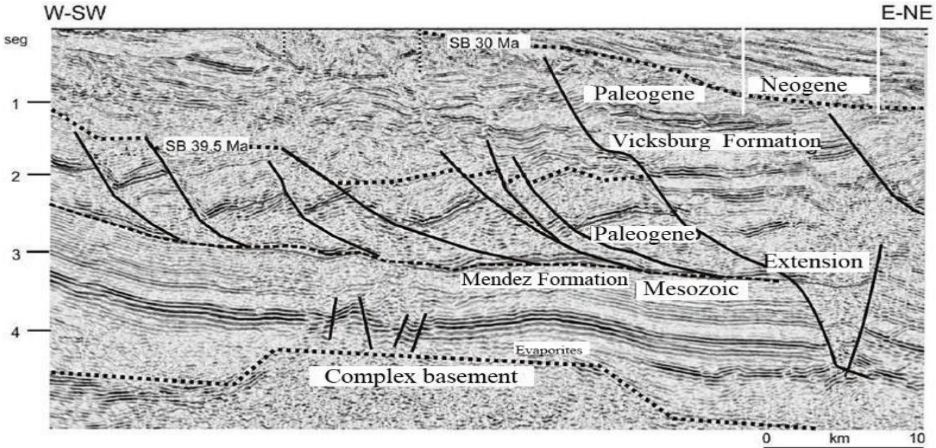


Figure 5. Regional seismic section showing a basement that is stepped and tilted toward the east with a level of detachment on upper Jurassic evaporites and folds limited by a superior level of detachment on the shales of the Méndez Formation of the Upper Cretaceous that affect the Paleogene. Two prominent **SB** discordances are interpreted; one corresponds to 39.5 Ma and another to 30 Ma (from Eguiluz de Antuñano [18] 2011a). See location in Fig. 2.

Hydrocarbon exploration

In the Burgos Basin, the first hydrocarbon explorations began in the 1920s and resulted in the discoveries of the La Presa, Rancherias, Lajitas and Laredo fields. The second exploration period began in 1942 and gave very satisfactory results with the discovery of the Mission Field in 1945 (Schlumberger [74] 1984).

Since 2010, Pemex has been developing exploration activities in the Burgos Basin, with the aim to assess unconventional hydrocarbon fields in the shales of the Pimienta (equivalent to La Casita Fm.) and Agua Nueva (equivalent to Eagle Ford Fm.) formations (**Fig. 6**) applying hydraulic fracking techniques through overpressured fluid injection (Roux and Flores Torres[71] 2015). In this exploration period, 20 wells have been drilled with depths between 2850 and 5300 m and substantial volumes of water have been injected (**Table 1**).

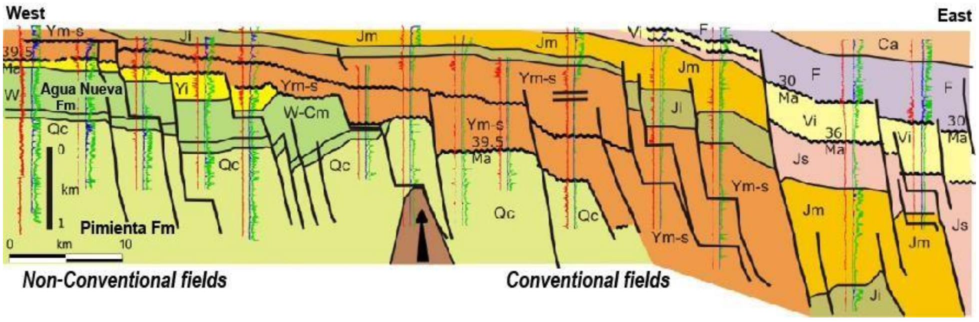


Figure 6. Schematic cross section across the Burgos basin showing the hydrocarbon production wells from older non-conventional sequences towards the West and conventional on the East (modified from Eguiluz de Antuñano [18] 2011a). Queen City Fm. (Qc); Weches and Cook Mountain Fm. (WCm), Lower Yegua Fm. (Yi), Middle-Upper Yegua Fm. (Ym-s), Lower Jackson Fm (Ji), Middle Jackson Fm. (Jm), Upper Jackson Fm. (Js), Vicksburg Fm. (Vi), Frío Fm. (F), Catahoula Fm. (Ca). Extensional faults: Eocene (**E**), Yegua (**Y**), Jackson (**J**), Vicksburg (**V**) and **M** and **N**. The thick black arrow corresponds to injections of clayey domes. Logs curves: IP and GR in red toward left and Resistivity in blue on the right side (0-20 Ω/m) and green (0-4 Ω/m).

Well	Location	Date of drilling	Total Depth (m)	Injected water volume (m^3)
Emergente 1	Hidalgo, Coahuila	13/09/2010	4071	28,589.00
Montañés 1	Guerrero, Coahuila	08/08/2011	3200	9,871.00
Nómada 1	Nava, Coahuila	08/10/2011	3850	9,114.00
Percutor 1	Progreso, Coahuila	30/10/2011	2483	12,884.00
Habano 1	Hidalgo, Coahuila	06/12/2011	3770	19,403.00
Habano 21	Hidalgo, Coahuila	12/10/2012	3850	17,816.00
Habano 2	Hidalgo, Coahuila	28/01/2014	4200	18,870.00
Habano 71	Hidalgo, Coahuila	08/12/2012	4500	19,387.00
Arbolero 1	Anáhuac, N.L.	08/01/2012	4007	14,265.00
Anhélido	Cruillas, Tamaulipas	07/07/2012	4500	12,928.00

Chucla 1	Hidalgo, Coahuila	20/10/2012	4200	15,092.0
Durian 1	Anáhuac, N.L.	14/11/2012	5150	19,527.00
Nuncio 1	Burgos, Tamaulipas	04/12/2012	5200	22,715.00
Gamma 1	Guerrero, Coahuila	14/12/2012	4500	12,996.00
Serbal 1	Cruillas, Tamaulipas	29/08/2013	5300	23,138.00
Tangram1	China, N.L.	10/04/2013	3528	25,808.00
Kernel 1	Melchor Ocampo, N.L.	10/04/2013	3906	16,190.00
Mosquete 1	Cruillas, Tamaulipas	18/08/2013	4500	19,064.00
Neritas 1	Los Ramones, N.L.	26/10/2013	3800	13,039.00
Batial 1	Los Herreras, N.L.	30/01/2014	4200	12,515.00

Table 1. Completed exploratory wells in reservoirs in the Burgos Basin (source Pemex [60] 2015 2012).

The target exploration reservoir levels in the northwestern part of the studied area of the Burgos basin are: **i**) the Pimienta Formation (Upper Jurassic-Tithonian, Cantú-Chapa 1971) constituted by carbonaceous limestones that gradually change to a sequence of limestones with lamination and black chert lenses with abundant organic matter and thin layers of bentonite on top, and **ii**) Agua Nueva Formation (Late Cretaceous-Turonian, Carrillo 1971) conformed by clay-carbonaceous limestones and calcareous shales where they are more accessible by their lower depths towards the northwestern portions of the basin. The Pimienta Fm. has up to 100 m thick with TOC contents ranging between 0.21 % to 5.55 % (average 3.2 %) with kerogene type III (**Fig.7**)

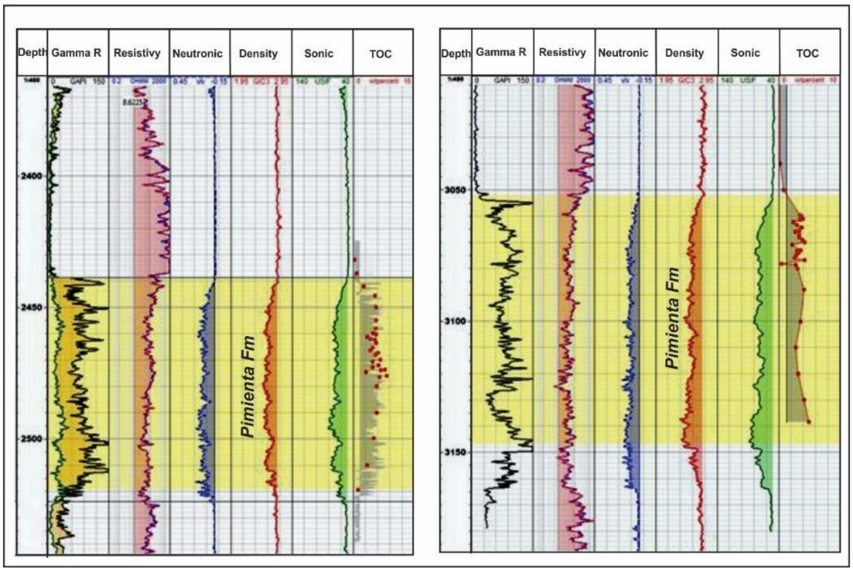


Figure 7. Representative logs of Pimienta Formation related to producing hydrocarbon wells:

Mosquete-1 (left), Nuncio-1 (right) (taken from Comision Nacional de Hidrocarburos [9] 2014).

The total volume of water injected through those wells was 220,590 m³ for the Burgos Basin, and only an average of 10 % returns back to the surface (Fig. 8).

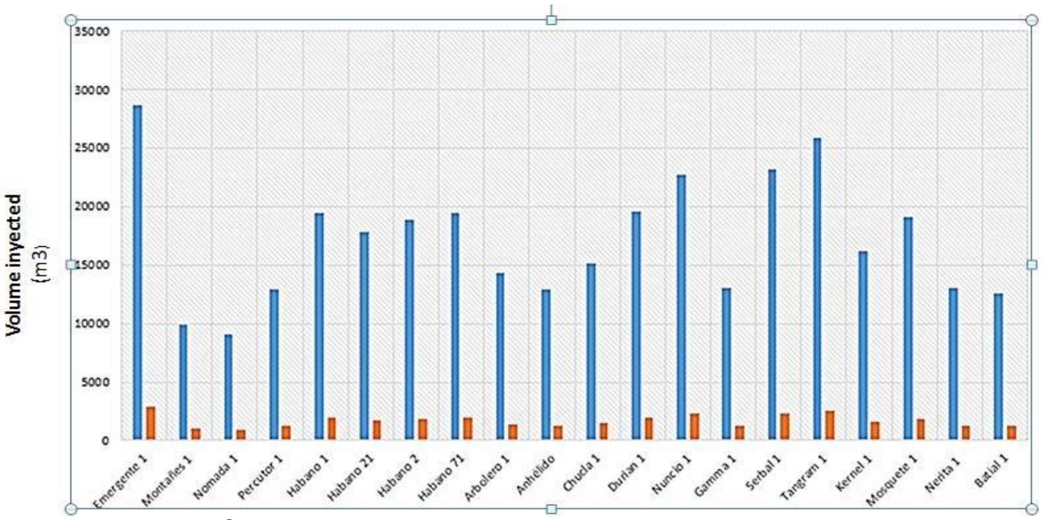


Figure 8. Volumes of water (m^3) injected during hydraulic fracturing for shale gas production in northeastern Mexico. Blue: injected volume. Orange: recovered volume (From RodríguezMartínez [69] 2014).

4. Results of the seismicity in the northern burgos basin

According to the seismic information registered by the Mexican National Seismic Network (Spanish SSN), the northeastern part of the Burgos Basin is considered seismically quiet (García-Acosta y Suárez-Reynoso[30] 1996; Galván-Ramírez y Montalvo-Arrieta[29] 2009; Montalvo-Arrieta[57] et al. 2011; Ramos-Zúñiga[64[65]] et al. 2012a; 2012b). Nevertheless, between the years 2012 and 2016, after decades of conventional production of hydrocarbons and fluid injection for re-pressurization, the inhabitants of the municipalities El Porvenir, Los Ramones, General Terán and Cadereyta began to perceive moderate seismic events that caused damage to some structures (**Fig. 9**).

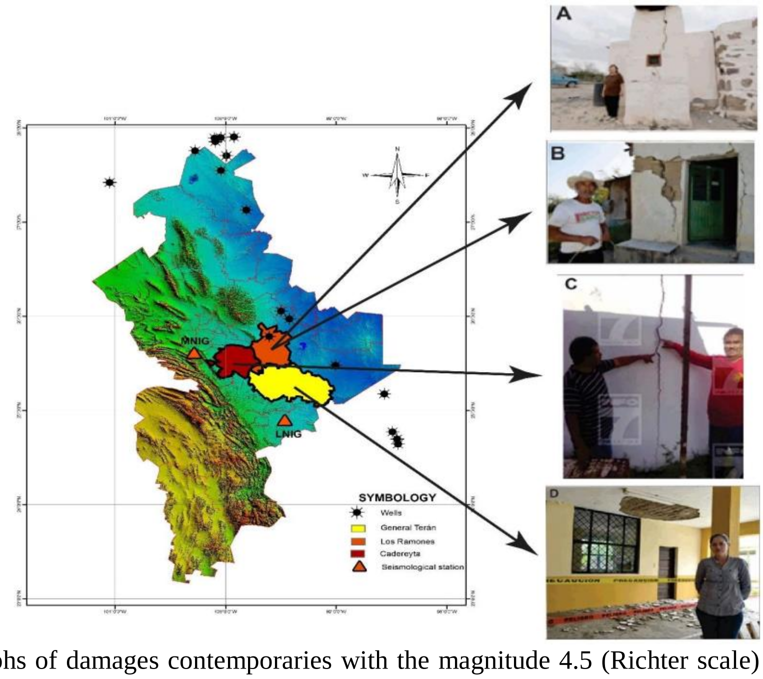


Figure 9. Photographs of damages contemporaries with the magnitude 4.5 (Richter scale) earthquake in Nuevo León, México. **A** y **B**: Residences in Los Ramones. **C**: House wall in Cadereyta. **D**: Ceiling of the Revolución Elementary School, El Llano, Gral. Terán (From Rodríguez-Martínez [69] [70] 2014, 2016, from the La Jornada newspaper of 30/03/2014).

Between the years 2006 and 2016 the quantity of 304 earthquakes occurred in the State of Nuevo León extracted from the Mexican National Seismic Network (SSN) database with a remarkable increase in the frequency and magnitude of events registered since 2012 (**Fig. 10).**

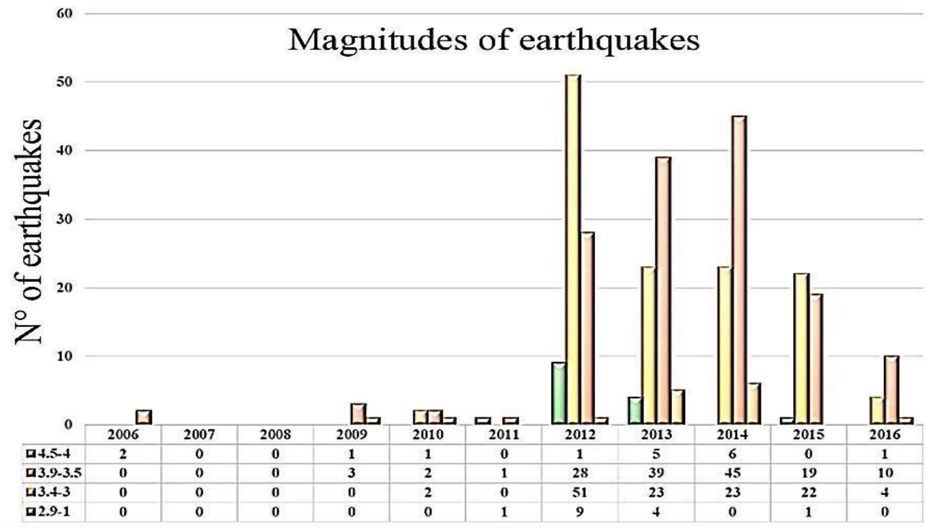


Figure 10. Graph showing the increase in frequency (number of events per year) and earthquake magnitudes (Mw) during the years 2006 to 2016, recorded in the study area (source SSN).

Moreover, significant changes were observed in the frequency of events if compared since 2006 with only 2, 4 in 2009, 5 in 2010, and 2 in 2011. In 2012, the number of earthquakes increased dramatically with a total of 89 in 2013, 69 in 2014, 75 in 2015, and finally 27 in 2016 for a total of 304 earthquakes. According to these frequencies, there is no relationship with the random fluctuations of natural seismicity rates.

Some statistical inferences were obtained from magnitude, frequency, distribution, depth and epicenter location analysis, allowing us to suppose that there is a relationship between the recorded earthquakes and the extractive works. It is worth mentioning that in 2012, Pemex suggested that the hydraulic fracking and fluid injection activities in the Burgos Basin trigger small earthquakes; a statement that was reiterated in 2015 by the Secretariat of Environment and Natural Resources in Mexico (SEMARNAT in Spanish).

From an evaluation of the hypocenter depths, two main observations emerge regarding the 2012-2016 SSN earthquake data (**Fig. 11**): (I) 96 % appear in a regular, consistent way, and (II) they occur at depths ranging between 1 and 6 km, the majority of them having magnitudes from 3 to 3.5.

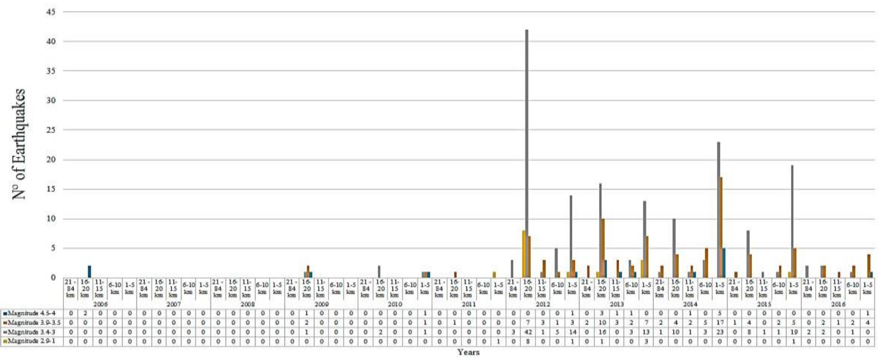


Figure 11. Graph showing the relationship between magnitudes and depths of earthquakes registered in the Burgos Basin between 2006 and 2016 (source SNN).

Vicinity of wells and epicentres

The depths of the non-conventional reservoir targets are between 3 and 4 km which approximately coincides with the depth of the seismic hypocenters recorded in the area with magnitudes between 3.0 and 4.0 in the region, most of them are temporally coincident with hydraulic fracturing activities.

Furthermore, the epicenters of earthquakes in the Burgos Basin from 2012 to 2016 years are spatially coincident with the locations of the exploratory wells: Anhélido 1, Arbolero 1, Batial 1, Durian 1, Kernel 1, Mosquete 1, Neritas 1, Nuncio 1, Serbal 1 and Tangram 1 (Fig. 12).

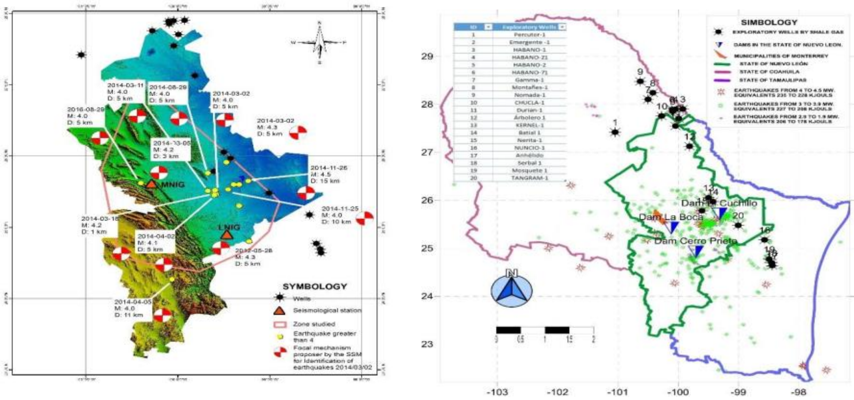


Figure 12. Location of earthquakes registered in the State of Nuevo León between 2006 and 2016. Left: yellow small circles represent micro earthquakes; black star indicates the locations of wells drilled by Pemex; and the yellow circles correspond to the moderate earthquakes of magnitude 4 on the Richter scale. Right: lesser earthquakes are represented by pink start. The inverted triangle indicates dams in the State of Nuevo Leon. The red and white circles represent the focal mechanism of earthquakes taken from the SSN database. The orange color indicated the Monterrey city location. Green color line shows the State of Nuevo Leon boundary, pink line shows the State of Coahuila and the purple line shows the State of Tamaulipas (From Rodríguez-Martínez[70] 2016).

The largest seismic events occurred in the earthquake on November 26th, 2013 with a magnitude of 4.5 (Richter), followed by another on March 2nd, 2014 with M 4.3 and one on March 5th, 2014 with M 4.2. From the 304 events in the Burgos Basin between 2006 and 2016, 17 of them had magnitudes greater than 4.0 and 268 had magnitudes between 2 and 3. The average thickness for the Agua Nueva Formation in the Burgos Basin ranges from 160 to 200 m. For the El Burro Peyotes Platform the Eagle Ford Formation (equivalent to Agua Nueva in the Burgos Basin) is approximately 170 m and the Pimienta Formation equivalent to La Casita in the Arbolero 1 well is 381 m

(**Table 2**).

Date	Local time	Northern Latitude	Western Longitude	Depth Km	Magnitude
2013-11-26	**01:13:58**	**25.65**	**-99.23**	**15**	**4.5**
2009-06-14	**06:04:06**	**25.3**	**-99.33**	**20**	**4.4**
2006-04-17	**11:25:10**	**25.32**	**-100.38**	**20**	**4.3**
2012-05-28	**19:27:20**	**24.77**	**-99.18**	**5**	**4.3**
2014-03-02	**11:30:16**	**25.52**	**-99.59**	**5**	**4.3**
2014-03-18	**17:41:58**	**24.45**	**-99.60**	**1**	**4.2**
2014-03-05	**08:40:32**	**25.50**	**-99.59**	**3**	**4.2**
2006-04-17	**11:58:04**	**25.23**	**-100.29**	**20**	**4.1**
2013-10-07	**00:03:39**	**25.91**	**-99.47**	**16**	**4.1**
2014-04-02	**13:06:10**	**25.46**	**-99.58**	**5**	**4.1**
2010-01-20	**15:56:28**	**25.62**	**-100.40**	**5**	**4.0**
2013-09-11	**20:23:49**	**25.60**	**-99.33**	**20**	**4.0**
2013-11-25	**16:25:56**	**25.53**	**-99.45**	**10**	**4.0**
2013-12-22	**05:52:26**	**26.60**	**-99.39**	**20**	**4.0**
2014-04-05	**15:16:57**	**24.27**	**-100.06**	**11**	**4.0**
2014-03-11	**08:28:41**	**25.51**	**-99.67**	**5**	**4.0**
2016-08-29	**20:11:57**	**25.76**	**-99.67**	**5**	**4.0**

Table 2. Epicentral location of earthquakes with Mc ≥ 4.0 in the State of Nuevo León, México, during the period from October 7, 2013 to August 29, 2016 (source SSN 2016).

Based on the earthquakes magnitudes and the total events per year, some valuable observations emerge: all events appear temporally and spatially coincidental with the hydraulic fracturing and fluid injection activities focused into the Agua Nueva and Pimienta reservoirs (**Figs. 12** and **13**). From these relationships, it is valid to suppose that the frequency of occurrence of earthquakes in the Burgos Basin is considered to be directly associated with the effects of the exploitation of underground fluids.

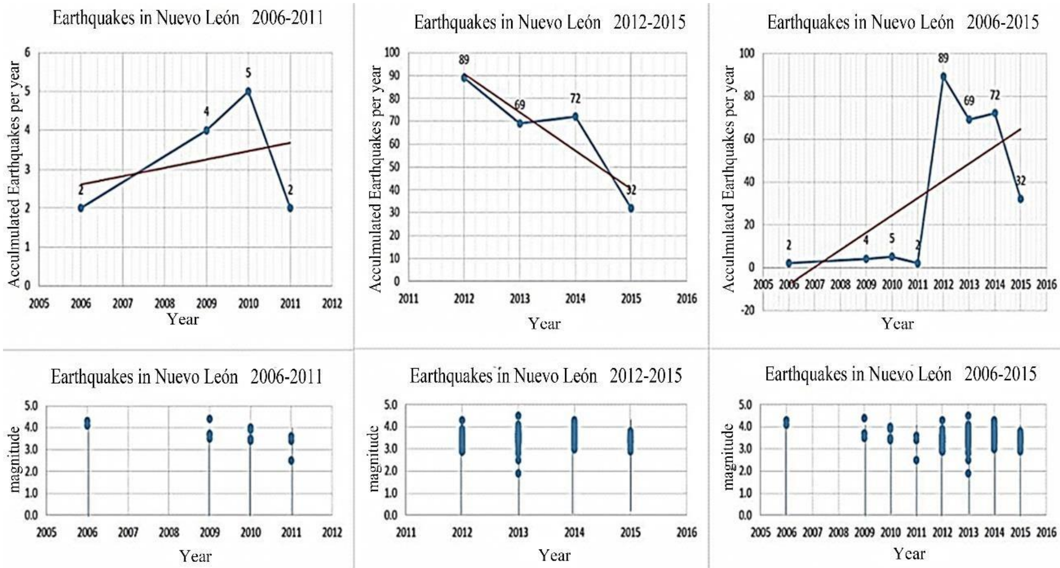


Figure 13. Plots of the number of earthquakes vs. year, and magnitude vs. year (From Rodríguez-Martínez [70] et al. 2016).

According to Shapiro and Dinske[81] (2009), Johann, Shapiro and Disnke[45] (2018) there are in nature three stress types that contribute to the generation of seismicity induced by the action of hydraulic fluids as well as by anthropogenic activities, as described below:

1. Stresses generated by the pore pressure can diminish the resistance of the rocky massif and trigger the beginning of the displacement from the surrounding rock along a fault (Sibson [83] 2000).
2. Hydrostatic stresses can act through a failure, transferring pressure from one injection zone to another, creating the appropriate tensional conditions for the earthquake (Scholz [78] 2003).
3. The difference in pressure can cause a gradient where the fluids migrate from the injection zone to the initiation zones of earthquakes.

In the case of the Burgos Basin the seismicity can be trigger by the production of hydrocarbons from the fracture of unconventional reservoirs and the injection of fluids (i.e., Tangram 1 well) such as the exploitation of water resources near the locality of China, Nuevo Leon (**Fig. 14**).

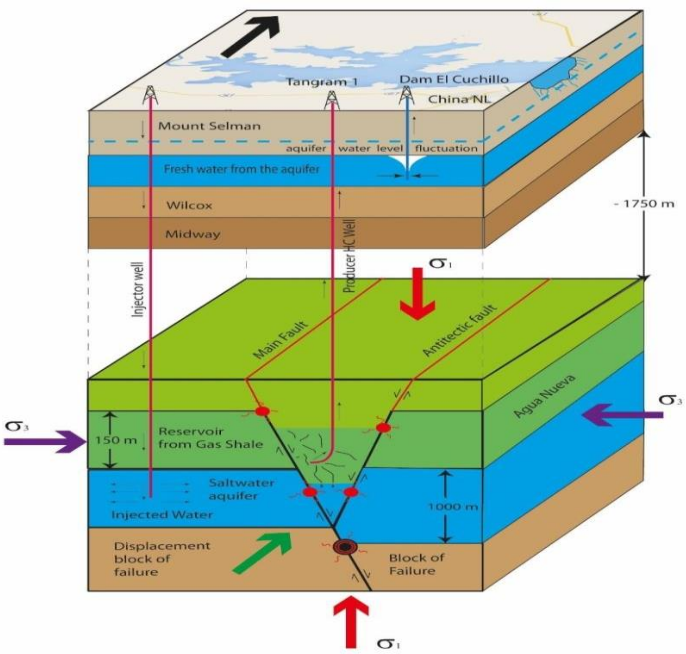


Figure 14. Schematic block diagram showing the deformations of the rocky massif produced by the exploitation of hydrocarbons and water in the Burgos Basin (modified from RodríguezMartínez [70] 2016, and Ellsworth [20] 2013).

The map of seismic activity in the hydrocarbon exploitation area shows a clear spatial variability in level of activity. For this purpose, the seismic activity per km^2 was calculated by means of a quantitative average adding the cubic roots of the energies of all the earthquakes that occurred between the years 2006 to 2016 (**Fig. 15**). Most of the seismic activity quantified in this way is located in proximity to the wells where the hydraulic fracturing was performed (Rodríguez-Martínez [70] 2016).

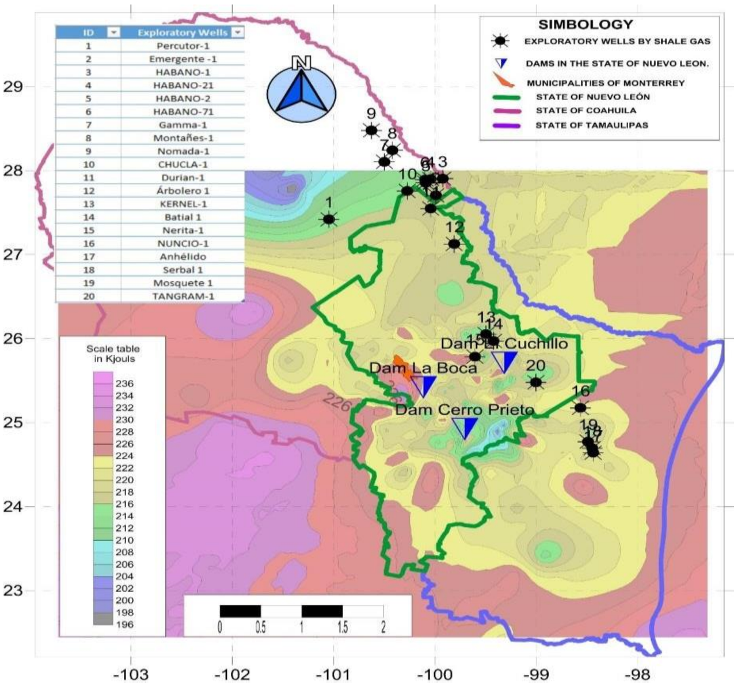


Figure 15. Distribution of quantified seismic activity in Joules (**j/km^2**) in the Burgos Basin. The quantified seismic activity is the sum of the cubic roots of the energy of the seismic event that occurs in each km^2 (From Rodríguez-Martínez [70] 2016). (See references in Fig. 12).

5. Discussion

The quantified seismic activity is one of the most useful parameters to determine the seismicity of a region (Ponomaryov and Tejtelbaum [63] 1974) providing a way to transform the visualization of seismic events in the Burgos Basin from a discrete system to a continuous system. The point-to-point representation of seismic events by means of the 3 spatial coordinates plus the time of the event and the magnitude, converts a continuous graphic representation into a system of different coordinates. The selected quantitative measure of activity is first described as the sum of the cubic roots of the energies in all events occurring in each km^2. To minimize the influence of an arbitrary selection of the way the area is divided into squares and start time selection, the activity values for the areas are calculated in overlapping time intervals (Adushkin [1] et al. 2000). In consequence, the registered earthquakes in the region from 2006 to 2016 exhibit a linear relationship between the magnitude of seismic events recorded in a time interval and the number of events (frequency) of that magnitude. The frequency plot vs. magnitude shows deviations from a linear trend, and the represented graphically earthquakes are not representative of all seismic activity in the area (**Fig. 16**). A deviation from the linear trend for lower magnitudes indicates that the seismic network is not sufficiently sensitive to low magnitude events while a deviation at the extremes of high magnitude shows that the observation period was not long enough.

Given the lack of previous studies on this issue, the subject of the seismic activity in the basin was approached through two methods:

a) The comparison of the known natural seismicity characteristics with zones of induced seismic activity.
b) The correlation between natural seismic activity and human activity in the area, in relation to the volumes of water injected from 2010-2016, where the largest swarm of earthquakes registered in a radius of 60 km located in the vicinity of the wells Arbolero 1, Batial 1, Durian1 Kernel 1, Montes1, Neritas 1, Tangram 1, etc. (**Fig. 12**).

To ensure consistency, the frequency-magnitude ratios were separately represented in seven time intervals: 2006, 2009, 2010, 2011, 2012, 2013 and 2014 (**Fig. 16**). We also considered an average annual number of events for these time intervals. In the case of the seismic activity recorded by the stations of the SSN network in the localities of Linares and Mederos, the graphical representation of frequency vs. magnitude is mainly linear (**Fig. 16**).

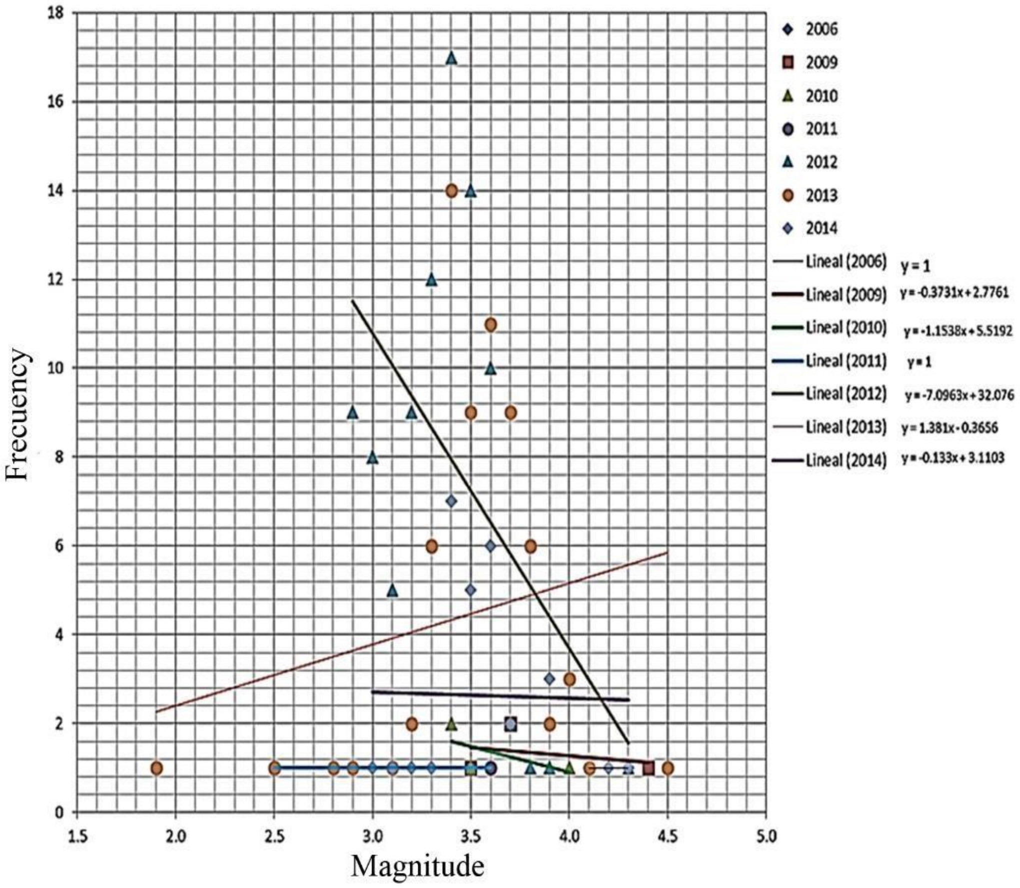


Figure 16. Relationship between the frequency of the events and the magnitude of the events listed in the catalogs from 2006 to 2014 in the Burgos Basin (Taken from RodríguezMartínez [70] 2016).

The least squares method was used to find the values of $\mathbf{b_o}$ and $\mathbf{b_i}$, which allow making the sum of the squares of the deviation between the observed values of the dependent variable: $\mathbf{y_i}$ and the estimated values of the sum $\check{\mathbf{y}}_i$ (Andrea and Andrews [3] 2013). That is, the sum is minimized: $\sum (\mathbf{y}_i - \check{\mathbf{y}}_i)^2$

$$Y_t = b_0 + b_i x_i + b_2 x_2 + b_p x_p + \varepsilon \qquad (1)$$

$$\sum \mathbf{y}_i = \mathbf{nb}_o + (\sum \mathbf{xi})_{\mathbf{i}} \qquad (2)$$

$$\sum \mathbf{x}_i\mathbf{y}_i = (\sum \mathbf{x}_i).\ \mathbf{b}_o + (\sum \mathbf{x}_i^2)\ \mathbf{b_i} \qquad (3)$$

Where $\mathbf{b_o}$ = initial frequency in year 2006, $\mathbf{b_i}$ = last frequency in the year 2014, and $\mathbf{x_i}$ = earthquake magnitude

For the years 2009 to 2014, the slope of the graphical representation of frequency and magnitude varies from -7.0963 to 1.1538; these values are considerably more negative than the value for natural seismicity which is -0.75 - 0.9 (Shapiro and Dinske[81] 2009). The slope in the year 2012 is -7.0963, in the year 2013 is -0.3656, and in the year 2014 is -0.1333. The slopes of the graphs in the Burgos Basin compared with data obtained in other regions of the world (Shapiro and Dinske [81] 2009) suggest normal values of induced seismicity caused by human activities associated with hydraulic fracturing.

One of the main hazards associated with fracturing procedures in unconventional reservoirs is frequently related to the generation of induced seismicity. This type of seismicity produced by human activity forms a vast field of studies well documented for decades in countries such as the United States (Nicholson and Wesson[59] 1990, Marone[51] 1998, Scholz[77][78] 1998, 2003, Ikari[44] et al. 2013, McGarr[54][55] et al. 2002, 2015, Committee on Induced Seismicity Potential in Energy Technologies[10], 2012, Brodsky and Lajoie[5], 2013, among many others).

McGarr [53] (2014) argues that the maximum potential magnitude of an injection induced earthquake is limited by the total injected volume, whereby the largest earthquake possible increases in magnitude with increased injection volume. The largest United States induced earthquake has been in 2011 with M5.6 Prague (Oklahoma) earthquake (Keranen[46][47] et al. 2013). However, earthquakes greater than M6.0 or M7.0 also have been generated near impounded dams or near sites of gas withdrawal. For example, Gupta [34] (2002) indicated that the 1967 Koyna (India) earthquake M6.3 was the largest and most damaging reservoir-triggered earthquake. Simpson and Leith [84] (1988) suggested that the 1984 M7.0 Gazli (Uzbekistan) earthquake may have been induced by gas withdrawal. There is also some debate about whether the 2008

M7.9 Wenchuan (China) earthquake was induced by reservoir impoundment (Kerr and Stone [49] 2009, Deng [15] et al. 2010, Gahalaut and Gahalaut[28] 2010). Also, the induced seismicity may trigger tectonic earthquakes on adjacent fault structures (Keranen[48] et al. 2014).

We consider that hydraulic fracturing-induced seismicity is a reality in the northern portion of the Burgos Basin in the State of Nuevo León where it has intensified especially since 2012. The total number of microseisms reported in this recent interval was 304, of which 17 were of magnitude greater than 4 on the Richter scale, and 268 with magnitudes in the range of 2,0 – 3.0. Rodríguez-Martínez[70] (2016) reported on the damages caused by the M 4.5 earthquake on November 26, 2013 in the China, General Terán and Los Ramones towns of Nuevo León (**Fig. 17**). By statistical analysis, it was determined that the sequence of swarms of earthquakes spatially and temporally coincide with the activity of exploration wells in the Burgos Basin, with the objective of unconventional hydrocarbon in the Agua Nueva prospects of the Upper Cretaceous and Upper Jurassic Pimienta Formation (Pérez Aquiahuatl 2014). Only 17 of the total recorded earthquakes have had Richter magnitudes ranging from 4.0 - 4.5 and they are associated with the Anhélido 1, Arbolero 1, Batial 1, Durian 1, Kernel 1, Mosquete 1, Neritas 1, Nuncio 1, Serbal 1 and Tangram 1 exploratory wells (**Fig. 12**). These can be satisfactorily associated with hydraulic fractures compared to data obtained in different parts of the world where the technique is applied (Murray and Hitzman[58] 2013; Shapiro and Dinske[81] 2009; Fitz-Diaz[24] et al. 2011; Wei and Froehlich[87] 2013).

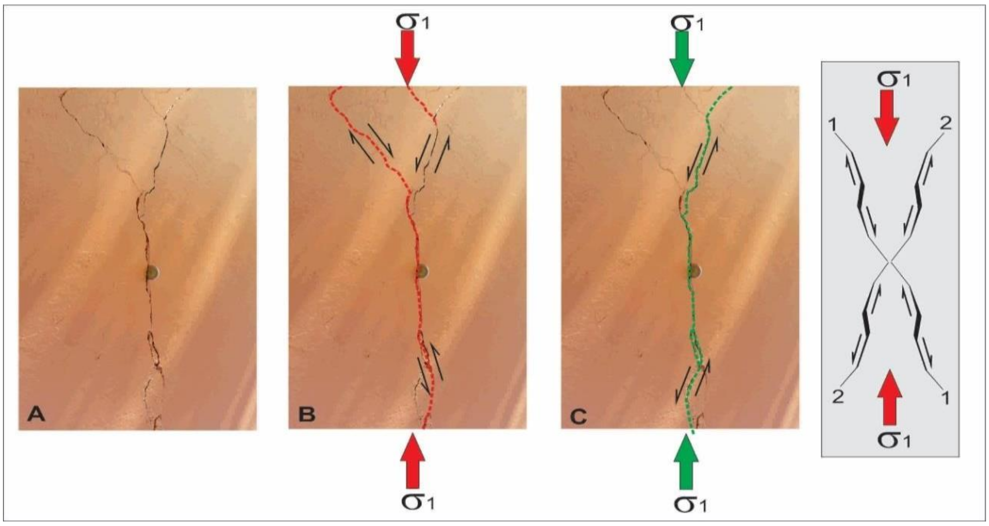


Figure 17. Details photographies and interpretation of the fractures affecting a wall of the Revolución Elementary School. **A**: Status registered by a photograph of October 12nd, 2016. **B**: Faulting produced contemporary with seismic events registered by the SSN in the State of Nuevo León. **C**: Faulting partly due to reactivation of the previous, associated with seismic events March 11th, 2014 (4.0 Richter scale magnitude) and/or from August 29th, 2016 (4.3 Richter Scale magnitude). On the right, schema of the transpresional and transtensional flexural segments related with dextral (1) and sinistral (2) faulting components.

From a detailed analysis of the existing fractures in a wall of the Revolucion Elementary School it is possible to interpret two different stages of its generation before and after it was painted between the years 2012 and 2014. In both cases, the maximal stress is located subvertical and we interpret spatially associated with the differential accommodation process of the substrate due to the induced seismicity produced by the exploitation of fluids from the underlying reservoirs (**Fig. 17**).

The mechanical response of fluid-producing reservoir levels that trigger microearthquakes can be activated by extractive activities in two ways:

1) By positive dilatance, which occurs naturally when diagenesis of sediments that have accumulated much fluids in their reservoir (Hacker[36] 1997) and artificially by pore pressure effect when injections of fluids are made at high pressure to produce the fracking into producing hydrocarbon wells (Sibson[82][83] 1986, 2000). These fluids lubricate the faulting planes and cause a decrease in the effective energy required to achieve their displacement (Hubbert and Rubey [43] 1959; Ellsworth [20] 2013; Scuderi and Collettini [79] 2016).

By negative dilatance, when by loss of pore volume due to the extraction of the interstitial fluids, collapses occur by accommodation favored by overloading the burial of the overlying sedimentary pile (Simpson and Leith [84] 1988).

6. Conclusions

The studied portion of the Burgos Basin is located in a region tectonically related to the Sierra Madre range; nevertheless, many shallow earthquakes have occurred with epicenters that coincide with both hydrocarbon and hydrogeological fluid production sectors. The depths of the producing sedimentary levels of the Pimienta and Agua Nueva hydrocarbon producing fields are between 3,000 m to 4,000 m, coinciding with the hypocenters of the earthquakes.

Between the years 2009 and 2014 the slope of frequency vs. magnitude of the seismicity in the studied sector of the Burgos Basin varies from -7.0963 to -1.1538. These values are considerably more negative than the values of - 0.75 to - 0.9 related to natural seismicity generated by regional tectonics where the slope in 2012 is -7.0963, in 2013 was - 0.3656, and in 2014 was -0.1333. These slopes are considered compatible with the induced seismicity generated by human activities.

The commercial exploitation of gas and condensate fields in the Burgos Basin for 68 years and the extraction of water from aquifers caused changes and alterations of the stress field that act on the rocky massif. Thus, the fluctuations of the pressures of these fluids in near-surface reservoirs can cause low intensity seismicity due to volumetric adjustments by differential burials.

It is assumed that the frequency of earthquakes detected in the state of Nuevo León from the year 2012 changed significantly contemporaneously with the beginning of exploratory activity of hydrocarbons by hydraulic fracturing. According to the linear behavior of the total of 304 earthquakes recorded between 2012 to 2016 there is no relationship with random fluctuations in the regional natural seismicity rate associated with the tectonics of the cortical convergence. For 2009 - 2014 slope of frequency vs. magnitude ranged from -7.0963 to -1.1538; values considerably more negative than the natural seismicity values which range from -0.75 to -0.9. For this reason we consider that the northern Burgos Basin had values of induced seismicity related to human activities trigger by hydraulic fracturing and fluids exploitation for the reactivation of preexisting natural structures.

The epicenters of earthquakes registered in the China, General Terán, Montemorelos and Los Ramones municipalities of Nuevo León the seismicity coincides in time and space with the existence of exploratory wells in the Upper Cretaceous Agua Nueva and Upper Jurassic Pimienta fields.

Considering that PEMEX (2012) estimated prospective resources (in place) ranging between 150 and 495 trillion cubic feet of gas from unconventional shale gas reservoirs, it can be supposed that the extractive activity in Mexico will tend to increase (Eagle Ford Consortium [22] 2014; SENER [80] 2015).

Finally, the induced seismic activity by exploitation of fluids (hydrocarbons or water) and the consequent topographic subsidence must be taken into account in the safety protocols related to planning, prevention and/or remediation of potential damages in civil construction projects (Green and Styles[33] 2012; Zoback[88] 2012). They do not usually have significant consequences in uninhabited or deserted regions but they may be crucial in densely populated sectors whose infrastructure was not properly designed to withstand these events.

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