Nat. Hazards Earth Syst. Sci. Discuss., 2, 7507–7519, 2014
www.nat-hazards-earth-syst-sci-discuss.net/2/7507/2014/
doi:10.5194/nhessd-2-7507-2014

Natural Hazards and Earth System Sciences Discussions
Open Access

Earthquakes and depleted gas reservoirs: which comes first?

M. Mucciarelli[1,2], F. Donda[1], and G. Valensise[3]

[1]Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), Borgo Grotta Gigante 42/c, 34010 Sgonico (Trieste), Italy
[2]School of Engineering, Basilicata University, Viale dell'Ateneo Lucano 10, 85100 Potenza, Italy
[3]Istituto Nazionale di Geofisica e Vulcanologia (INGV), Via di Vigna Murata 605, 00143 Rome, Italy

Received: 24 September 2014 – Accepted: 23 November 2014 – Published: 12 December 2014

Correspondence to: M. Mucciarelli (marco.mucciarelli@unibas.it)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

While scientists are paying increasing attention to the seismicity potentially induced by hydrocarbon exploitation, little is known about the reverse problem, i.e. the impact of active faulting and earthquakes on hydrocarbon reservoirs. The recent 2012 earthquakes in Emilia, Italy, raised concerns among the public for being possibly human-induced, but also shed light on the possible use of gas wells as a marker of the seismogenic potential of an active fold-and-thrust belt. Based on the analysis of over 400 borehole datasets from wells drilled along the Ferrara-Romagna Arc, a large oil and gas reserve in the southeastern Po Plain, we found that the 2012 earthquakes occurred within a cluster of sterile wells surrounded by productive ones. Since the geology of the productive and sterile areas is quite similar, we suggest that past earthquakes caused the loss of all natural gas from the potential reservoirs lying above their causative faults. Our findings have two important practical implications: (1) they may allow major seismogenic zones to be identified in areas of sparse seismicity, and (2) suggest that gas should be stored in exploited reservoirs rather than in sterile hydrocarbon traps or aquifers as this is likely to reduce the hazard of triggering significant earthquakes.

1 Introduction

Over the past months the potential for fluid withdrawal and injection to trigger earthquakes has fueled vigorous scientific and political debates. Most of the recent studies on this topic maintain that seismic activity is being increased by human-induced earthquakes (e.g. Ellsworth, 2013). Special attention is being given to the hydraulic fracturing technique (fracking) used to stimulate hydrocarbon production in low-permeable reservoirs (e.g. gas shales), but this seems less likely to induce destructive earthquakes than does the disposal of wastewater retrieved from productive wells (e.g. the 2011, $M_w = 5.7$ Oklahoma earthquake; Keranen et al., 2013). The recent report by ICHESE, an international commission appointed to study the relationships between hydrocar-

NHESSD
2, 7507–7519, 2014

bon exploitation and the 20 and 29 May 2012 earthquakes in Emilia, Italy ($M_w = 6.1$ and 6.0), concluded that it cannot be ruled out that these events were triggered by human activity (Cartlidge, 2014; ICHESE, 2014), while further investigations by Astiz et al. (2014) consider this hypothesis negligible. Very few investigators, however, have paid attention to the opposite case, i.e. to the impact of natural seismicity on gas and oil reservoirs. In literature, it is possible to find papers dealing with the impact on hydrocarbon reservoir by intersecting faults (Gartrell et al., 2004, and references therein), but without specific focus on seismogenic faults and related earthquakes. This latter case is interesting in areas where significant hydrocarbon reservoirs are hosted by growing anticlines driven by faults extending to seismogenic depth, and where natural earthquakes should be carefully distinguished from induced ones.

The Po Plain is one such area. The May 2012 earthquakes occurred in a relatively small portion of this large, roughly E–W elongated alluvial plain extending for $\sim 50\,000\,\text{km}^2$ over much of northern Italy. The Po Plain conceals the front of the Northern Apennines fold-and-thrust belt and is actively contracting at rates ranging from 1 to $3\,\text{mm}\,\text{yr}^{-1}$, respectively from west to east (Devoti et al., 2011). Shortly after these destructive earthquakes took place, rumours began to circulate that they were somehow related to hydrocarbon exploitation. Very few studies on induced seismicity have been carried out in Italy (Mucciarelli, 2013); the only paper dealing explicitly with the possible relationships between hydrocarbon exploitation and seismicity dates back to the 50s' (Caloi et al., 1956).

The Po Plain is punctuated by a number of gas fields as well as a few oil-and-gas fields, all of which have been systematically and heavily exploited from the 50s' onwards. The continuing evolution of the two major opposing orogens surrounding the Po Plain – the Alps to the north and to the west, and the Apennines to the south – has created two characteristic fold-and-thrust-belts – the former verging south to east, the latter verging north-northeast – which have been subsequently covered by thousands of meters of sediments eroded from their most uplifted portions (Bartolini et al., 1996; Carminati and Martinelli, 2002). The outermost thrust front of the Apennines

NHESSD
2, 7507–7519, 2014

chain is formed by three distinct arc-shaped fold systems: the Monferrato, Emilia and Ferrara-Romagna arcs, respectively from west to east (Toscani et al., 2009). The 2012 earthquakes occurred along the Ferrara-Romagna arc, a NE-verging stack of faults and folds overlain by a Plio-Quaternary succession several kilometres thick that is mostly represented by syn-tectonic sedimentary wedges.

2 The data

We investigated the relationships between hydrocarbon fields and seismicity by focusing on a ~150 km × 70 km portion of the central-southern Po Plain straddling the Ferrara-Romagna Arc, from its western end near Correggio to it eastern end near the Adriatic Sea (Fig. 1). To this end we used a large, public database made available by the project "Visibility of Petroleum Exploration Data in Italy (ViDEPI)" (http://www.videpi.com). In our study area eight major gas fields have been discovered in Plio-Quaternary deposits, whereas three oil-and-gas fields have been found in the Mesozoic carbonate sequences (ENI, 1996; Casero, 2004; Bertello et al., 2010). Hydrocarbon reservoirs lie within anticlines that formed during the construction of the Apennines fold-and-thrust belt between the Lower and the Upper Pliocene. Sustained Pleistocene activity of these thrusts is locally documented by subsurface data in addition to geomorphic (Burrato et al., 2003), geodetic (Devoti et al., 2011) and seismological evidence (Rovida et al., 2011). In some areas, thrusting also involves the Mesozoic carbonate succession, bringing it at shallow depth where it can be easily drilled (e.g. the Cavone oil field).

For our study area the database includes the composite logs of 417 wells (for a full list see Supplement). We first subdivided all wells into three main categories:

a. positively sterile, i.e. wells that have been drilled down to the prospective reservoir but encountered no hydrocarbons;

b. positively productive, i.e. wells that have been or are presently producing;

NHESSD
2, 7507–7519, 2014

c. wells that returned ambiguous results, i.e. exploration boreholes that encountered potentially productive gas/oil reservoirs that were never exploited, or gas reservoirs that are too shallow (< 500 m) to provide information on seismogenic processes.

All wells were then plotted along with the inferred surface projection of a number of Individual Seismogenic Sources (ISS) and Composite Seismogenic Sources (CSS), inferred structures based on regional surface and subsurface geological data taken from the Italian DISS database (Basili et al., 2008; DISS Working Group, 2010). This national database has been recently updated with evidence from the 2012 Emilia earthquakes (Vannoli et al., 2014) and extended to the rest of Europe (Basili et al., 2013). All listed seismogenic sources are assumed to be able to generate earthquakes of $M_w = 5.5$ and larger, based on the size of the corresponding faults (for the Po Plain specifically on the inferred down-dip width). The ISSs represent the causative faults of individual earthquake ruptures, whereas the CSSs are more loosely defined, unsegmented tectonic structures, each of which may span an unspecified number of ISSs.

We focused on the four CSSs and five ISSs falling in our study area (Table 1). The ISSs represent the causative source of four damaging earthquakes that are known to have occurred in the study region over the past five centuries: two are historical (1, 2), whereas the other two belong to the 2012 sequence (3, 4).

The largest oil-and-gas field discovered in our study area is Cavone, which includes two main reservoirs in Lower Cretaceous calcareous breccias and fractured Liassic oolithic limestones (Nardon et al., 1991; Casero, 2004). It was based on the levels of extraction and reinjection from this field that ICHESE (2014) said they were possibly associated with the occurrence of the 20 May 2012 earthquake. In contrast, limited information is available for the reservoirs of the gas fields, which can be inferred to lie at a mean depth of 100–1200 m, mainly within the Pleistocene Asti Formation.

All gas and oil-and-gas fields lie in or just above the structural highs that form the complex architecture of the Ferrara-Romagna arc. The analysis of all boreholes reveals that wells where gas has never been encountered throughout the drilled sequence lie

NHESSD
2, 7507–7519, 2014

next to fully productive wells (Supplement). Since the stratigraphic setting of the whole study area is rather homogeneous, the juxtaposition of patches of productive/sterile wells must be related to something else.

3 Data analysis

There can be several reasons why hydrocarbons do not accumulate in a natural reservoir. One of the key pre-requisite for the formation of an efficient gas reservoir is that the geological formations overlying the porous layers where hydrocarbons can migrate and accumulate must be unaffected by fractures and faults, which might allow fluids to escape. This is not warranted in earthquake-prone areas; basic principles of source mechanics (e.g. Scholz, 2002) suggest that earthquakes of $M \geq 5.5$ are capable of rupturing a considerable thickness of the seismogenic layer. Thus, in a thrust faulting environment, earthquakes at least as big as this may generate new fractures and cause sympathetic slip on secondary faults above the tip of the master fault, possibly damaging the reservoir and the impermeable caprock and allowing fluids to migrate upwards. The generation of extrados extensional faults and the progressive reduction of the lithospheric load near the Earth's surface may further promote the escape of fluids from the core of the fault-driven anticline. To summarize, we contend that in an active area like the Po Plain the lack of gas in a reservoir may reflect the state of fracturing of the reservoir and of the caprock, and ultimately the presence and state of activity of a fault capable of $M\,5.5+$ earthquakes. All else being equal, longer-wavelength anticlines generated by wider – and presumably longer – faults would be less suited to preserving the integrity of a reservoir than smaller anticlines driven by smaller faults. In the Po Plain wider faults are also more likely to affect the more rigid Mesozoic basement, which is assumed to be more prone to stick-slip behavior and hence to larger earthquakes (Bonini et al., 2014).

To substantiate this scenario, we used a binomial test to see if the observed correlation between gas production and anticline/fault size is statistically significant (Table 2).

NHESSD
2, 7507–7519, 2014

Hence only one out of 19 wells falling on the surface projection of the presumed causative faults of $M\,5.5+$ earthquakes is currently productive. According to the binomial test, the probability of this result occurring by chance is $< 0.01\,\%$. In contrast, the highest success rate is found outside the Composite Seismogenic Sources, that is to say, in portions of the fold-and-thrust belt where faults capable of a $M\,5.5$ and larger earthquake should not exist. Although these figures may be affected by uncertainties in the location of the faults, the results are quite striking.

4 Conclusions

The observation that a reservoir's productivity is anti-correlated with the presence of a large seismogenic fault has two potential yet very practical outcomes:

1. when investigating the seismogenic potential of any active area subjected to compressional tectonics, the consistent absence of productive gas wells within fault-driven anticlines may help identify areas lying above large seismogenic faults;

2. when designing an underground natural gas storage facility in a tectonically active area, depleted gas reservoirs are more likely to be intact, i.e. unaffected by shallow active faults, thus greatly reducing the hazard of triggered seismicity. This solution should be preferred over other options, such as oil-only depleted reservoirs or aquifers (as it was proposed for the Rivara storage in the epicentral area of Emilia earthquake). The September 2013 earthquake sequence that took place off the coast of Spain at Vinaròs near Valencia (Cesca et al., 2014) supplied living evidence of the hazard associated with using oil-only depleted reservoirs located next to a major active fault (see Amposta fault in Basili et al., 2013).

The Supplement related to this article is available online at doi:10.5194/nhessd-2-7507-2014-supplement.

References

Astiz, L., Dieterich, J. H., Frohlich, C., Hager, B. H., Juanes, R., and Shaw, J. H.: On the potential for induced seismicity at the Cavone oilfield: analysis of geological and geophysical data, and geomechanical modeling, Report for the Laboratorio di Monitoraggio Cavone, 139 pp., available at: http://labcavone.it/documenti/32/allegatrapporto-studiogiacimento.pdf, last access: 11 December 2014.

Bartolini, C., Caputo, R., and Pieri, M.: Pliocene-quaternary sedimentation in the northern Apennine Foredeep and related denudation, Geol. Mag., 133, 255–273, 1996.

Basili, R., Valensise, G., Vannoli, P., Burrato, P., Fracassi, U., Mariano, S., Tiberti, M. M., and Boschi, E.: The Database of Individual Seismogenic Sources (DISS), version 3: summarizing 20 years of research on Italy's earthquake geology, Tectonophysics, 453, 20–43, doi:10.1016/j.tecto.2007.04.014, 2008.

Basili, R., Kastelic, V., Demircioglu, M. B., Garcia Moreno, D., Nemser, E. S., Petricca, P., Sboras, S. P., Besana-Ostman, G. M., Cabral, J., Camelbeeck, T., Caputo ,R., Danciu, L., Domac, H., Fonseca, J., García-Mayordomo, J., Giardini, D., Glavatovic, B., Gulen, L., Ince, Y., Pavlides, S., Sesetyan, K., Tarabusi, G., Tiberti, M. M., Utkucu, M., Valensise, G., Vanneste, K., Vilanova, S., and Wössner, J.: The European Database of Seismogenic Faults (EDSF) compiled in the framework of the Project SHARE, available at: http://diss.rm.ingv.it/share-edsf/, last access: 11 December 2014, doi:10.6092/INGV.IT-SHARE-EDSF, 2013.

Bertello, F., Fantoni, R., Franciosi, R., Gatti, V., Ghielmi, M., and Pugliese, A.: From thrust and fold belt to foreland, hydrocarbon occurences in Italy, in: Petroleum Geology: From Mature Basin to New Frontiers, 7th Petroleum Geology Conference, edited by: Vining, B. A. and Pickering, S. C., Geol. Soc., London, 113–126, 2010.

Bonini, L., Toscani, G., and Seno, S.: Three-dimensional segmentation and different rupture behaviour during the 2012 Emilia seismic sequence (Northern Italy), Tectonophysics, 630, 33–42, doi:10.1016/j.tecto.2014.05.006, 2014.

Burrato, P., Ciucci, F., and Valensise, G.: An inventory of river anomalies in the Po Plain, northern Italy: evidence for active blind thrust faulting, Ann. Geophys.-Italy, 46, 865–882, 2003.

Caloi, P., De Panfilis, M., Di Filippo, D., Marcelli, L., and Spadea, M. C.: Terremoti della Val Padana del 15–16 maggio 1951, Ann. Geofis., 9, 63–105, 1956.

NHESSD

2, 7507–7519, 2014

Carminati, E. and Martinelli, G.: Subsidence rates in the Po Plain, northern Italy: the relative impact of natural and anthropogenic causation, Eng. Geol., 66, 241–255, 2002.
Cartlidge, E.: Human activity may have triggered fatal Italian earthquakes, panel says, Science, 344, 141, doi:10.1126/science.344.6180.141, 2014.
Casero, P.: Structural setting of petroleum exploration plays in Italy, in: Geology of Italy, Special Volume of the Italian Geological Society Special Volume for the, IGC 32 Florence, Chieti, Italy, 18–199, 2004.
Cesca, S., Grigoli, F., Heimann, S., González, A., Buforn, S., Maghsoudi, S., Blanch, E., and Dahm, T.: The 2013 September–October seismic sequence offshore Spain: a case of seismicity triggered by gas injection?, Geophys. J. Int., 198, 941–953, 2014.
Devoti, R., Esposito, A., Pietrantonio, G., Pisani, A. R., and Riguzzi, F.: Evidence of large scale deformation patterns from GPS data in the Italian subduction boundary, Earth Planet. Sc. Lett., 311, 230–241, doi:10.1016/j.epsl.2011.09.034, 2011.
DISS Working Group: Database of Individual Seismogenic Sources (DISS), Version 3.1.1, a compilation of potential sources for earthquakes larger than M 5.5 in Italy and surrounding areas, available at: http://diss.rm.ingv.it/diss (last access: 11 December 2014), 2010.
Ellsworth, W. L.: Injection-induced earthquakes, Science, 341, 6142, doi:10.1126/science.1225942, 2013.
ENI: Area ENI, Dominio appenninico orientale, Lineamenti geologico minerari, Technical report, available at: www.videpi.com (last access: 11 December 2014), 1996.
Gartrell, A., Zhang, Y., Lisk, M., and Dewhurst, D.: Fault intersections as critical hydrocarbon leakage zones: integrate field study and numerical modelling of an exampl from the Timor Sea, Australia, Mar. Petrol. Geol., 21, 1165–1179, 2004.
International Commission on Hydrocarbon Exploration and Seismicity in the Emilia-Romagna region (ICHESE): Report on the Hydrocarbon Exploration and Seismicity in Emilia Region, available at: http://mappegis.regione.emilia-romagna.it/gstatico/documenti/ICHESE/ICHESE_Report.pdf, last access: 11 December 2014, 213 pp., 2014.
Keranen, K. M., Savage, H. M., Abers, G. A. and Cochran, E. S.: Potentially induced earthquakes in Oklahoma, USA: links between wastewater injection and the 2011 M_w 5.7 earthquake sequence, Geology, 41, 699–702, 2013.
Mucciarelli, M.: Induced seismicity and related risk in Italy, Ingegneria Sismica, 30, 118–122, 2013.

Nardon, S., Marzorati, D., Bernasconi, A., Cornini, S., Gonfalini, M., Romano, A., and Terdich, P.: Fractured carbonate reservoir characterisation and modelling: a multisciplinary case study from the Cavone oil field, Italy, First Break, 9, 553–565, 1991.
Rovida, A., Camassi, R., Gasperini, P., and Stucchi, M. (Eds.): CPTI11, the 2011 version of the Parametric Catalogue of Italian Earthquakes, Milano, Bologna, available at: http://emidius.mi.ingv.it/CPTI/ (last access: 11 December 2014), 2011.
Scholz, C. H.: The Mechanics of Earthquakes and Faulting, 2nd Edn., May 2002, Cambridge University Press, 464 pp., 2002.
Toscani, G., Burrato, P., Di Bucci, D., Seno, S., and Valensise, G.: Plio-quaternary tectonic evolution of the northern Apennines thrust fronts (Bologna–Ferrara section, Italy): seismotectonic implications, It. J. Geosc., 128, 605–613, doi:10.3301/IJG.2009.128.2.605, 2009.
Vannoli, P., Burrato, P., and Valensise, G.: The seismotectonics of the Po Plain (northern Italy): tectonic diversity in a blind faulting domain, Pure Appl. Geophys., doi:10.1007/s00024-014-0873-0, in press, 2014.

NHESSD
2, 7507–7519, 2014

Earthquakes and depleted gas reservoirs: which comes first?

M. Mucciarelli et al.

Table 1. Summary of 4 ISSs (1–4) and 5 CSSs (a–e) used in this work (from DISS Working Group, 2010, and Vannoli et al., 2014).

Source #	DISS code	Associated earthquake	Assigned/ Max M_w	Fault length (km)	Fault width (km)	Min dep (km)	Max dep (km)	Fault dip (°)	Slip rate ($mm\,yr^{-1}$)
1	ITIS090	17 Nov 1570	5.5	5.1	4.0	1.4	4.5	50	0.1–0.5
2	ITIS141	19 Mar 1624	5.7	8.0	5.7	3.0	6.3	35	0.49–0.55
3	ITIS134	20 May 2012	6.1	10.0	6.4	4.0	8.4	43	0.25–0.50
4	ITIS107	29 May 2012	6.0	9.0	5.9	4.0	7.0	30	0.50–1.04
a	ITCS049	–	5.5	–	4.0	3.0	10.0	30–50	0.04–0.16
b	ITCS050	–	5.5	–	–	1.0	8.0	25–55	0.10–0.50
c	ITCS051	–	6.0	–	–	3.0	10.0	25–45	0.50–1.04
d	ITCS012	–	6.1	–	–	2.0	8.0	20–40	0.49–0.55
e	ITCS103	–	6.0	–	–	3.5	10.0	40–50	0.25–0.50

NHESSD
2, 7507–7519, 2014

Earthquakes and depleted gas reservoirs: which comes first?

M. Mucciarelli et al.

Table 2. Summary of the results. Wells falling within an ISS are counted also within the parent CSS.

Well groups	Productive	Sterile	Total	Success rate (%)
Study area (whole sample)	191	226	417	46
Outside SSs (background)	74	63	137	54
Within CSSs only	116	145	261	44
Within ISSs only	*1*	*18*	*19*	*5*

NHESSD
2, 7507–7519, 2014

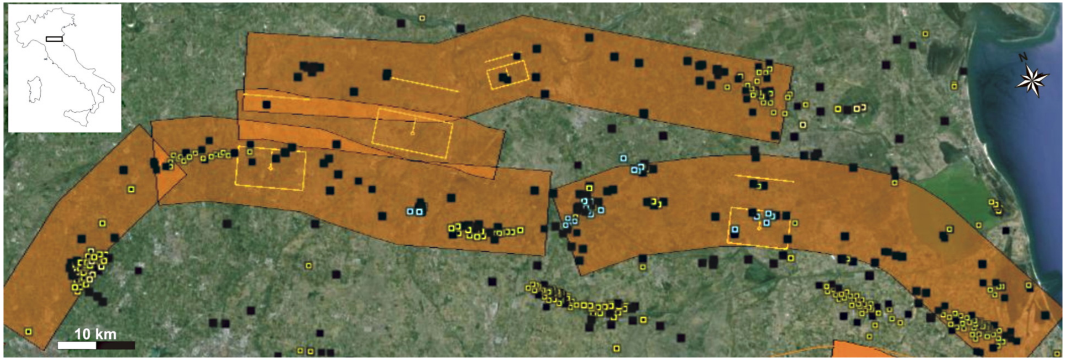

Figure 1. Our study area, showing the location of the 417 wells used for the analysis (listed in Supplement). Orange and yellow boxes are the surface projection of Composite Seismogenic Sources (CSS) and Individual Seismogenic Sources (ISS), respectively, all from DISS Working Group (2010) (see text and Table 1). The ISSs represent the sources of the four largest earthquakes that have occurred within the study area over the past five centuries: 29 May 2012 ($M_w = 6.1$), 20 May 2012 ($M_w = 6.0$), 11 November 1570 (Ferrara, $M_w = 5.5$) and 1624, and 19 March Argenta ($M_w = 5.7$), respectively from west to east. All faults are blind: their top and bottom depth fall in the range 1.4–4.0 and 4.5–10.0 km, respectively (see Table 1). The yellow line next to the box marks the fault cutoff, i.e. the surface projection of the fault plane. Black, yellow and cyan squares indicate Sterile, Productive and Ambiguous wells, respectively.

NHESSD
2, 7507–7519, 2014