Jury Member Report – Doctor of Philosophy thesis.

Name of Candidate: Daniel Wamriew

PhD Program: Petroleum Engineering

Title of Thesis: Location and source mechanisms of induced seismic events

Supervisor: Professor Dmitri Koroteev
Co-supervisor: Professor Roman Pevzner, Curtin University

Name of the Reviewer: Sergey Tikhotskiy

I confirm the absence of any conflict of interest	**Date: 24-08-2022**

The purpose of this report is to obtain an independent review from the members of PhD defense Jury before the thesis defense. The members of PhD defense Jury are asked to submit signed copy of the report at least 30 days prior the thesis defense. The Reviewers are asked to bring a copy of the completed report to the thesis defense and to discuss the contents of each report with each other before the thesis defense. *If the reviewers have any queries about the thesis which they wish to raise in advance, please contact the Chair of the Jury.*
Reviewer's Report

The overall impression from the thesis is very positive. Despite the fact that the main aim of the study is the DL algorithms development and application, the thesis covers much wider area of the related subjects, including the data acquisition (specifically the DAS), the physics behind the microseismicity and the importance of its studies for the practical application in hydrocarbon field development.

The topic of the study is indeed actual and well corresponds to the industry demands. The scientific novelty follows from the fact that two modern technologies – DAS and DL – are used together for the purpose of microseismic monitoring. Though this is not a first attempt in this direction the presented study is a first systematic approach.

The review of the microseismicity is very comprehensive and present a lot of examples. Meanwhile, the shortcoming of the presented considerations is that it does not pay attention to the principal difference between the "triggered" and "induced" seismicity (though the mentioned terms are not widely accepted). The former relies to the triggering of the natural tectonic stress release by artificial influences: fluid injection, mining, etc. Here the small changes in the pore pressure or external load led to the loss of stability in pre-stressed media and, in most cases – shear fracturing. While the latter corresponds to the true artificial stress induced by the intense and fast pressure increase (as in the course of the HF) or drop (while drilling). In this case the pre-stress of the media and additional stress change are of the same magnitude and thus the focal mechanisms more variable, including those leading to dilatation and compaction. These two cases must be considered independently to clarify the physics and obtain better fit between the theory and experiment. Specifically, the same amount of the injected fluid will lead to very different microseismic events depending on the rate of pumping: fast, as in the course of HF, or low, as in the course of waste disposal.

Author argues that microseismic monitoring is important for the reservoir characterization and monitoring and reviews the methods for data acquisition and processing. Cases of oil recovery and CO2 disposal monitoring are considered separately and in many details. This part of the review is of special interest.

Regarding the following review of the DAS technology, it is worth to mention that it starts from the historical mistake. In fact, the acoustic and electromagnetic waves propagation including the effects of scattering is studied since the XVII century, not from the beginning of the XX century, as stated. Specifically, the Raleigh scattering that is the base for the DAS technology was recovered and explained by Raleigh in 1871. Of course, this is a very obvious but not really important mistake. The review of the DAS application in different fields and in reservoir characterization is very comprehensive and interesting. The review of the DL application is rather concise.

Chapter 2 ends with the conclusion that two cutting-edge technology is used for the study: DAS and DL. Well, it is true, but the shortcoming of the approach is the absence of the critical comparison of this choice with other possibilities. What will be if we used 3-component velocimeters downhole array with the similar CNN DL technique? And so on.

Chapters 3.1-3.3 are devoted to the review of the conventional events detection and location algorithms as well as to the focal mechanisms' solutions. It is rather sufficient for the purpose of the study.

Chapter 3.4 deals with the review of the DAS technology, its advantages and shortcomings. Unfortunately, it lacks some important details. The most important point is the absence of the analysis of the frequency response of the DAS sensor, which is rather complicated and depends on the gauge length (GL) as well as on the angle of the wave incidence. That is, the nature of DAS technology leads to the fact that the frequency content of the recorded signal will be different for the waves that come to the sensor at different angles w.r.t. to the cable axis. The problem is that for the modern DAS systems the GL is of lengths of 1-2 meters and the corresponding shortest wavelength that may be adequately recorded is about 4-8 meters if the wave travels along the axis. This is in conflict with the actual frequency content of the microseismic signals, especially in the case of the HF monitoring. This problem is important and worth to be studied.

Chapter 4 is devoted to the actual study performed by the author: development and implementation of the algorithm for the DAS data processing for the purpose of microseismic monitoring. Chapter starts with the very brief description of the conventional processing workflow and continues with the description of the DL-based workflow.

The study is based on the synthetic modelling. This includes the construction of the velocity model, implementing a set of synthetic microseismic sources and forward seismic modelling. Then the inverted result is compared with the model. This approach is well-suited for the problem.

The following chapters are compiled from the published papers, and this is not a good choice, because they in some sense contradict each other.

The major issue with the chapter 4.2 («Location and velocity inversion in real time», published in «Computers and geosciences») is the forward modelling procedure. Author uses the dynamic ray tracing algorithm, i.e. the ray-theoretical assumption is implied. The travel times and amplitudes are calculated and then convolved with the Ricker wavelet. According to the equation 4.1 the ray-theoretical displacements are calculated. It is not clear from the text how these displacements were converted to the signal that will be recorded by DAS. It is known that the DAS is recording the deformation along the cable axis averaged over the GL (or deformation rate depending on DAS pre-processing). There are no signs that these deformations were really calculated. The above-mentioned problem with the frequency response of the DAS line comes out here. According to the text the central Ricker wavelet frequencies were chosen in the range 50-500 Hz. The mean P-wave velocity is about 4500 m/s. I.e., the shortest wavelength is about 9 m which may be difficult to record by modern DAS line without the significant distortion. Moreover, the different frequency wavelets coming at different angles will be recorded with different distortions. This issue must be taken into account, because the NN must be trained on data that are adequate to the real field data.

The above-mentioned shortcoming is resolved to some extent in the chapter 4.3 (“Detection, location and velocity model inversion”, published in “Sensors”). Here the synthetic displacement data are converted to DAS signal via the calculation of strain rate (equation 4.4). Nevertheless, the actual frequency response of the DAS line is not considered and analyzed, and this issue is not mentioned in the section 4.3.7.1 “Limitation of DAS”, though this is a very important limitation.

Data frequency analysis appears in the section 4.4 (next paper), but it is again not analyzed w.r.t. the frequency response of the DAS line.

Chapter 4.5 is of special interest because in includes the moment tensor inversion – difficult and important problem. Ricker wavelet with the central frequency of 60 Hz was chosen for synthetic forward modeling. The corresponding wavelength is about 75 meters and thus will be well-reproduced by DAS line, but it is not clear whether this frequency is adequate to the real signal. The result is impressive, but it was not applied to the real data set. It is not clear whether the inversion quality will remain with the real data of different wavelengths.

Despite of the mentioned shortcomings the thesis possesses very good quality and represent an important step in the passive seismic monitoring data processing. The results of the study are published in the high-ranked scientific journals. The study corresponds to the state-of-the-art at an international level. I suggest that the results will be useful for the practical microseismic monitoring in many fields not only hydrocarbon studies.

Signed by Sergey Tikhotskiy

at 24.08.2022

Provisional Recommendation

☒ *I recommend that the candidate should defend the thesis by means of a formal thesis defense*

☐ *I recommend that the candidate should defend the thesis by means of a formal thesis defense only after appropriate changes would be introduced in candidate's thesis according to the recommendations of the present report*

☐ *The thesis is not acceptable and I recommend that the candidate be exempt from the formal thesis defense*