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Earthquakes and depleted gas reservoirs: which comes first?

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Abstract. While scientists are paying increasing attention to the seismicity potentially induced by hydrocarbon exploitation, so far, little is known about the reverse problem, i.e. the impact of active faulting and earthquakes on hydrocarbon reservoirs. The 20 and 29 May 2012 earthquakes in Emilia, northern Italy (M_w 6.1 and 6.0), 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. We compared the location, depth and production history of 455 gas wells drilled along the Ferrara-Romagna arc, a large hydrocarbon reserve in the southeastern Po Plain (northern Italy), with the location of the inferred surface projection of the causative faults of the 2012 Emilia earthquakes and of two pre-instrumental damaging earthquakes. We found that these earthquake sources fall within a cluster of sterile wells, surrounded by productive wells at a few kilometres' distance. 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. To validate our hypothesis we performed two different statistical tests (binomial and Monte Carlo) on the relative distribution of productive and sterile wells, with respect to seismogenic faults. Our findings have important practical implications: (1) they may allow major seismogenic sources to be singled out within large active thrust systems; (2) they suggest that reservoirs hosted in smaller anticlines are more likely to be intact; and (3) they also suggest that in order to minimize the hazard of triggering significant earthquakes, all new gas storage facilities should use exploited reservoirs rather than sterile hydrocarbon traps or aquifers.

1 Introduction

Over the past few years, the potential for fluid withdrawal and injection to trigger earthquakes has fuelled 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), although this practice seems less likely to induce potentially 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 hydrocarbon 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 fields. For instance, Gartrell et al. (2004, and references therein) have discussed the role of fault intersections on the integrity of the hydrocarbon reservoirs. Their work focused on structural relationships but not specifically on the interaction between seismogenic faults and associated earthquakes on the one hand, and the integrity of hydrocarbon reservoirs on the other hand. This latter case is especially interesting in areas where large hydrocarbon reservoirs are hosted by growing anticlines driven by faults that extend to

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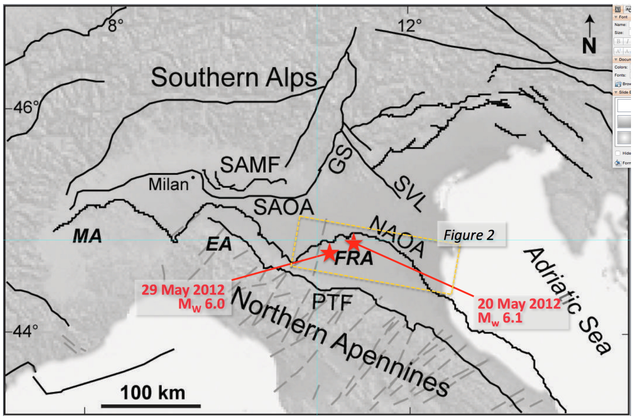

Figure 1. Simplified sketch of northern Italy, centred on the Po Plain and showing the southern Alps and Northern Apennines fold and thrust belts. The location of the largest shocks of the May 2012 Emilia earthquake sequence is shown with red stars. The yellow rectangle outlines the study area (see Fig. 2). Key: SAMF: southern Alps mountain front; SAOA: southern Alps outer arc; GS: Giudicarie system; SVL: Schio-Vicenza line; NAOA: Northern Apennines outer arcs; PTF: pede-Apennines thrust front; MA: Monferrato arc; EA: Emilia arc; FRA: Ferrara-Romagna arc. Modified from Vannoli et al. (2015).

seismogenic depth, a condition shared by many oil and gas fields worldwide.

The Po Plain is one such area (Fig. 1). The destructive May 2012 earthquakes occurred in a relatively small portion of this large, roughly east–west elongated alluvial plain extending for about 45 000 km^2 over much of northern Italy. The Po Plain conceals the front of two fold and thrust belts, the Northern Apennines to the south and the southern Alps to the north, and is actively contracting at rates ranging from 1 to 3 mm y^{-1}, respectively, from west to east (Devoti et al., 2011). Recent elaborations (Maesano et al., 2015) have shown that contraction is accommodated by a number of blind faults slipping at 0.1–1.0 mm y^{-1} over the past 1.8 My, several of which are large enough to generate M 5.5+ earthquakes (DISS Working Group, 2015; Vannoli et al., 2015).

Shortly after the May 2012 earthquakes, rumours began to circulate that they were somehow related to hydrocarbon exploitation. This hypothesis was unexpected by most scientists and professionals working in the oil industry as very few studies on induced seismicity have been carried out in Italy (Mucciarelli, 2013). The first paper dealing explicitly with the possible relationships between hydrocarbon exploitation and seismicity was written at the dawn of modern hydrocarbon exploitation in Italy (Caloi et al., 1956), and it has taken almost 60 years for a new paper on this subject to appear in the international literature (Stabile et al., 2014). As clearly shown by the lively debates following the May 2012 Emilia earthquakes, separating natural earthquakes from induced seismicity is crucial for the public acceptance of hydrocarbon exploration, exploitation and storage.

The Po Plain is punctuated by a number of gas fields as well as by a few oil and gas fields, all of which have been systematically and heavily exploited from the 1950s onwards (ENI, 1996; Casero, 2004). About 50 gas fields have been discovered within the Tertiary and Plio–Quaternary succession, whereas four oil fields have been found in Mesozoic carbonate sequences (ENI, 1996). The continuing evolution of the two major opposing orogens surrounding the Po Plain – the Alps to the north and to the west, the Apennines to the south – has created two characteristic fold and thrust belts – the former verging south to east, the latter verging north–north-east – which have been subsequently buried by thousands of metres of intervening sediments eroded from their highest levels (Bartolini et al., 1996; Carminati and Martinelli, 2002). The outermost thrust front of the Apennines chain is formed by three distinct arc-shaped fold systems: the Monferrato, Emilia and Ferrara-Romagna arcs from west to east, respectively (Toscani et al., 2009, and references therein). The 2012 earthquakes occurred along the Ferrara-Romagna arc, a north-east-verging stack of faults and folds overlain by a Plio–Quaternary succession several kilometres thick, that is mostly represented by syntectonic sedimentary wedges (Anzidei et al., 2012, and references therein; Bonini et al. 2014; Maesano et al. 2015; Vannoli et al., 2015).

The nature of the rocks being folded beneath the Po Plain and their structural setting is highly variable with depth. Based on a detailed analysis of the pattern of co-seismic slip associated with the 20–29 May 2012 Emilia earthquakes, Bonini et al. (2014) contended that "seismogenic ruptures were confined in the Mesozoic carbonates and were stopped by lithological changes and/or mechanical complexities of the fault planes, both along dip and along strike. Our findings highlight that along the active structures of the Po Plain slip tends to be seismogenic where faults are located in Mesozoic carbonate rocks...". Because Mesozoic carbonate rocks are not always encountered at the typical depth of major Po Plain faults (3–10 km), these results imply that many such faults have limited or no seismogenic potential. In the following section we discuss how these circumstances may affect the integrity of hydrocarbon traps.

2 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 Reggio Emilia to it eastern end near the Adriatic Sea (Fig. 2). To this end, we analysed all wells reported for the area in a large, public database made available by the project "Visibility of Petroleum Exploration Data in Italy" (ViDEPI) (http://www.videpi.com). Eight major gas fields have been discovered in Plio–Quaternary deposits of our study area, whereas three oil and gas fields have been found in the Mesozoic carbonate sequences (ENI, 1996; Casero, 2004). Hydrocarbon reservoirs lie within fault-driven anticlines that formed during the construction of the Apennines fold and thrust belt between the Miocene and the Upper Pliocene (ENI, 1996; Casero, 2004; Bertello et al., 2010; Casero and Bigi, 2013). 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 ViDEPI database includes the composite logs of 455 gas wells (see Appendix 1 for a full list). Their location is generally known with an accuracy of about 100 m. Non-geographic information (e.g. borehole depth, stratigraphy, presence or absence of hydrocarbon) is supplied by the drilling companies under the supervision of the relevant national authorities, and hence is sufficiently reliable for our scope.

The largest oil and gas field discovered in our study area is known as Cavone. It includes two main reservoirs in Lower Cretaceous calcareous breccias and fractured Liassic oolitic limestones (Nardon et al., 1991; Casero, 2004). It was based on the levels of extraction and re-injection from this field that ICHESE (2014) stated that a relationship between their exploitation and the occurrence of the May 2012 earthquakes could not be ruled out.

All gas and oil and gas fields in the study area 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 next to fully productive wells (Appendix 1). Since the stratigraphic setting of the whole study area is rather homogeneous, such irregularity in the distribution of productive/sterile wells is likely to result from differences in the evolution of each individual gas field.

We analysed all wells one by one to gather their fundamental parameters and verify their reliability. The wells were then subdivided into four categories (the number of wells falling in each category is shown in parentheses):

1. positively sterile, i.e. wells that have been drilled down to the prospective reservoir but encountered no exploitable hydrocarbons (227);

2. positively productive, i.e. wells that have been or are presently being exploited (190);

3. unexploited, i.e. exploration boreholes which revealed a gas/oil reservoir, but for which the VIDEPI database does not specify whether or not they ever went into production (12);

4. shallow, i.e. wells drilled in gas reservoirs lying above 500 m depth (26).

All wells were then plotted along with the surface projection of four Individual Seismogenic Sources (ISS) and five Composite Seismogenic Sources (CSS), inferred structures based on regional surface and subsurface geological data taken from the most recent version of the Italian DISS database (Fig. 2; Basili et al., 2008; DISS Working Group, 2015). 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. The DISS database has been recently updated with evidence from the 2012 Emilia earthquakes (Vannoli et al., 2015) 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 (in the specific case of the Po Plain, based on their inferred downdip width).

The ISSs we selected 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 (nos. 1, 2) and two belong to the 2012 sequence (nos. 3, 4). All CSSs and ISSs are necessarily affected by uncertainties concerning both their location and their parameters. For the scope of the present analysis we must focus specifically on the former, while the impact of the latter is less significant. The ISSs derived for the 2012 earthquakes may be affected by a horizontal uncertainty of a few kilometres in their size and absolute location, whereas the ISSs associated with historical earthquakes may exhibit an uncertainty in the order of 5 km, again both for size and location.

3 Data analysis

There may be several reasons why hydrocarbons do not accumulate in a natural reservoir. Perhaps 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, a circumstance confirmed by seismological practice. Thus, in a thrust-faulting environment, earthquakes of this size or larger 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 cap rock 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 potential reservoir formation

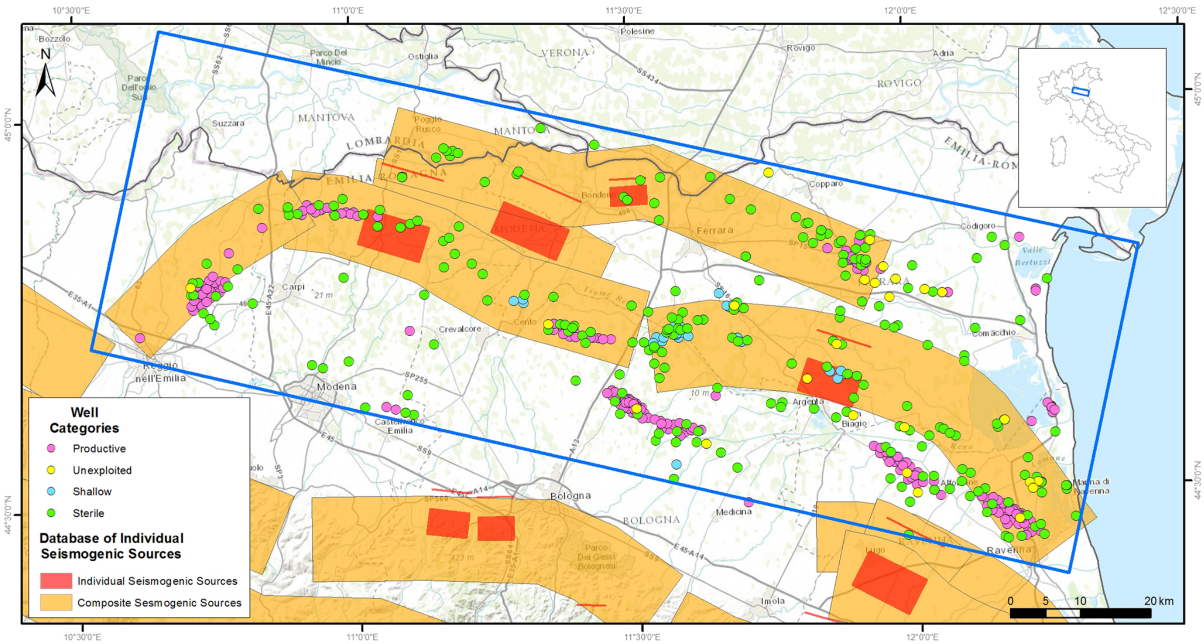

Figure 2. Our study area, showing the location of the 455 wells used for the analysis (listed in Appendix 1). Orange and red areas are the surface projection of Composite Seismogenic Sources (CSS) and Individual Seismogenic Sources (ISS), respectively, all from DISS Working Group (2015) and Vannoli et al. (2015) (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 ($M_W = 5.5$) and 19 March 1624 ($M_W = 5.7$) from west to east, respectively. All faults are blind: their top and bottom depths fall in the range of 1.4–4.0 and 4.5–10.0 km, respectively (see Table 1). The red line next to the box marks the geometrical intersection of the fault plane with the topographic surface. Green, magenta, yellow and cyan dots indicate positively sterile, positively productive, unexploited and shallow wells, respectively (see text).

Table 1. Summary of four ISSs (1–4) and five CSSs (a–e) used in this work (from DISS Working Group, 2015, and Vannoli et al., 2015; see Fig. 2).

Source no.	DISS code	Associated earthquake	Assigned/ max M_W	Fault length (km)	Fault width (km)	Min depth (km)	Max depth (km)	Fault dip (°)	Slip rate (mm y^{-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

may reflect the state of fracturing of the reservoir and of the cap rock, 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 shorter and narrower 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 behaviour and hence to larger earthquakes (Bonini et al., 2014).

To substantiate this scenario, we initially used a binomial test to see if the observed correlation between gas production and anticline/fault location and size is statistically significant (Table 2). As discussed in the following, binomial statistics may be affected by a spatial bias in the distribution of wells. Nevertheless, this type of statistics is the primary approach

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

Well groups	Productive	Sterile	Total	Success rate (%)
Study area (whole sample)	190	227	417	46
Outside SSs (background)	74	64	138	54
Within CSSs only	115	145	260	44
Within ISSs only	1	18	19	5

in many validation tests concerning seismicity patterns (e.g. Albarello and D'Amico, 2008).

Prior to running the test, we removed all wells from group no. 4; since we contend that in the seismotectonic context of the Po Plain, a typical M 5.5+ earthquake may cause sizable dislocation over faults lying between 3 and 10 km depth, we decided to disregard shallow reservoirs as they are likely to be insensitive to what happens at seismogenic depth. As for wells of group no. 3 (unexploited), since the available information does not allow us to assess how much gas was found, and hence if the relevant reservoirs can be considered to be intact, we decided to use them in a statistical test based on two different simulations; the first considering all wells of this group as productive, the second considering them all sterile.

Our binomial test shows that the highest success rate – i.e. the largest number of productive wells – 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. More importantly, our test shows that there is only one productive well out of 19 falling on the surface projection of the presumed causative fault of a M 5.5+ earthquake. According to the test, the probability of this result occurring by chance is < 0.01 %. Although all these figures may be affected by uncertainties in the location and size of the faults, the results are quite striking.

A possible limitation to the use of binomial statistics stems from the observation that productive and sterile wells may follow different spatial distributions: productive wells are expected to be more clustered than sterile wells because the probability of finding an exploitable well is highest next to a well that is already known to be productive. On the contrary, sterile wells tend to be more spread out as a result of subsequent attempts to intercept the main reservoirs. To address this circumstance we performed an alternative test based on a spatial analysis using a Monte Carlo simulation. Four boxes representing the four ISSs selected for our study were located at random over the study area. All boxes were assigned the average size of the typical Emilia-Romagna seismogenic faults, about 10 km × 5 km (Table 1). The exercise was repeated 10 000 times, and for each realization we sampled the content of the four boxes, counting the number of intercepted sterile and productive wells. All possible combinations of sterile and productive wells obtained from the simulations were then plotted in a two-dimensional histogram (Fig. 3).

We remark that the distribution of the results of our simulation highlights two distinct behaviours, which together lend additional statistical support to our hypotheses.

1. The distribution of the number of productive wells falling inside the fault boxes decays more slowly than the number of sterile wells for larger numbers of wells inside the same areas, supporting the assumption that productive wells tend to be more clustered. This implies that several productive wells are likely to enter a box that intercepts a productive field simultaneously, but also that there will be many realizations that intercept few of no productive wells.

2. The probability of having a large number of sterile wells and no or few productive wells inside the fault boxes is lower than the probability of having a large number of sterile wells and some or many productive wells. This is probably due to the fact that a substantial number of sterile wells can be found surrounding the more productive areas; most likely they result from the oil companies' attempts to probe the boundaries of the reservoir. Moreover, it is unlikely that many sterile wells are drilled close one to another, unless a seismic survey returned a subsoil image similar to a nearby productive reservoir. This means that the sterile tectonic traps look similar to the productive tectonic traps, but the fact that one is seismically active and the other is not makes the difference that forms the basis of our hypothesis.

As discussed earlier on, we ran the test twice to account for the uncertainty caused by the existence of unexploited wells; once assuming that the unexploited wells were all productive, and once assuming they were all sterile. The results obtained under these two assumptions differ slightly as there is only one unexploited well falling within a seismogenic source: counting it as productive or sterile changes our statistics from "18 sterile plus 2 productive" to "19 sterile plus 1 productive", respectively. Notice that neither of the two combinations (shown by red squares in Fig. 3) occurred over our 10 000 simulations.

4 Conclusions

Based on the analysis of the composite logs of 455 drillings taken from a government-supervised database, we explored the spatial distribution of productive and sterile wells over a large, earthquake-prone portion of the southern Po Plain. We found that the causative faults of the May 2012 earthquakes and the presumed sources of two pre-instrumental earthquakes fall within clusters of sterile wells surrounded by productive wells at a few kilometres' distance, a conclusion strongly supported by statistical tests. Since the geology

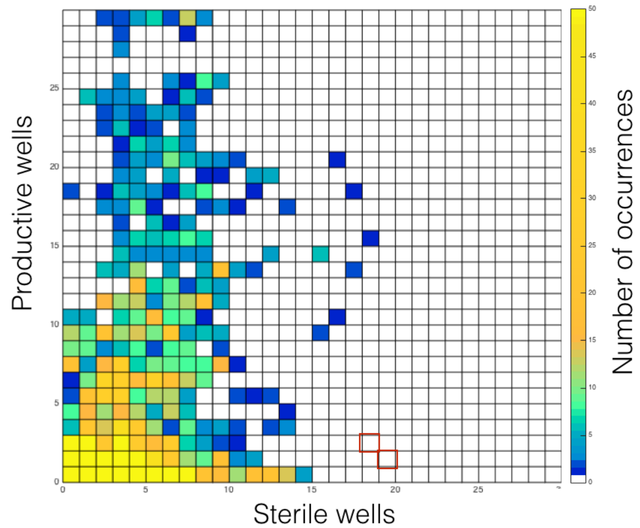

Figure 3. Bi-dimensional histogram showing the results of 10 000 simulations attempting to reproduce the observed combination of sterile/productive wells. This is obtained by randomizing the position of four faults comparable in size with the Emilia ISS. The red squares mark the two combinations obtained by changing the attribution category of unexploited wells from productive to sterile (see text for details).

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.

We wish to stress that the mechanism we advocate as being able to fracture the reservoir seals is not the shaking per se: in fact we contend that the shaking alone is unable to cause hydrocarbon leaks. We believe that what causes such leaks is the actual slip on faults underlying the reservoir, including the main seismogenic rupture plane and any significant splays that may occur above it. In our view earthquakes of M 5.5+ are large enough to (1) guarantee that the causative fault slipped by at least a few centimetres during the main shock, and (2) cause sizable dislocation along all faults, extending over a considerable thickness of the upper crust (e.g. from 8 to 3 km). Both these conditions increase the chances that the earthquake will create open gaps in the cap rock through which the gas may escape.

To summarize, we believe that what causes the gas leaks is not "fault-induced shaking of the reservoir" but rather "fault-induced finite dislocation of potential fluid pathways".

The observation that the productivity of a reservoir is anti-correlated with the presence of large seismogenic faults has at least three 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 a large seismogenic fault. Assuming that our reasoning is correct, the significant occurrence of productive wells within the composite seismogenic sources (115 productive vs. 145 sterile; see Table 2) would indicate that large portions of the CSSs are in fact unable to generate earthquakes that are large enough to threaten the integrity of the overlying reservoirs.

2. Reservoirs hosted in smaller anticlines are more likely to be intact than reservoirs created by larger folds as these are more likely to be driven by deeper and hence larger faults, which in turn are more likely to generate large earthquakes. In addition, the folding associated with larger faults is more likely to have involved deeper, older and usually more rigid rocks; in our study area these rocks correspond to Mesozoic limestones, which are considered to be especially prone to stick–slip behaviour, and hence able to generate significant earthquakes such as the 2012 Emilia earthquakes (Bonini et al., 2014).

3. Evans (2008) has shown that depleted gas reservoirs have produced a fraction of incidents at gas storage plants with respect to oil depleted fields and aquifers, and that most of such incidents in aquifer storage plants were caused by gas migrated to shallower levels due to the predicted cap rock not having been gas-tight or to faulting of the cap rock. 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 saline aquifers; an example of the latter option is the CH_4 storage facility that was planned in Rivara (ICHESE, 2014), right above the source of the 29 May 2012 earthquake (the facility was never completed). The 2013 earthquake sequence that took place off the coast of Spain at Vinaròs near Valencia (Cesca et al., 2014), culminating with a M 4.3 event on 2 October, supplied evidence of the hazard associated with using oil-only depleted reservoirs located next to a major active fault (see the eastern Amposta fault in the European Database of Seismogenic Faults, Basili et al., 2013: http://diss.rm.ingv.it/share-edsf/sharedata/SHHTML/ESCS115INF.html).

The southern portion of the Po Plain turned out to be an especially promising area for testing the impact of earthquake activity on hydrocarbon reservoirs. We are aware that our hypotheses should now be strengthened by extending the testing to other earthquake-prone gas and oil fields worldwide such as in California, North Africa and the Middle East; however, this requires that the relevant information is publicly available and that the location of the local seismogenic sources is known with at least the same accuracy as that available for Italian sources.

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