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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: Pavel Golikov

I confirm the absence of any conflict of interest (Alternatively, Reviewer can formulate a possible conflict)	**Date: 26-08-2022**

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 PhD Thesis under review presents an interesting and very promising approach of utilizing a combination two cutting-edge data acquisition and processing techniques – Distributed Acoustic Sensing (DAS) and Deep Learning (DL) – for detecting and locating the hypocenters of induced seismic events. While induced seismicity is a broad phenomenon which could be observed in various scenarios, as author outlined in Chapter 2.1, the specific focus of this Thesis is the microseismic events location and characterization in the oil and gas applications.

The Thesis is well written and structured. The title accurately outlines the topic of the dissertation. Author provides a general introduction describing the aim and objectives of the Thesis and then gives some background and theory information. The specific details of the research are then explained in Case study section where comprehensive details of the methods and data examples are provided.

The microseismic monitoring is an essential tool for conducting and optimizing hydraulic fracturing which plays important role in the modern oil and gas industry. Therefore, any new research aiming to improve the performance and accuracy of the method has immediate practical value. A novel approach presented

in the Thesis aims to automate microseismic event location and reservoir properties estimation with minimal preprocessing through machine learning techniques which unlocks the potential of the real-time applications. Moreover, author inllustrates the applicability of the DAS technology for the microseismic monitoring which potentially leads to significant decrease in cost and improved robustness of the monitoring.

The main part of the dissertation – Case studies – consists of the papers already published in the international peer reviewed journals or proceedings of the major conferences. There is no doubt that the material presented in these papers positively contributes into the global professional community.

I believe that this work demonstrates a high level of knowledge and expertise in the area of research, and it is fully compliant with the international standards of conducting research. I recommend that the candidate should defend the thesis by means of a formal thesis defense.

There are a few general comments and questions from my side:

1. The Background and Theory sections have many similarities especially in parts related to DAS. Some terms are mentioned in Chapter 2.3 but being introduced and explained only in Chapter 3.4. For example, $\phi - OTDR$. I suggest revising the Background section focusing it on the previous works and basic principles.
2. DAS cable deployment and coupling are one of the most important aspects for the successful DAS acquisition. I recommend adding a couple of paragraphs in Chapter 2.3 describing various options of the DAS cable deployment in general and for microseismic monitoring purposes in particular. Also, it would be great to mention that the quality of the cable coupling to the formation can greatly affect the result of the DAS measurements. The coupling issue could be mentioned in the Chapter 3.4.3 as well.
3. In Chapter 2.4, it is worth mentioning briefly what kind of data preprocessing is required to make an input for DL workflow. Can the raw optical data from interrogator be used as an input? The data preprocessing is mentioned in Chapter 4.1.2 and in the Figure 4-2 but no details provided.
4. For the DAS data modeling and inversion, the synthetic seismograms from raytracing are 150x2000 samples (150 receivers with each trace 1s at 0.5ms sampling). Later they were converted into 256x256 images for CNN input. How did resampling affect the temporal and spatial frequency content of the data?
5. What was the rational for selecting different acquisition parameters and different CNN architectures for geophone and DAS data? Why not treat DAS data as single component geophone (before conversion to strain rate)?
6. It is not obvious how the FORGE data analysis from the Chapter 4.3 is compared to the one from the Chapter 4.4. Was the same data analyzed? Were the detected microseismic events identical? It would be great to hear more details on this.
7. Can both the location and the focal mechanisms inversion be combined and performed with one complex DL architecture? How will it affect the performance and the accuracy of the inversion?

In addition, please see below some minor comments mainly related to the text readability.

There are different styles of capitalized terms in the text such as Deep Learning, Deep learning and deep learning. Sometimes, some or all styles in one page. Please revise the text and stick to the unified style.

Please check the reference formatting style on pages 1 ([Molenaar et al., 2012]) and 9 (Foulger et al. [2018])

Page 2, Figure 1-1: There are 5 different surface structures that cause induced seismicity in the Figure. 3 of the are briefly explained in the caption. I believe that the other 2 (mining and reservoir impoundment) should be briefly explained too for completeness.

Page 7, line 5: Please fix typo in 'theoretical'.

Page 10, paragraph 1: 'It is un- doubtedly challenging to effectively connect all the various disciplines in reservoir characterisation, especially for unconventional **reservoirs.**'

Page 12, paragraph 1: The AI abbreviation was not introduced before.

Page 13, paragraph 2: The CCUS abbreviation must be introduced first.

Page 15, Chapter 2.3: It would be good to add here some general reference describing basic principles of the DAS recording such as Hartog [2017].

Page 17, Chapter 2.3.2: "...The DAS system has replaced conventional accelerometers due to its low cost on a large scale…." This is not true. MEMS-based accelerometers are still widely used in surface seismic and to the lesser extent in borehole applications. Moreover, the DAS system is not measuring the particle acceleration directly, thus cannot be direct replacement of the accelerometers.

Page 19, paragraph 2: "The DAS technology has successfully replaced traditional sensing methods across multiple sectors and industries." Perhaps it's too early to talk about full replacement. It's better to use terms: 'complemented' and 'improved'.

Page 20, paragraphs 2 and 3: These 2 paragraphs are better be placed at the beginning of this chapter as a brief introduction to the basic principles of DAS measurements.

Page 21: "It is possible to generate reasonable uncertainty in spite of cylindrical symmetry by making several assumptions based on production logs." This sentence is unclear, please reformulate.

Page 30: Figure 3-2: The STA in the Figure is less than the signal dominant period while it should be 3 to 5 times dominant period.

Page 42, line 3 from the bottom: "…Equation (3.30), where..."

Page 43: Please stick to the same Greek letter when referring to phase.

Page 44: The TGD-OFDR term is not explained in the text.

Page 45, Chapter 3.4.3: It is worth mentioning here that DAS directivity issue can be (partially) resolved by utilizing helically wound cables [Kuvshinov, 2016]. Baird [2020] modelled DAS response of the helically wound cables for microseismic applications which is more relevant to the main thesis topic.

Page 47, paragraph 2: "…the manual and the artificial **intelligence** systems improved…"

Page 48, paragraph 2: "…monitoring of seismic activities in less seismic activities regions…" Please rewrite this sentence.

Page 48, last line: "Past cosmic exploration has utilized DAS systems on a mission for different purposes." It would be great to put some relevant references here.

Page 52, paragraph 2: "…alongside other hyperparameters is achieved using trial and improvement…"

Page 58, paragraph 2: the ρ sign is missing in the model parameters description.

Page 66, paragraph 6: Is the X, Y and Z here denotes seismic components or coordinates of the microseismic event? Clarification is needed here.

Page 74, paragraph 2: Please correct the reference at [Energy and at the University of Utah, 2019]

Page 85, paragraph 2: Please correct the reference at [Energy and at the University of Utah, 2019]

Reference list:

A. Baird. Modelling the Response of Helically Wound DAS Cables to Microseismic Arrivals. In First EAGE Workshop on Fibre Optic Sensing, 2020. doi: 10.3997/2214-4609.202030019. URL https://doi.org/10.3997/2214-4609.202030019

Arthur H. Hartog. An introduction to distributed optical fibre sensors. CRC Press, 2017. doi:10.1201/9781315119014. URL https://doi. org/10.1201/9781315119014.

B.N. Kuvshinov. Interaction of helically wound fibre-optic cables with plane seismic waves. Geophysical Prospecting, 64(3):671-688, May 2016. doi: 10.1111/1365-2478.12303. URL https://doi.org/10.1111/1365-2478.12303.

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*