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Interactive comment on "Subsidence associated with oil extraction, measured from time-series analysis of Sentinel-1 data: case study of the Patos-Marinza oil field, Albania" *by* Marianne Métois et al.

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We would first like to thank reviewer 1 for his comments and suggestions related to our work on the subsidence of the Patos-Marinze oil field.

As noted by the reviewer, the main result of this paper is a map of LOS (i.e. nearly vertical) surface velocity based on an InSAR time series analysis of Sentinel-1 radar images acquired on the 2014-2018 time-span, that covers the entire Myzeqeja alluvial plain. This is the first InSAR study in this area. Our analysis focusses on a particularly

strong subsidence signal (>1.5 cm/yr) that happens to be concentrated on the northern part of the Patos-Marinza oil field where the oil extraction is currently the most intensely conducted. Our intention in this paper is to bring new and original observations of undocumented subsidence that may constitute a serious societal issue. Therefore, most of the paper is focused on the method used to obtained the LOS time-series, its description, analysis and modeling. We note that no criticism is formulated on the InSAR analysis or modeling by itself in the review, and we conclude that the characteristics of the subsiding signal that we document are not disputed.

On the other hand, the reviewer points that (i) surface deformation should be analyzed on other regional hydrocarbon fields, (ii) the oil field history is too briefly described and the deformation history too short, and (ii) Âń crude use of seismological catalogs unbalances the detailed technical analysis for the interferograms Âż. In the following, we address these concerns and propose substantial modifications to the current manuscript : we propose to add supplementary figures, modify fig.2 and 3, and develop section 2 in order to give a broader view of the context of the study. We will clarify the discussion section and make clear that our conclusions point toward an induced subsidence that is most probably recent and does not extend in time, at least at the present-day rate. We will also clarify the fact that because of the sparseness of the seismic catalogs and of the too recent seismological networks available for the area, we do not claim to conclude on whether induced seismicity did occur in response to oil extraction, but we note that this assertion cannot be disproved either. Again the originality of our study is to map and quantify a previously unknown rapid subsidence over the largest oil field of Albania, that remains poorly studied in the literature.

1 Surface deformation over other regional hydrocarbon fields

As stated in the main text, external Albanides host many active oil and gas fields that are roughly represented in Fig.1. Before focusing on the high subsidence pattern observed in the interferograms in the Patos Marinza area, we indeed had a look at the surface deformation in all other oil and gas fields.

As evidenced in figures 1 and 2 of this answer, no comparable motion could be observed in the other oil or gas fields in the area. In particular, the strong subsidence (1 cm/yr) observed west of the Balla-Divjaka gas field and noted by the reviewer is not related to oil extraction near Divjaka but we interpret it as associated with the Skumbini delta subsidence (we will make this clearer in the new version of the manuscript). This interpretation is consistent with the fact that this large subsidence pattern is distant by more than 5 km from the gas field itself, and with the description of major reorganization of the deltaic system there (Ciavola and Simeoni, 1995; Ciavola, 1999; Bedini, 2007). We reckon that this useful information is currently lacking in the manuscript and could be added either by incorporating one of the attached figures to Fig.4 or to add both figures as supplementary information.

We agree with the reviewer's statement that subsidence and induced seismicity are usually more often observed above gas fields than above oil fields, because the pressure jumps at depth are larger and because of increased compressibility of the fluids. However, since we do not observe any clear sign of subsidence in the albanian gas fields, nor in the other active oil fields, the Patos-Marinze context may be unique. We recognize that, at this stage, we have no explanation for this apparent peculiarity of the Patos oil field (an hypothesis is that both oil and gas are extracted there, see section 2 below).

We propose to add in the context and discussion parts a brief description of the other oil and gas fields and to make clearer that only the Patos-Marinza filed is affected by significant ground deformation.

2 Oil extraction and deformation history

"From another perspective, the comparison of seismicity and deformation with long term production history is missing. The current 15mm/yr subsidence should drive a more than one-meter subsidence in the past 80 years if sustainable over time. Another possible change point may be used as before-after 2009 when Enhanced Oil Recovery processes started. The one-meter subsidence in the past 80 years should be evidenced locally independent from any detailed instrumental subsidence survey. It will put in context if the current subsidence rate was stable over time or if there is an increase in the recent deformation relatively to past subsidence. These deformation patterns (steady-state or not) are critical parameters for forecasting the future deformation of the area."

We agree with the reviewer that, since the oil field has been operated for decades, it would be very interesting to look at surface deformation on a time-frame longer that what we currently propose in the paper, which represents only a recent snapshot of ground deformation (i.e. LOS velocities on the 2014-2018 time span), highlighting significant localized subsidence.

However, if a leveling network exists in Albania since 1860 and has been densified, remeasured and upgraded since then, we do not have access to the data (see http://asig.gov.al/images/Relacioni%20permbledhes.pdf or Nikolli Idrizi, 2011). One easiest way to go back further in time and better constrain the history, and thus the controlling parameters of the observed subsidence, would be to process older InSAR data sets such as ALOS images that are available for the 2006-2011 period, or the older ERS-Envisat archive from 1991 to 2011. This will indeed be done in the coming years but requires a huge processing work and is beyond the scope of this study. Nevertheless, we believe that our study may be commended for documenting for the first time this recent and significant subsidence spot.

This being said, we can imagine some speculative scenarios on the possible evolution of the subsidence history in the area, based on the scarce but existing knowledge of the oil production history. The current version of the paper (from line 21 p.4 to line 4 p.6) proposes a brief overview of the oil production history based on the available references [Weatherhill, 2005, and Bankers Corporative Reports, 2010, 2015]. We agree that this description could be refined and more detailed, and we will do so in the next version of the manuscript.

In particular, we should indeed underline the fact that the Patos-Marinza field has been indeed producing oil and gas simultaneously for many years, before oil production became largely dominant. As pointed out by the reviewer, gas extraction usually goes together with larger pressure drops in the reservoirs in comparison with oil extraction. We could therefore expect that, if surface subsidence is indeed caused by reservoir compaction as we do suggest, it may have been significant from 1958 to $\sim$1963 during the maximum gas production period (see figure 3 of this answer). This point will be added to the manuscript and we will discuss an hypothesis that we have previously discarded : that the localized subsidence seen in the northern part of the Patos-Marinze oil field could be associated with local gas extraction that is still ongoing (we recall that there was a gas leakage in 2015 in the zone).

Second, the Patos-Marinze field is composed of numerous reservoirs. In the main text, we focus on the soft siliclastic shallow reservoirs of the Driza, Gorani and Marinza suites that appear to be currently the most intensely operated, though limestone reservoirs have also been, and are still, operated. Obviously, compaction would be higher in the siliclastic reservoirs than in limestones.

Finally, as shown in figure 3 of this answer that corresponds to an enlarged view of figure 3b of the main text, the production history of the oil field is complex and unsteady. In particular, after the primary recovery period, the production dropped in the 90's and nearly stopped in 1999. If our hypothesis of extraction-induced compaction is valid, we doubt that the subsidence rate observed on the 2014-2018 time span could have remained stable for 80 years. We agree that this discussion is of interest for the readers

and propose to : - provide in the text a more exhaustive history of the oil field production based on the available literature (it is to note that the bibliography on the area is scarce), - extend the time span of figure 3b so that the entire production history could be visible (figure 3 of this answer).

"In several places in the manuscript (including the abstract) the authors point on the subsidence bowl to be centered above the area where horizontal production wells are located. There is neither discussion nor reference to support why horizontal production wells should increase the subsidence. We can find in existing reports (not cited in the manuscript) a one order magnitude change in production rate on that period. Such a more quantitative information should be discussed in the context of subsidence rate change over time."

Again, we would like to point out that very little bibliography is available on this particular oil field, and on the Myzeqeja plain in general. This is also the reason why we believe our original study could be of interest for a broad audience. If a reference is missing, we would be glad to read it and include it in the bibliography section. We have based our description of the oil field structure on the reports available on the Banker's company web site (Bankers report 2010, 2015) that helped us to indicate on Fig.3a of the main text three subzones of the field where different extraction techniques have been used since 2009. We agree with the reviewer that describing the area of maximal subsidence only as hosting horizontal wells may cause confusion and could suggest a relationship between horizontal wells and subsidence that is not supported by the observations. This area, plotted in green in Fig.3a and in bold black in others, also coincides with the highest density of wells observed from satellite images. Waterflooding recovery technique is also used there (Bankers reports). We think that the spatial relationship between the subsidence peak and this intensely operated area is an important observation that sheds some light on the causal link between both phenomena. Because we do not have access to individual well location and production history, we are not able to conclude on whether the subsidence could be associated with the extraction technique by itself or with the volume of extracted fluid only.

As already said, we will provide a longer version of figure 3b yet showing the production evolution in BOPD for 1990 to present. As stated in the text, oil production is steadily and rapidly increasing since 2009.

"Also, it appears there are problems with how the oil reservoirs are described in the paper (100m-2 km depth) when the available literature points on "Measured drilling depths are typically 2,500 meters, with 500- to 700-meter horizontal legs." (e.g., Mazerov, 2011). Also, Weatherill et al. (2005) report on "The two separate fields (Patos in the south and Marinza in the north) have productive sands at different depths, i.e., 0 - 1200 m for Patos and 1200 - 1800 m for MA". These differences are not discussed in the manuscript."

Some discrepancies in the depth of the reservoirs indeed exists in the literature, mainly due to the fact that these formations are gently dipping north ($\sim 10°$) away from the eroded anticline trap located in the "core" zone of the field, close to the area of maximum subsidence. The papers cited in the main text (Silo et al., 2013; Prifti and Muska, 2013) are consistent with the informations given in the Bankers Corporate Presentation (2015) stating that well's depth varies from 300 to 2000m, or in Weatherhill (2015) "The productive sands under cold production occur across a gross interval of 250 m at a depth range of from 875 to over 2000 m." The cross section provided in Sejdini et al. Fig.9 also confirms this range of depth. It appears that in average, in the intensely operated area, wells are $\sim$1500m depth. However, we reckon that the caption of Figure 2d is misleading. We will clarify the vertical scale of this cross section and complete the description of the oil field in the text.

The terminology used to describe the oil field by itself depends on the author. Though, in general, as stated by the reviewer, one distinguishes two distinct parts in the Patos Marinza field : the Marinza part North of 40.7°N roughly, and the Patos one south of 40.7°N. The Banker's development plan since 2009 has mainly focused on the Marinza

zone. This is why we chose to focus on it on Figure 3a of the main text and explain why the oil field contour is different from previous figures where the entire oil field is shown (that should also answer to one reviewer comment just below).

"Hydrocarbon field locations and numbers for other nearby oil-gas reservoirs do not overlap with other existing maps (e.g., Mezini and Musai, 2012, Velaj SPE, 2015)."

We will add numbers referring to names of the main fields represented in Fig.1. This map is consistent with the one published by Velaj et al. 1999 (fig.2 "Thrust Tectonics and the Role of Evaporites in the Ionian Zone of the Albanides").

3 crude use of seismological catalogs unbalances the detailed technical analysis for the interferograms

"The well-constrained technical results for subsidence are discussed against poor seismicity and production history and without the proper fluid manipulation context, concerning the cited literature (most cited references relate to seismicity driven by wastewater disposal which is not the case in the submitted manuscript). The lack of production information and the misused of seismicity catalogs weaken the central message of the manuscript. Most of the discussions on the possible anthropogenic seismicity are flawed in several ways."

As pointed out by the reviewer, the core of this study is the detection, quantification and modeling of the surface subsidence in the basin and above the oil field in particular. As stated in the manuscript, the seismic catalogs available in the area do not provide sufficient historical records nor register small enough magnitude to conclude on a possible induced seismicity in the last years. We reckon that some sentences of the main text are misleading and may appear too affirmative and that some complementary analysis can be done on the seismic catalogs to assess most of the reviewer's remarks. However, we would like to stress the fact that this paper has no ambition to be a seismological study and rather brings new and independent InSAR observations of the ongoing ground deformation over the oil field.

"First, there is no information on how the regional earthquake catalog is built on or selected by merging existing catalogs (USGS and EMSC)."

In Fig.3 caption, the sentence : "Seismic events since 1950 are color-coded based on their occurrence time and sized depending on their magnitude (CSEM-EMSC; USGS, before and after 2004, respectively)." is wrong. It should be corrected to state that we use USGS catalog for the period pre-2004, and CSEM-EMSC catalog after 2004. We choose to use the more complete EMSC catalog for most recent seismicity since event location is often more precise than USGS for Europe, and its completion magnitude is lower (see above). However, no further data selection has been done.

"Second, the lack of threshold values (i) for selecting an earthquake at a given distance from the reservoir to be a triggered event or a tectonic event and (ii) for a magnitude completeness value over time, prevent any robust analysis of space-time seismicity patterns."

If we reckon that interpreting the increase of seismicity plotted in Fig.3b for the area requires a more thourough analysis of the completeness magnitude and of the regional seismic rate over a longer time-span (see following answers), we fear there may be a misunderstanding : we have no ambition to say whether an event is triggered or not, nor are we claiming to distinguish the triggered events in the main text. Nonetheless, the fact that seismic events in the last years have increased the population questioning about a potential impact of the oil extraction on its environment should not be ignored. Accordingly, this question would deserve a more specific investigation in the future.

Fig.3b (that is discussed by the reviewer) shows only a plot of cumulative moment over time on the restricted area ranging from 19.6 to 19.7°E and from 40.65 to 40.8°N. We previously chose this area as the most restrictive encompassing the oil field, and as suggested by the reviewer, we agree that we should compare this rate with the seismic

rate observed elsewhere and over a longer time-span. Nevertheless, our point is not to conclude on the induced or natural nature of the recorded seismicity.

We propose to clarify our reasoning in the revised version of the paper, based on the following arguments :

- We combine both USGS and EMSC catalogs to make a brief analysis of the regional and local seismicity in order to keep a magnitude completeness around 3.5 for the 1990-2019 time span (see figure 4 of this answer that will be added as supplementary figure in the revised version)

- We will discuss more carefully the history of both production and regional seismicity based on figure 5 of this answer. We calculate the cumulative moment released since 1939 (start of the Patos-Marinza oil field operation) by moderate earthquakes (Mw 3 to 6) on circular areas of 50 km and 15 km around the center of the oil field, taken as the maximum subsidence point (19.6492°E, 40.7395°N). The 50 km radius area encompasses the whole Myzeqeja plain and therefore remains n the same tectonic context. Before 1976, these curves have to be taken with caution since the completeness magnitude was around 4 to 5 (see figure 4 of this answer). On the long term on the large 50 km-wide area, no correlation appears between the production rate and the released seismic moment and no significant increase in the seismic moment rate is observed in the past years.

- In order to better understand the recent history of the oil field, we propose a new version of figure 3 of the submitted version of the manuscript presented in figure 6 of this answer. In figure 6a, the Mw 3.5+ 2013 earthquakes that stirred concern among the local population are contoured in bold black so that they could be easily identified. All of them are within 10 km from the oil field contour presented in this figure. Figure 6b has been enlarged in time (1990-2019) and the cumulative moment curve is now calculated over 15 km radial distance from the center of the oil field (see above). The 1997 Mw 4.8 event that did not appear on the previous version of this figure is now associated to a clear jump in the released moment curve. On this time-span, the cumulative moment rate seems to increase after 2009, though, as pointed out by the reviewer and illustrated in figure 5 of this answer, this apparent change in moment release rate is not significant based on the longer term evolution.

- Finally, we will complete the bibliography with the references suggested by the reviewer that are focused on oil-field induced seismicity.

Fig.1 : LOS velocity map (ascending track) together with the main known faults and the location of major oil and gas fields (with names indicated in small capital letters). The fields contours have been extracted from the IHS map of Albanian ressources of february 2001. The contour of the Patos-Marinza oil field is larger than the one plotted in figures 1 to 6 of the main text, that has been extracted from a more recent reference [Bankers corporate presentation 2015].

Fig.2 : Same as figure 1 for descending track.

Fig.3 : History of production of oil (plain line in BOPD) and gas (ticked line, in BOED) in the Patos-Marinza field (BKC, 2015).

Fig.4 : Test of the Gutemberg-Richter relationship over the southern Balkans area (top) and Albania (bottom) for different time-spans and catalogs. Inset map in the top right corner of the graphs shows the region over which the seismicity is considered. Since 1990, the completeness magnitude can be safely estimated between 3 and 3.5. Interestingly, EMSC catalog is much more complete than USGS catalog for Albania on the 2004-2018 time span.

Fig.5 : a- History of production of oil (plain line in BOPD) and gas (ticked line, in BOED) in the Patos-Marinza field (BKC, 2015). b- Cumulative seismic moment released since 1939 based on the combined USGS-EMSC catalog over a 50 km radius area around the oil field (plain line) and a 15 km radius area around the oil field (dashed line).

Fig.6 : a- Same caption as figure 3 of the submitted version except that Mw 3.5+ 2013

earthquakes referred in the text are contoured in bold black together with the Mw 4+ 2016 earthquake. b- Zoom on the 1990-2019 cumulative seismic moment released in a 15 km radius area around the oil field center (black) together with the oil-field production evolution (purple).

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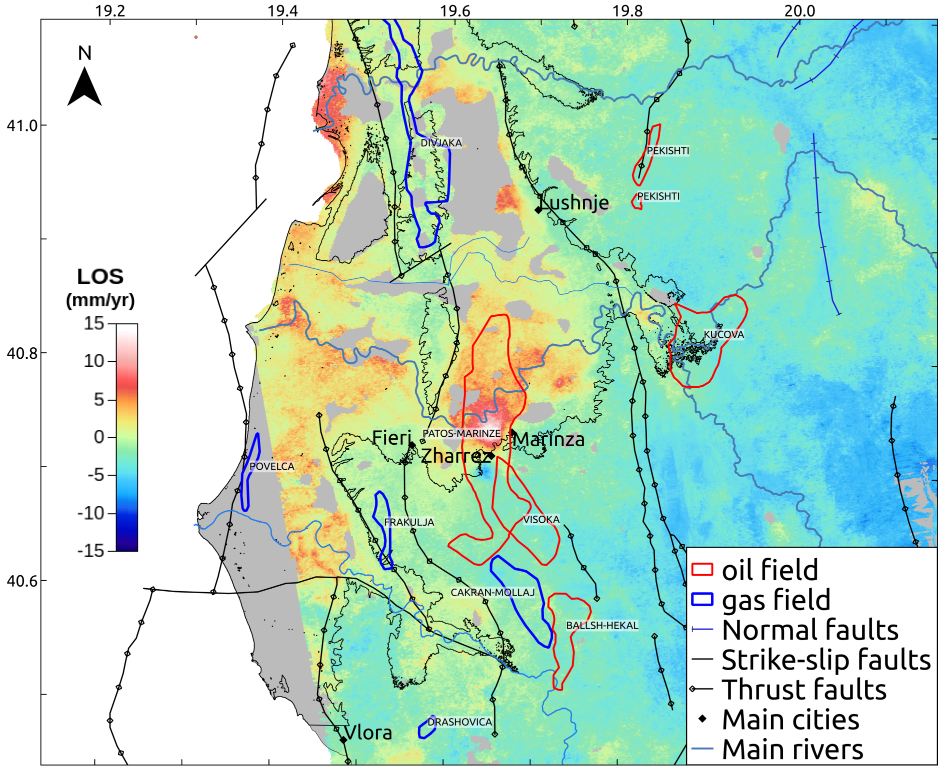
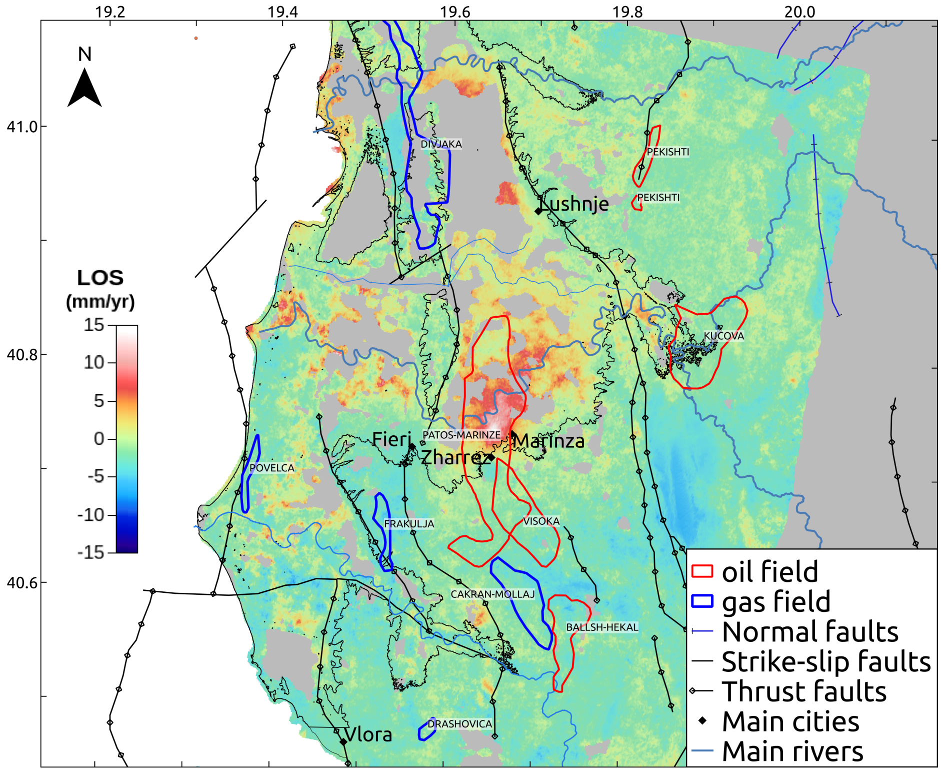

19.2
19.4
19.6
19.8
20.0
41.0
40.8
40.6
N
LOS
(mm/yr)
15
10
5
0
-5
-10
-15
DIVJAKA
PEKISHTI
PEKISHTI
Lushnje
KUCOVA
Fieri
PATOS-MARINZE
Marinza
Zharrez
POVELCA
FRAKULJA
VISOKA
CAKRAN-MOLLAJ
BALLSH-HEKAL
DRASHOVICA
Vlora
oil field
gas field
Normal faults
Strike-slip faults
Thrust faults
Main cities
Main rivers

Fig. 1.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15
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DIVJAKA
PEKISHTI
PEKISHTI
Lushnje
KUCOVA
Fieri
PATOS-MARINZE
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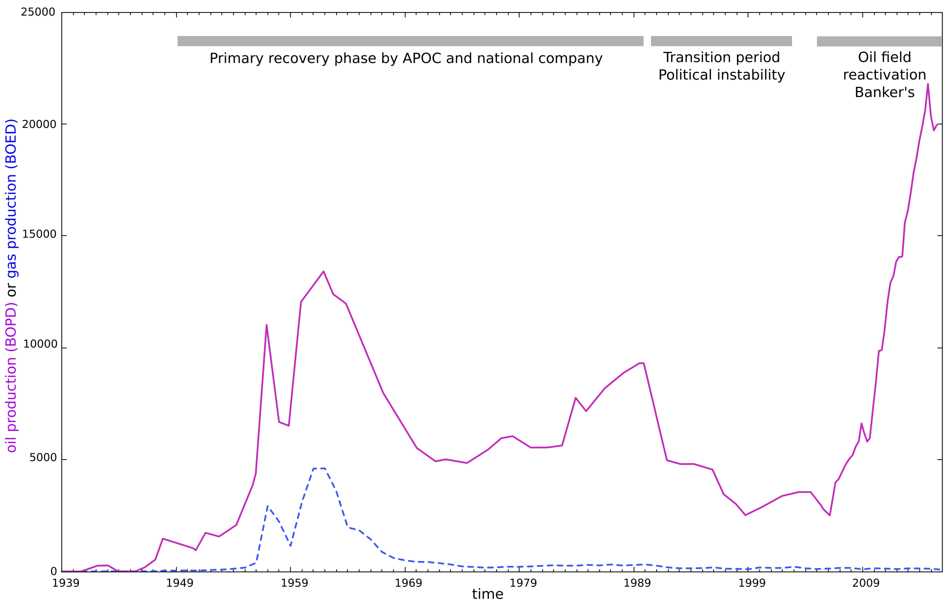
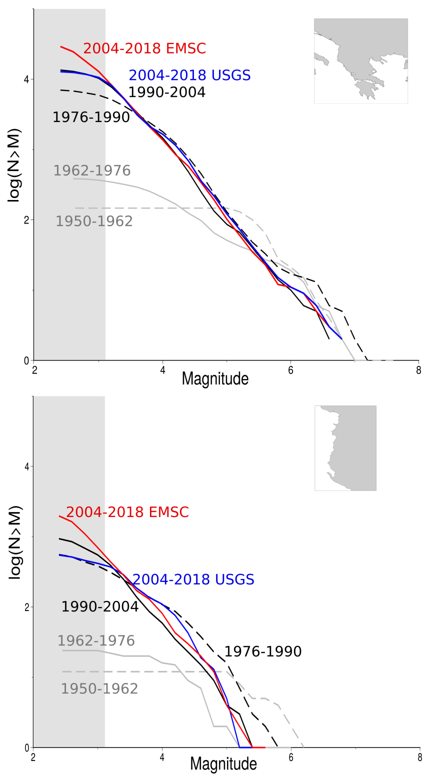
Fig. 2.



oil production (BOPD) or gas production (BOED)
time
Primary recovery phase by APOC and national company
Transition period
Political instability
Oil field
reactivation
Banker's

Fig. 3.



2004-2018 EMSC
2004-2018 USGS
1990-2004
1976-1990
1962-1976
1950-1962
log(N>M)
Magnitude

Fig. 4.

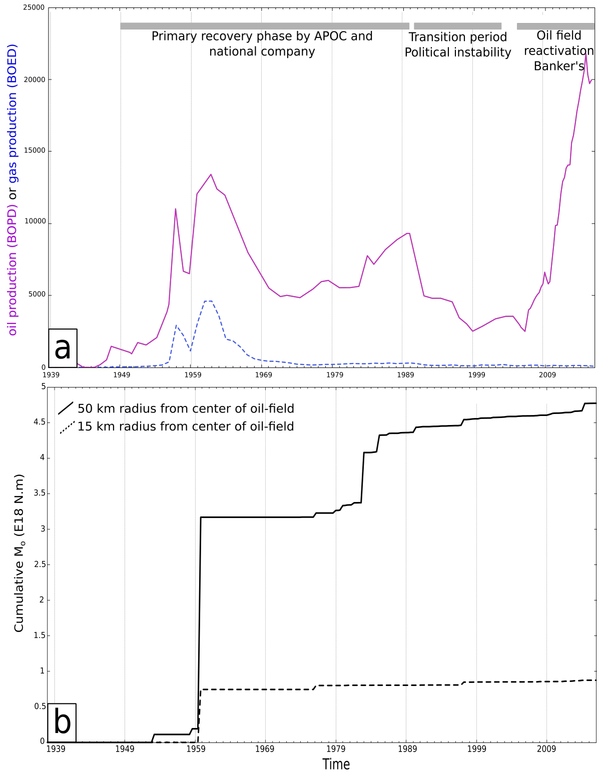

Primary recovery phase by APOC and national company
Transition period Political instability
Oil field reactivation Banker's
oil production (BOPD) or gas production (BOED)
a
50 km radius from center of oil-field
15 km radius from center of oil-field
Cumulative M_0 (E18 N.m)
b
Time

Fig. 5.

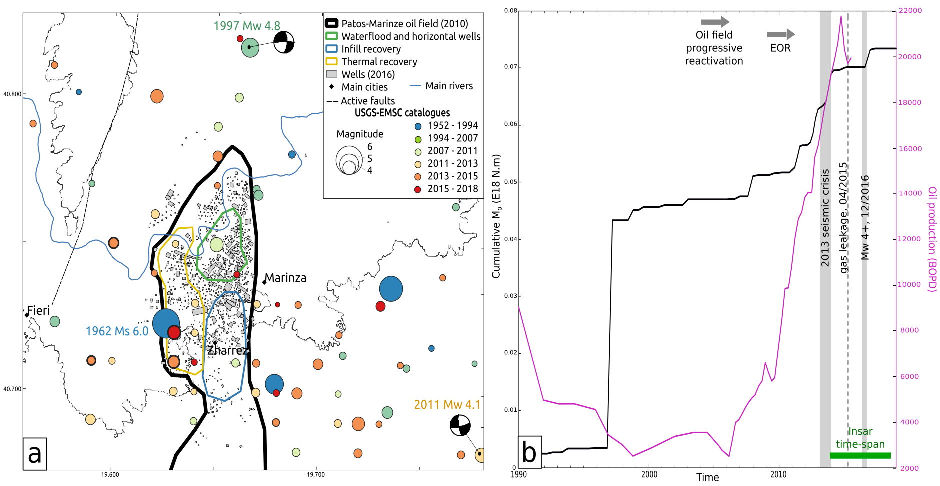

Patos-Marinze oil field (2010)
Waterflood and horizontal wells
Infill recovery
Thermal recovery
Wells (2016)
Main cities
Main rivers
Active faults
USGS-EMSC catalogues
Magnitude
1952 - 1994
1994 - 2007
2007 - 2011
2011 - 2013
2013 - 2015
2015 - 2018
1997 Mw 4.8
1962 Ms 6.0
2011 Mw 4.1
Marinza
Fieri
Zharrez
a
Oil field progressive reactivation
EOR
2013 seismic crisis
gas leakage, 04/2015
Mw 4+, 12/2016
Insar time-span
Cumulative M_0 (E18 N.m)
Oil production (BOPD)
Time
b

Fig. 6.