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

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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 León 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 León, 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 [5] 1998, Scholz [77][78] 1998, 2003, Ikari [44] et al. 2013, McGarr [43][55] et al. 2002, 2015; Committee on Induced Seismicity Potential in Energy Technologies [10] 2012, Brodsky and Lajoie [5] 2013, Ellsworth [53] 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).
Studies conducted by Adushkin et al. (2000), Froehlich and Davis (2002), Mazzotti (2007), Andrea and Andrews (2013), Keranen et al. (2013a, 2013b, 2014), Wei and Froehlich (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 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 2016), including the productive regions: i) Barnett Shale, with approximately 15,000 active wells in the middle of 2011 (Frohlich 2012), ii) Texas Haynesville Shale, with 390 wells, and iii) Eagle Ford Shale, with 1,040 wells (Eagle Ford Consortium 2014). In addition, Shelly et al. (2015) describe equivalent situations in the state of California. The injection of fluids or wastewater into different types of hydrocarbon reservoirs (Kim 2013; Ake and Mahrer 2005; Horton 2012; Keranen et al. 2013a, 2013b; van der Elst et al. 2013; Kim 2013) as well as the exploitation of geothermal fields, have also triggered induced seismicity (Deichmann and Giardini 2009; Evans et al. 2012; Gupta 2002; González 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’ - 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 2011).

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 2011).
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\cite{13} 1986), which gave rise to tilting blocks with horsts and grabens (Echánove\cite{16} 1976).

The sedimentary record of the basin exhibits several tectonic events of cortical subsidence with accumulation of preectonic and syntectonic marine infill sequences, mainly spanning from the Late Jurassic to the Eocene (Echánove\cite{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\cite{11} et al. 2004; Eguiluz de Antuñano\cite{18}\cite{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\cite{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).

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\cite{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\cite{73} 1991; Hernández-Mendoza\cite{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](Image)

Table 1: Hydrocarbon wells drilled in the Burgos Basin

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


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)

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).
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-Zaúñiga[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](image)

**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).
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 fracturing 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.
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).

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.
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 Rodríguez-Martínez\(^{70}\) 2016, and Ellsworth\(^{20}\) 2013).](image)

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).
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).
The least squares method was used to find the values of $b_0$ and $b_i$, which allow making the sum of the squares of the deviation between the observed values of the dependent variable: $y_i$ and the estimated values of the sum $\bar{y}$ (Andrea and Andrews [3] 2013). That is, the sum is minimized: $\sum (y_i - \bar{y})^2$

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

$$\sum y_i = n b_0 + (\sum x_i) b_i$$ (2)

$$\sum x_i y_i = (\sum x_i). b_0 + (\sum x_i^2) b_i$$ (3)

Where $b_0 =$ initial frequency in year 2006, $b_i =$ last frequency in the year 2014, and $x_i =$ 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 [53] 2014, 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] 2013, 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

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](image.png)

Figure 17. Details photographs and interpretation of the fractures affecting a wall of the Revolución Elementary School. A: Status registered by a photograph of October 12th, 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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