ORIGINAL ARTICLE
DOI: https://doi.org/10.18599/grs.2021.4.6 Russian Original 2021. Vol. 23. Is. 4. Pp. 51–57

Seismicity and development of Romashkino hydrocarbon field's Almetyevskaya area

I.N. Ognev, A.I. Stepanov*
Kazan Federal University, Kazan, Russian Federation

Abstract. The relationship between the various human activities and seismic activity has become more evident in the last several decades. One of the important domains where such a relationship manifests itself is hydrocarbon fields' development. South East Tatarstan (Russia) is a region where the link between seismicity and the development of the giant Romashkino hydrocarbon field has been established. The goal of the current study is to conduct the causative analysis between the seismic activity and the development of the Romashkino hydrocarbon field's Almetyevskaya area which is located in the most seismically active zone of the south-eastern Tatarstan.

Keywords: seismicity, hydrocarbon field development, induced seismicity, Romashkino oilfield

Recommended citation: Ognev I.N., Stepanov A.I. (2021). Seismicity and development of Romashkino hydrocarbon field's Almetyevskaya area. *Georesursy = Georesources*, 23(4), pp. 51–57. DOI: https://doi.org/10.18599/grs.2021.4.6

Introduction

Seismic activity in regions with actively developing hydrocarbon reservoirs is a phenomenon that has been actively studied over the past few decades (Ellsworth, 2013; Grasso, 1992; Suckale 2009). Most often we are talking about the so-called induced seismicity or seismicity caused by the impact on the reservoir, accompanied by the production and injection of fluids. At the same time, some studies investigate the possibility of an inverse relationship, when increased seismicity is not a consequence, but a cause of changes in the processes of hydrocarbon reservoirs development (Adushkin et al., 2000; Ognev et al., 2020).

The purpose of this research is to study the relationship between seismic activity and the development parameters of the Almetyevskaya area of the unique Romashkino hydrocarbon field with the determination of the cause-and-effect relationships of changes in seismic activity and development parameters of the Almetyevskaya area.

Data and method

The study area is located in South East Tatarstan – a region that, like the entire East European platform, is rather inactive in terms of its seismicity (Khisamov et al., 2012; Mirzoev et al., 2004). Nevertheless, since the 1980s, a local network of seismic observation stations operated by PJSC TATNEFT began to function and record seismic events on the territory of this region. This study uses a sample of seismic events recorded by PJSC TATNEFT in South East Tatarstan for 1996–2020 (Fig. 1).

The current research workflow consists of the following sequence of operations:

Analysis of the seismic events' catalog to determine the magnitude of completeness.

Calculation of the integral characteristics of the region's seismic activity and its averaging.

Averaging the selected development parameters of the Romashkino oil field's Almetyevskaya area.

Analysis of the relationship between the seismic activity of the region and the selected development parameters. Determination of the probable causal relationship between seismic activity and the studied parameters.

Description and analysis of seismic catalog

The seismic catalog is one of the seismic monitoring results, providing information on the chronological order of earthquakes, their epicenters coordinates, depths of hypocenters, and energy classes of earthquakes.

This study uses a catalog of local earthquakes recorded by the seismic network of PJSC TATNEFT in South East Tatarstan for 1996–2020. At the time of analysis, this catalog included 393 local earthquakes with magnitudes from -2.5 to 3.9. The main peaks of seismic activity were observed in the second half of the 1990s and 2018 (Ognev et al., 2020). Localization of hypocenters in depth corresponds to the normal law with

*Corresponding author: Igor N. Ognev
E-mail: ognev.igor94@gmail.com

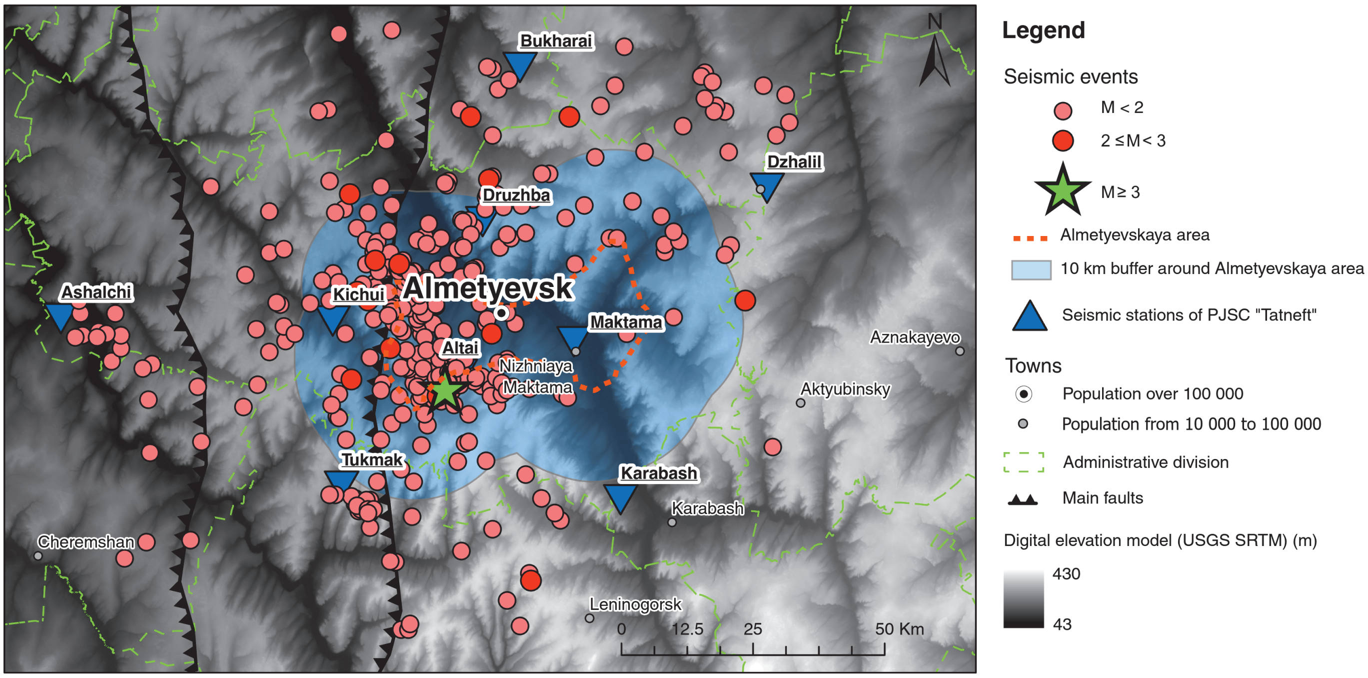

Fig. 1. Map of seismic events in the South East Tatarstan for the period of 1996–2020

most seismic events occurring in the upper part of the crust at a depth of 2-3 km. The distribution of earthquake epicenters also cannot be called uniform. Most of the earthquakes occur in the western part of the Romashkino and central part of the Novo-Elkhovskoye fields and have a submeridional strike parallel to the Altun-Shunak trough. As noted by Khisamov et al. (2012), this tendency is observed precisely for the earthquakes with hypocenters located at depths of 0–8 km, which can be caused by both technogenic and tectonic reasons. The deeper exclusively tectonic earthquakes are evenly distributed over the area without a visible geographical connection with the boundaries of large hydrocarbon deposits (Khisamov et al., 2012).

As one can see, the total number of seismic events in the territory is not large. At the same time, not all the available seismic events are representative and can be used in further analysis of the seismic activity. The first step in analyzing the seismicity of a territory is to assess the quality of the seismic catalog for the studied region, which consists of determining the catalog's magnitude of completeness M_c. The magnitude of completeness corresponds to the minimum magnitude of seismic events at which they are recorded by a given seismic network of observations with a probability of 100 % (Rydelek, Sacks, 1989).

In order to determine the studied catalog's magnitude of completeness, we applied the maximum curvature method (MAXC) (Wiemer, Wyss, 2000) by calculating the maximum value of the first derivative of the cumulative frequency-magnitude distribution (FDM) plot (Fig. 2).

After determining M_c, we calculated the value of the slope coefficient (b-value) using the maximum likelihood technique (Aki, 1965; Mignan, Woessner, 2012):

$$b = \frac{\log_{10}(e)}{\langle M \rangle - \left(M_C - \frac{\Delta M}{2}\right)} \qquad (1)$$

where $<M>$ – the average magnitude of earthquakes from the analyzed catalog with magnitude $\geq M_c$; ΔM – binning width.

In this study, we used the ZMAP seismic event analysis software for the calculations (Wiemer, 2001). The binning width was taken as 0.3. To increase the statistical accuracy of the calculation, the bootstrapping method was used with the number of resampling steps equal to 10 000.

As a result, we obtained the magnitude of completeness of M_c =1.0 and the b-value of b = 0.63±0.13. The resulting value of the slope coefficient turned out to be significantly less than the values of 1.02-1.3 determined earlier in (Adushkin et al., 2000), which may indicate a decrease in the share of technogenic seismicity in the territory of South East Tatarstan from 1980 to 2020.

Thus, for further analysis, we used 166 seismic events with $M_c \geq 1$ out of the original 393 events recorded for the period from 1996 to 2020.

Calculation of seismic activity's integral characteristic

After the seismic catalog processing and excluding all seismic events with a magnitude of less than 1 on the Richter scale, we calculated the integral characteristic of the region's seismic activity. In this case, we used the sum of cubic roots from the energy of earthquakes that occurred during 1 month period as such a characteristic, by analogy with the study of Aduskin et al. (2000). The energy of an earthquake depends on its energy class

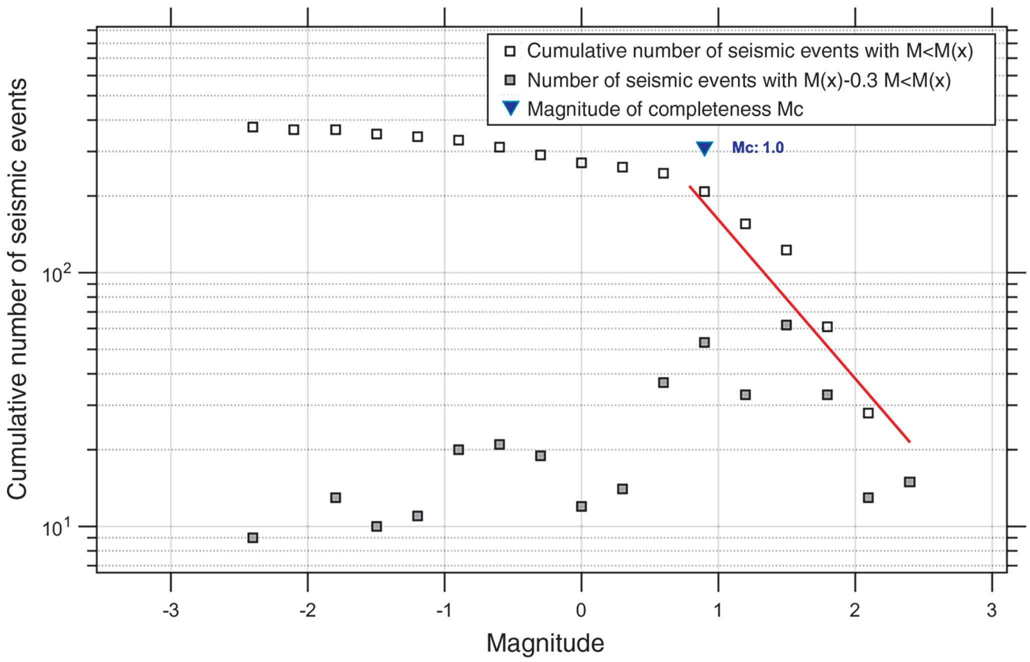

Fig. 2. Cumulative frequency-magnitude distribution plot for the earthquakes of the South East Tatarstan occurred in the period from 1996 to 2020

according to the following formula (Rautian et al., 2007):

$$K = log_{10}E\ (in\ Joules) \quad (2)$$

For a smoother result, we averaged the energies of earthquakes occurring over 1 month by a 12 months' moving average window. The obtained result was normalized to the average value of seismic activity for the entire measurement period.

When assessing the integral characteristics of seismic activity, we have taken into account only those seismic events, the location of which was within a 10-km zone from the contour of the Almetyevskaya area (Fig. 1). This has been done to exclude remote seismicity from the analysis.

The final graph of changes in the seismicity of the studied region is shown in Figure 3.

As one can see from Figure 3, there are two peaks with increased seismic activity separated in time by 12.5 years – in 1996 and 2008. It should also be considered that in the period from 2006 to 2008 the local seismic network did not function, and therefore, zero seismicity was shown during this period.

Analysis of the relationship between region's seismic activity and Almetyevskaya area's development parameters

The next step was to determine the relationship between seismic activity and the development parameters of the Almetyevskaya area. This relationship was determined through correlation analysis of the integral characteristics of seismic activity with individual

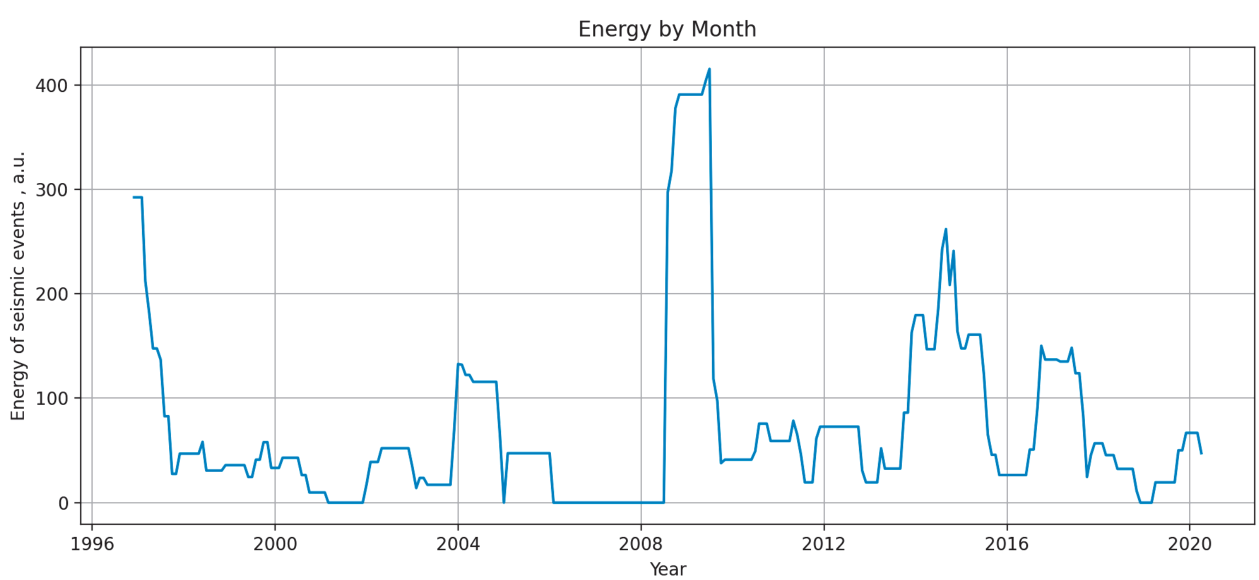

Fig. 3. Change in the seismic activity of the studied region for the period from 1996 to 2020

development parameters. The analyzed parameters included the number of active injectors, number of active producers, injection efficiency, disbalance, water cut, average oil production, average liquid production, oil production, liquid production, water injection, and bottomhole pressure.

It is important to determine not only the presence of such a relationship, but also to find out its causality, i.e. to answer the question: Which development parameters change under the influence of seismic activity variations and, conversely, a change in which development parameters itself leads to seismicity activation? To find a proper answer, it is necessary to calculate the correlation coefficients of seismic activity and selected development parameters, provided that seismic activity and development parameters are shifted relative to each other in time. As a result, if we shift seismic activity forward in time relative to variations of a certain development parameter and then get an increase in the value of the correlation coefficient, then it is more likely that the change in seismic activity entailed a change in the analyzed development parameter. Conversely, when we have an increase in the correlation in the case of seismic activity shift back in time, it is more likely that a change in the field development process entailed a change in seismic activity. Also of interest are the values of the correlation coefficients obtained for datasets without time shifts, since in the case of maximum values of the correlation coefficient without a time shift, one can assume the instantaneous relationship between seismicity and the considered development parameter.

Due to the absence of seismic activity measurements for 2006–2008, all available data were divided into two parts and considered separately for time intervals before 2006 and after 2008, respectively. The value of 1 month was taken as the shift period (lag).

When calculating the correlation coefficients, the analyzed development parameters, as well as seismicity, were averaged by a 12 months' moving average window and normalized to average values of the corresponding parameters for the entire analysis period. Correlation analysis results for data from 1996 to 2006 as well as for data from 2008 to 2020 are presented in Figures 4 and 5 respectively.

Results and discussion

Considering the data acquired over the period from 1996 to 2006, a number of development parameters can be distinguished (oil production, liquid production, water cut, injection efficiency, disbalance, number of active injectors, average liquid production by wells, average water injection by wells), which are characterized by an increase in the absolute values of the correlation coefficients with a positive shift of seismicity in time. In this case, we can talk about the influence of seismic activity on the abovementioned parameters for the studied area. An exception here is the number of active injectors, the change in which cannot be a consequence of a change in seismic activity. The maximum values of the correlation coefficients for the aforesaid development parameters are in the range of 0.45–0.8, which in general shows the presence of a moderate relationship between seismicity and these parameters.

For such development parameters as the number of active producers, water injection, and bottomhole pressure, there is a relative increase in the absolute values of the correlation coefficient with a negative shift in seismicity in time, which may indicate some influence of these development parameters on seismic activity. However, this effect either has a significant time lag, as in the case of water injection or is expressed in relatively low values of the correlation coefficients, which do not exceed 0.5.

The average oil production by wells can be highlighted separately. It shows a correlation coefficient with seismicity of ~ 0.45 with almost no lag in time.

Considering the data acquired for the period from 2008 to 2020, we can note a less pronounced correlation relationship between seismic activity and development parameters compared to the period from 1996 to 2006 with absolute values of the correlation coefficients not exceeding 0.5. Nevertheless, for such parameters as oil production, number of active injectors, and average water injection, the same correlation trend is observed in the second measurement period – an increase in the correlation coefficient with a positive time shift of seismicity. The trend of an increase in the correlation coefficient with a negative time shift of seismicity remains for the bottomhole pressure, but the sign of the correlation coefficient changes. This may indicate both the instability and randomness of the relationship between seismicity and bottomhole pressures, as well as a more complex and non-obvious nature of this relationship.

Such development parameters as liquid production, water cut, number of active producers, water injection, injection efficiency, disbalance, average oil production by wells, and average liquid production by wells do not show the preservation of the correlation trend when moving from observations for the period from 1996 to 2006 to the period from 2008 to 2020. This, coupled with the low values of the correlation coefficients does not allow us to assert that the relationship between these parameters and seismic activity is stable.

Conclusion

The performed correlation analysis made it possible to reveal the relationship between development parameters and seismicity for the Almetyevskaya area of the Romashkinskoye oilfield. At the same time, the maximum values of the correlation coefficients and the integral characteristics of seismic activity for the parameters under consideration reach 0.8 with a shift in seismicity relative to the analyzed development parameters up to 2 years. Restricting ourselves to a six-month shift period, it can be seen that the maximum correlation coefficients rarely exceed 0.5 and overall are below 0.6 (Fig. 4, 5). This indicates a statistically quite average relationship between seismicity and each of the considered parameters separately, which on the scale of the entire development area does not allow unambiguously predicting a change in one or another development parameter based on changes in seismicity and vice versa.

At the same time, the analysis revealed a stable relationship of oil production, number of active injectors, and the average water injection in wells with the preservation of the correlation trend in both measurement periods. This gives a reason to believe that with a more detailed consideration of the relationship between seismic activity and the development parameters, taking into account the spatial distribution of these parameters, the relationship between seismic activity and the development of hydrocarbon fields in the South East Tatarstan may manifest itself to a greater extent.

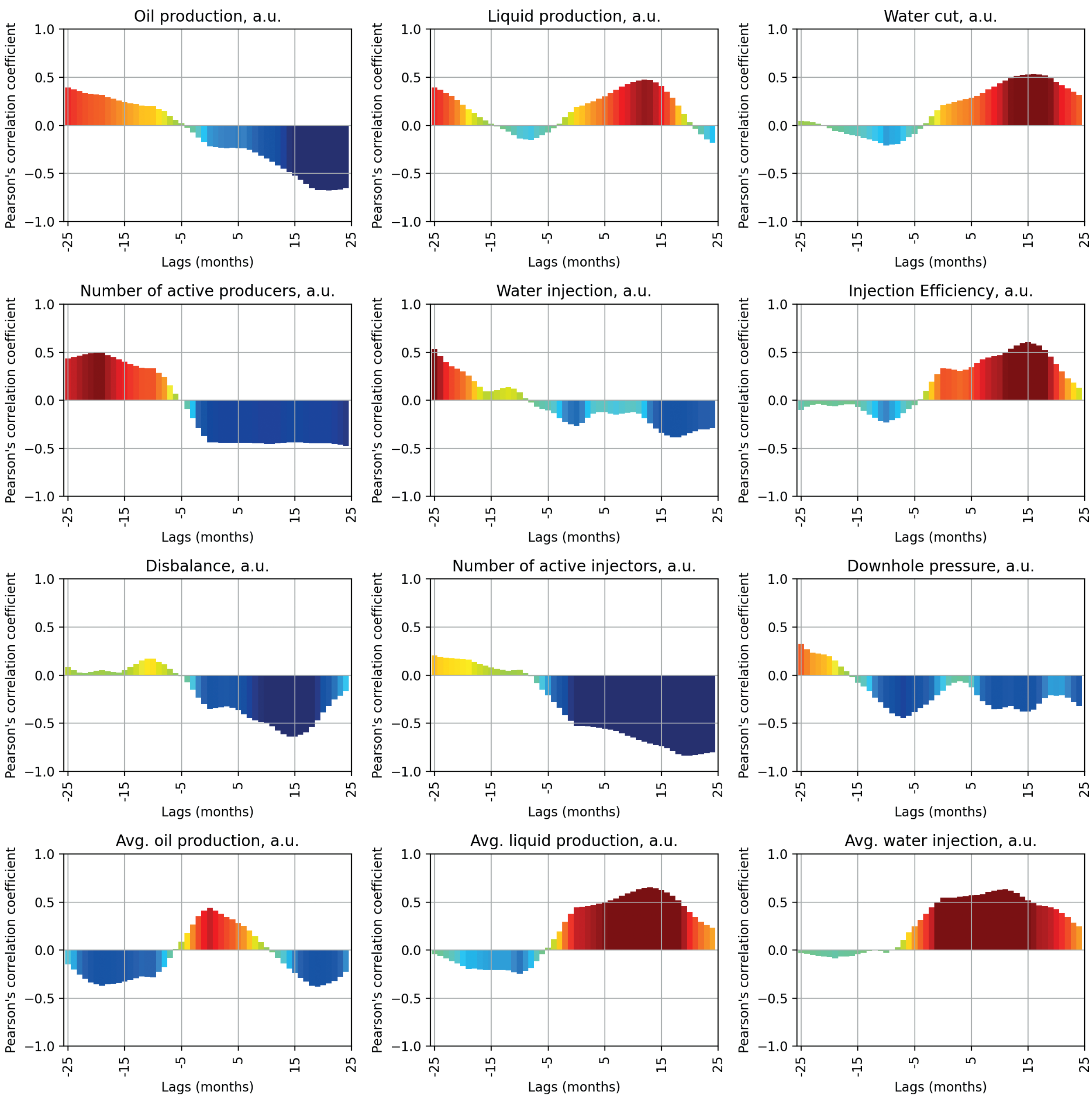

Fig. 4. Changes in the correlation coefficients of seismicity and development parameters of the Almetyevskaya area depending on the time shift of the seismic activity relative to the development parameters for seismic events occurred in 1996–2006. A.u. stands for arbitrary (or relative) units.

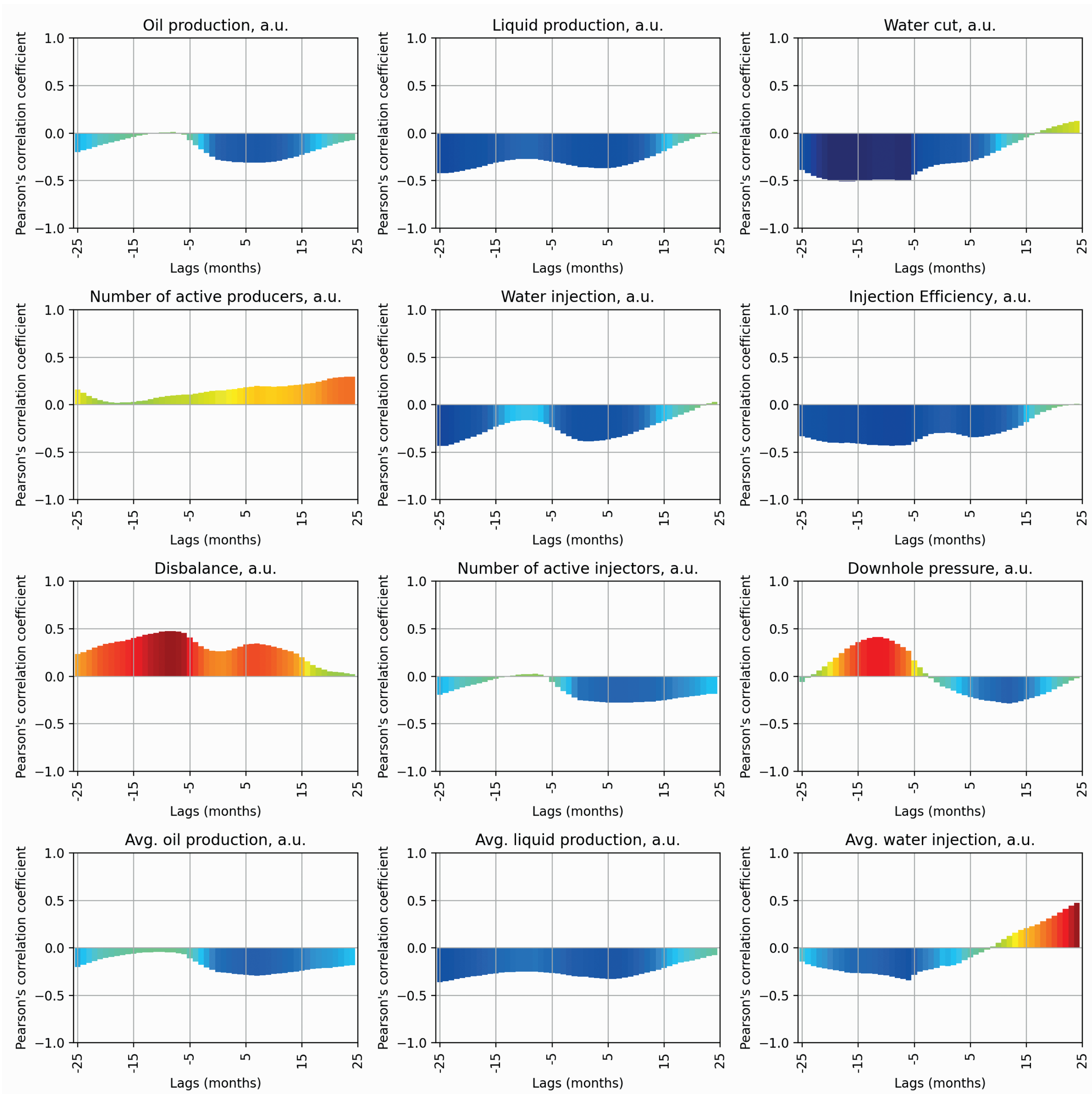

Fig. 5. Changes in the correlation coefficients of seismicity and development parameters of the Almetyevskaya area depending on the time shift of the seismic activity relative to the development parameters for seismic events occurred in 2008-2020

Acknowledgment and funding

The work was carried out with the financial support of the Ministry of Science and Higher Education of the Russian Federation in accordance with Agreement No. 075-11-2019-032 of 26.11.2019 within the framework of the project « Creation of a high-tech software and hardware complex based on neural network algorithms to improve the efficiency of the development of large hydrocarbon deposits at a late stage».

The authors express their gratitude to the reviewers and editor for the thorough analysis of the manuscript and recommendations which allowed to enhance the quality of the published paper.

References

Adushkin V.V., Rodionov V.N., Turuntaev S., Yudin A.E. (2000). Seismicity in the oil field. *Oilfield Rev*., 12(2), pp. 2–17.

Aki K. (1965). Maximum likelihood estimate of b in the formula log N=a-bM and its condence limits. *Bull. Earthq. Res.*, 43, pp. 237–239.

Ellsworth W.L. (2013). Injection-induced earthquakes. *Science*, 341, pp. 142–149. https://doi.org/10.1126/science.1225942

Grasso J.R. (1992b). Mechanics of seismic instabilities induced by the recovery of hydrocarbons. *Pure Appl. Geophys*., 139(3–4), pp. 507–534. https://doi.org/10.1007/BF00879949

Gutenberg R., Richter C.F. (1944). Frequency of earthquakes in California. *Bull. Seism. Soc. Am*., 34, pp. 185–188. https://doi.org/10.1785/BSSA0340040185

Keranen K.M. and Weingarten M. (2017). Induced seismicity, *Ann. Rev. Earth Planet. Sci*., 46, pp. 149–174. https://doi.org/10.1146/annurev-earth-082517-010054

Khisamov R.S., Gatiyatullin N.S., Kuzmin Yu.O., Bakirov R.Kh., Gatiyatullin R.N., Rakhmatullin M.Kh., Baratov A.R., Kashurkin P.I. (2012).

Modern geodynamics and seismicity of the southeast of Tatarstan. Kazan: Fen, 240 p. (In Russ.)

Mignan A., Woessner J. Estimating the magnitude of completeness in earthquake catalogs, Community Online Resource for Statistical Seismicity Analysis. doi:10.5078/corssa-00180805

Mirzoev K.M., Gatiyatullin N.S., Tarasov E.A., Stepanov V.P., Gatiyatullin R.N., Rakhmatullin M.Kh., Kozhevnikov V.A. (2004). Seismic hazard of the Tatarstan's territory. *Georesursy = Georesourses*, 1(15), pp. 45–48. (In Russ.)

Mousavi S.M., Ogwari P.O., Horton S.P. & Langston C.A. (2017). Spatio temporal evolution of frequency magnitude distribution and seismogenic index during initiation of induced seismicity at Guy Greenbrier, Arkansas. *Physics of the Earth and Planetary Interiors*, 267, pp. 53–66. https://doi.org/10.1016/j.pepi.2017.04.005

Ognev I., Stepanov A., Novikova S. (2020). Relation of South-East Tatarstan's seismicity to the Almetyevskaya Area's oil field development parameters. *SGEM Conference proceedings*. https://doi.org/10.5593/sgem2020/1.2/s06.095

Rautian T.G., Khalturin V.I., Fujita K., Mackey K.G. & Kendall A.D. (2007). Origins and Methodology of the Russian Energy K-Class System and Its Relationship to Magnitude Scales. *Seismol. Res. Lett.,* 78(6), pp. 579–590. https://doi.org/10.1785/gssrl.78.6.579

Rydelek P.A., Sacks I.S. (1989). Testing the completeness of earthquake catalogs and the hypothesis of self-similarity. *Nature*, 337, pp. 251–253. https://doi.org/10.1038/337251a0

Suckale J. (2009). Induced seismicity in hydrocarbon fields. *Adv. Geophys*., 51, pp. 55–106. https://doi.org/10.1016/S0065-2687(09)05107-3

U.S. Geological Survey (2021). Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global. https://doi.org/10.5066/F7PR7TFT

Wiemer S. (2001). A software package to analyze seismicity: ZMAP. *Seismol Res Lett.,* 72(3), pp. 373–382. https://doi.org/10.1785/gssrl.72.3.373

Wiemer S., Wyss M. (2000). Minimum magnitude of complete reporting in earthquake catalogs: examples from Alaska, the Western United States, and Japan. *Bull. Seism. Soc. Am*., 90, pp. 859–869. https://doi.org/10.1785/0119990114

Woessner J., Wiemer S. (2005). Assessing the quality of earthquake catalogues: Estimating the magnitude of completeness and its uncertainty, *Bull. Seismol. Soc. Am*., 95. https://doi.org/10.1785/0120040007

About the Authors

Igor N. Ognev – Senior Lecturer, Department of Development and Operation of Hard-to-Recover Hydrocarbons, Institute of Geology and Oil and Gas Technologies

Kazan Federal University

4/5 Kremlevskaya st., Kazan, 420008, Russian Federation

Alexey I. Stepanov – Engineer, Center for advanced training, quality management and marketing, Institute of Geology and Oil and Gas Technologies

Kazan Federal University

4/5 Kremlevskaya st., Kazan, 420008, Russian Federation

Manuscript received 12 November 2020;
Accepted 12 October 2021; Published 30 November 2021