Journal of South American Earth Sciences 71 (2016) 320–332

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

journal homepage: www.elsevier.com/locate/jsames

Stress field estimation based on focal mechanisms and back projected imaging in the Eastern Llanos Basin (Colombia)

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ARTICLE INFO

Article history:
Received 31 January 2015
Received in revised form
12 August 2015
Accepted 24 August 2015
Available online 4 September 2015

Keywords:
Induced seismicity
Back projection imaging
Moment tensor retrieval
Focal mechanisms
Colombia
Puerto Gaitán

ABSTRACT

At least 156 earthquakes (Mw 2.8–4.4) were detected in Puerto Gaitán, Colombia (Eastern Llanos Basin) between April 2013 and December 2014. Out of context, this figure is not surprising. However, from its inception in 1993, the Colombian National Seismological Network (CNSN) found no evidence of significant seismic events in this region. In this study, we used CNSN data to model the rupture front and orientation of the highest-energy events. For these earthquakes, we relied on a joint inversion method to estimate focal mechanisms and, in turn, determine the area's fault trends and stress tensor. While the stress tensor defines maximum stress with normal tendency, focal mechanisms generally represent normal faults with NW orientation, an orientation which lines up with the tracking rupture achieved via Back Projection Imaging for the study area. We ought to bear in mind that this anomalous earthquake activity has taken place within oil fields. In short, the present paper argues that, based on the spatio-temporal distribution of seismic events, hydrocarbon operations may induce the study area's seismicity.

1. Introduction

The confluence of declines in the volume of Colombian oil reserves and dynamics in the global hydrocarbon sector prompted the Colombian government to create the *National Hydrocarbons Agency* (NHA) (www.anh.gov.co) in 2003. The NHA's was tasked with promoting the Latin American nation as an attractive place for investors interested in new Exploration and Production (E&P) contracts, exploratory well drilling, daily production of oil and gas increases and mature field revitalization. Per ANH data, increased production has been driven by the reactivation of heavy oil fields such as Castilla, Chichimene and Rubiales-Pirirí. Today, these three fields boast higher productivity due to the successful implementation of new technologies and enhanced recovery methods, including water injection, internal combustion and steam injection operations. Recently, the Colombian government has sought to develop Unconventional Reservoirs (UR); thus, the NHA has also been involved in creating special regulations to mitigate the consequences brought about by the development of URs. Notable consequences of URs include water pollution and induced seismicity.

Let us focus our attention on the latter situation, induced seismicity. Starting in the mid-20th century, numerous cases have been reported worldwide. Most of these events have been attributed to high-pressure fluid injection into subsurface rock formations (Nicholson et al., 1992; McGarr et al., 2002). Fluid injections are associated with water waste disposal reservoirs, secondary recovery oil, waste fluid from coal bed methane production and brine from hydraulic fracturing of shale gas. With regard to magnitude ranges for these induced events, we find variation: Mw 3.9 at Ashtabula, Ohio, Mw 4.3 at Paradox Valley, Mw 4.7 at Guy, Arkansas, and Mw 4.9 at Rocky Mountain Arsenal (Herrmann et al., 1981).

In Colombia, induced seismicity has not been thoroughly studied, yet recent observations point to an increase in the number of earthquakes in Eastern Colombia. A total of 40 events (Table 1) with magnitudes greater than Mw 3.5 have been recorded since 2013 by the *Colombian National Seismological Network* (CNSN) in Puerto Gaitán, Colombia. To put this number in perspective, in the same region, only five events with Mw < 3.0 were recorded in the 20 years prior to 2013. Interestingly, annual reports published by the Colombian Ministry of Mines and Energy (www.minminas.gov.co) show greater oil production in the same area beginning in 2009 (Fig. 1). In fact, these reports discuss a maximum average monthly production of 212.000 Bbl/day reached in August 2013. When the study area's seismicity in 2013 and 2014 is compared to average monthly oil production volumes, some level of correlation is found; in other words, there exists a level of correlation between the date of production reports and seismic activity. In response to this correlation, this paper aims to evaluate the hypothesis that relates

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http://dx.doi.org/10.1016/j.jsames.2015.08.010
0895-9811/

Table 1
Regional events in Puerto Gaitán, Colombia with magnitudes greater than M_w 3.5 in 2013 and 2014. Highlight rows show events that were analyzed with BPI and Moment Tensor techniques. Source: CNSN (www.sgc.gov.co).

Date (dy/mo/year)	Time (hh:mm:ss)	Latitude (°N)	Longitude (°W)	Depth (km)	Magnitude (M_L)	Magnitude (M_W)	Rms	Gap	E_Lat (km)	E_Long (km)	E_Depth (km)
10/05/2013	1:45:02	3.8010	−71.2850	12.7000	3.50	3.90	0.5	238	3.4	6.8	8.3
11/05/2013	1:19:41	3.7630	−71.2350	8.0000	3.80	4.00	0.5	241	3.4	7.2	7.9
17/05/2013	6:36:39	3.7790	−71.3390	8.7000	3.50	4.10	0.6	231	3.6	7.3	6.6
01/06/2013	23:41:31	3.7970	−71.4850	4.1000	2.90	3.60	0.5	229	3.3	7.6	6
17/06/2013	1:41:19	3.7780	−71.2460	14.0000	3.50	3.90	0.6	240	4.2	8.3	7.7
27/06/2013	2:54:46	3.7850	−71.3380	5.6000	3.40	3.80	0.5	218	3.4	4.8	6.1
31/01/2014	**2:53:08**	**3.8610**	**−71.4090**	**1.8000**	**4.00**	**3.80**	**0.4**	**256**	**2.6**	**6**	**5.2**
20/02/2014	4:14:49	3.8850	−71.5490	4.1000	3.60	3.60	0.7	224	4.7	8.4	9.3
25/02/2014	13:18:10	3.8980	−71.6010	0.5000	3.50	3.50	0.5	222	2.6	4.8	4.9
28/02/2014	7:10:37	3.8880	−71.5860	4.1000	3.20	3.50	0.5	223	3.5	6.2	7
15/03/2014	6:55:43	3.8980	−71.5510	4.1000	3.50	3.70	0.6	224	4.1	6.8	8
17/03/2014	**10:26:05**	**3.8920**	**−71.5460**	**4.1000**	**3.90**	**4.00**	**0.5**	**224**	**2.5**	**3.9**	**4.7**
19/03/2014	11:13:26	3.8730	−71.5750	4.1000	3.40	3.60	0.6	223	3.4	5.9	6
24/03/2014	23:19:31	3.8500	−71.3910	4.1000	3.90	3.90	0.6	232	3.4	5.2	5.9
27/03/2014	**10:21:16**	**3.9260**	**−71.5790**	**4.1000**	**4.30**	**4.30**	**0.5**	**222**	**3.4**	**4.6**	**6.3**
30/03/2014	1:11:12	3.8740	−71.5890	1.3000	3.30	3.50	0.4	223	3.5	7.3	7.2
04/04/2014	4:25:57	3.8860	−71.5920	0.6000	3.60	3.70	0.5	222	3.1	5.5	5.3
10/04/2014	10:13:22	3.8620	−71.3950	4.1000	3.80	3.90	0.5	232	3.7	5.2	5.7
23/04/2014	15:19:28	3.8980	−71.5500	4.1000	3.50	3.80	0.5	224	2.7	4.6	5.3
23/04/2014	18:38:15	3.8850	−71.5950	5.7000	3.70	3.80	0.6	222	3.3	5.4	6.4
13/05/2014	**18:07:32**	**3.8980**	**−71.5670**	**2.8000**	**4.30**	**4.20**	**0.6**	**223**	**3.3**	**5.7**	**5.7**
14/05/2014	2:43:42	3.8630	−71.5910	4.1000	3.40	3.60	0.6	223	2.6	4.1	4.8
25/05/2014	15:25:03	3.9070	−71.5550	4.1000	3.70	3.80	0.4	185	2.6	3.3	4.4
26/05/2014	3:48:15	3.9110	−71.5770	4.1000	3.20	3.80	0.4	223	3.2	6	6.8
26/05/2014	16:03:08	3.9300	−71.6570	11.6000	3.30	3.60	0.6	204	3.3	5	4.8
27/05/2014	17:36:28	3.8900	−71.5730	0.9000	3.30	3.50	0.6	223	3.9	6.4	7.1
04/06/2014	**23:06:20**	**3.8810**	**−71.6110**	**0.1000**	**3.80**	**4.00**	**0.5**	**221**	**3**	**5.2**	**5.3**
04/06/2014	3:17:23	3.8810	−71.5800	4.1000	3.60	3.80	0.5	223	2.8	4.2	5
05/06/2014	1:04:43	3.9040	−71.5550	4.1000	3.60	3.80	0.5	224	3.2	4.7	5.4
20/06/2014	23:31:58	3.8620	−71.5790	4.1000	3.50	3.70	0.5	223	2.8	4.4	5.3
25/06/2014	**7:27:39**	**3.9240**	**−71.5060**	**4.1000**	**4.40**	**4.40**	**0.6**	**226**	**4.2**	**5.6**	**6.9**
26/06/2014	6:20:05	3.8860	−71.5890	4.1000	3.30	3.50	0.6	222	3.1	4.5	5.4
15/07/2014	17:44:33	3.8450	−71.3610	1.0000	3.40	3.60	0.5	234	4	6.7	6.8
20/07/2014	20:47:32	3.8960	−71.5660	0.7000	3.70	3.90	0.5	223	2.8	5.5	5.1
09/08/2014	0:30:58	3.8930	−71.5820	4.1000	3.50	3.80	0.5	223	2.6	3.9	4.6
09/08/2014	12:56:59	3.8840	−71.5920	0.8000	3.50	3.70	0.5	222	3.6	6.5	6.8
14/08/2014	8:04:07	3.8870	−71.5620	4.1000	3.60	3.70	0.6	224	3.4	5.4	6.6
19/10/2014	17:25:29	3.8600	−71.4110	6.4000	3.40	3.50	0.4	231	3.2	4.6	5.2
30/11/2014	19:45:34	3.9060	−71.5340	0.1000	3.60	3.80	0.5	225	2.4	4.1	4.2
30/11/2014	23:22:00	3.9770	−71.5230	5.7000	3.50	3.70	0.8	208	3.7	5.4	6.7

induced seismicity with increased production within the framework of recent recovery stimulation projects based on available data. To this end, this paper estimates the stress field in the study area, for once the stress field is determined, it is possible to establish whether the impact is significant regionally or only locally.

2. Tectonic setting

Colombia is located in the northwestern corner of South America. Three different lithospheric plates interact in the region: Nazca, South America and Caribbean. The Nazca Oceanic plate is converging eastward at 6 cm/yr relative to the Northwestern South America plate (NWSA); the Caribbean plate is moving at 1–2 cm/yr E–SE relative to the NWSA plate (Freymuller et al., 1993; Kellogg and Vega, 1995). Colombia's physiography is dominated by the Andes Mountains in the west and the Amazon-Orinoco basin in the east. With regard to the former, the Colombian Andes are split into the Western, Central and Eastern Cordilleras, which merge into a single range in the South (Ecuador). The Eastern Llanos Basin lies east of the Eastern Cordillera; an elevated savannah, the basin forms part of the Rio Orinoco's catchment area. A number of researchers have documented Colombia's stratigraphy, tectonic and regional tectonic setting. For further information, readers are directed to: Hettner (1892), Hubach (1957), Bürgl (1961), Etayo-Serna (1979), Fabre (1983), McCourt et al. (1984), Pilger (1984), Aspden and McCourt (1986), Ben Avraham and Nur (1987), Megard (1987), Burke (1988), Butler and Schamel (1988) and Montgomery (1992).

Complex geological processes have taken place in Colombia, and we now possess the technology to identify three main tectonic domains (Fig. 2) (Pardo et al., 2007):

1. *Eastern Region:* limited to the west by the foothills of the Eastern Cordillera, in turn defined by the projection of the Algecira-Garzon Fault System (A.G.F.S) and the Guaicaramo Fault System (G.F.S.). This region consists of a Paleozoic and Precambrian basement with a Paleozoic–Cenozoic sedimentary cover that has undergone mild deformation.
2. *Central Region:* comprises the Eastern Cordillera, Sierra Nevada de Santa Marta, the Magdalena River Valley and the Central Cordillera. Tectonic limits of this region run from the A.G.F.S – G.F.S. features to the Romeral Fault System (R.F.S.) in the west. A sedimentary-metamorphic cover rests on a Grenvillian basement believed to be the result of accretion of the South American border during Paleozoic time.
3. *Western Region:* located to the west of the R.F.S., this region is composed of Mesozoic–Cenozoic oceanic terrains accreted to the Continental margin during the Late Cretaceous, Paleogene and Neogene.