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Jury Member Report – Doctor of Philosophy thesis.

Name of Candidate: Anuar Shakirov

PhD Program: Petroleum Engineering

Title of Thesis: Determining thermal properties of sedimentary rocks from well-logging data

Supervisor: Professor Yuri Popov

Name of the Reviewer: Dr. Irina Bayuk

I confirm the absence of any conflict of interest (Alternatively, Reviewer can formulate a possible conflict)	**Date: 03-08-2021**

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

This thesis can be classified as a high-quality research aimed to develop a method to determine the rock's thermal conductivity from logging data.

The thesis consists of 5 Chapters that include 175 pages of texts, 45 figures, and 25 tables. The first Chapter is devoted to the analysis of current well-log based approaches for determining rock thermal properties. The second Chapter outlines method allowing a determination of thermal conductivity and volumetric heat capacity of anisotropic rocks based on regression analysis. Chapter 3 contains analysis of methods for estimating the thermal conductivity and volumetric heat capacity of anisotropic rocks based on theoretical modelling. Chapter 4 can be considered as a key part of the work. It represents a new method developed by the author named Well-Log Based Technique (WLBT) for determining rock thermal properties accounting for thermal anisotropy at *in situ* pressure, temperature and saturation. The final Chapter 5 exemplifies results of successful implementing WLBT for determining rock thermal properties during investigations of oil fields.

The topic of the dissertation is in relevance to its actual content. The methods used in the dissertation are well justified and physically plausible. An interesting and novel feature of this thesis is application of the machine learning approach. All results are verified by the experimental data. A good point to be

mentioned is an estimation of thermal conductivity prediction quality. The author used different factors for such an estimation: root mean squared error, precision and accuracy.

The obtained results are of great significance since allow one to estimate in situ thermal conductivity (that cannot be measured in the field experiment) from available logging data. The most helpful logging data are revealed for such an estimation. The knowledge of thermal conductivity is necessary in many fields of the human activity including hydrocarbon recovery form unconventional reservoirs, basin modeling, effective injection and storage of CO_2, geothermal energy, and estimation of the heat flux density. The method suggested in the thesis is new and has no analogs in the world practice. This is based on the up-to-date and even unique experimental methods and advanced approaches of the experimental data treatment, specifically, machine learning. All the obtained results are applicable in practice in the fields of human activity mentioned above.

The quality of publications is rather high. The author has 3 publications in the journals cited in Web of Science and Scopus databases (Geothermics, Geophysical Journal International, Journal of Petroleum Science and Engineering). One paper is submitted to Geosciences. The author has one patent of Russian Federation.

The summary of issues to be addressed before/during the thesis defense

1) The author of dissertation writes that the stiffness tensor can be simply estimated from the data provided by the dipole sonic tool. However, this is not always the case. It is only valid if two assumptions are met: (a) C12 = C13 and (b) the Thomsen parameters delta is close to zero. These assumptions follow from observations on shales, not from the theory. However, in some cases these assumptions are failed. Therefore, it would be more correct to pay attention on these assumptions and verify them in laboratory experiment for rocks under study.

2) The author suggests to estimate the principal axes of symmetry using geomechanical experiment. However, these experiments are rather expansive. Besides, samples are destroyed after the experiments. It would be better to use for this purpose laboratory measurements of elastic wave velocities, specifically, multilevel ultrasonic sounding. This method allows one to discriminate between the anisotropy and heterogeneity and estimate the anisotropy type. Besides, this method is non-destructive.

3) Figure 6. What do the solid and dashed grey lines mean?

4) Figure 6. For the VHC and PEF the correlation is very poor. Please, comments on this point.

5) For theoretical modeling of anisotropic rocks several methods that include correction factors for directions parallel and perpendicular to the bedding are used. The choice of two correction factors was needed to incorporate the anisotropy in thermal conductivity observed in experiment. This means that two unknown values (correction factors) should be found to satisfy the experimental data. The author compared a quality of the thermal conductivity prediction based on (a) theoretical modeling based on the methods with correction factors and (b) regressions combined with machine learning. The author demonstrated that variant (a) produces worse results compared to (b). I advise to use EMT methods here for the theoretical prediction. These methods take into account anisotropy since give resulting thermal conductivity in a tensorial form. Besides, to incorporate anisotropy, only one correction factor is required instead of two – aspect ratio of oriented non-isometric inclusions. However, the author understand that

more physically justified theoretical approaches should be used. Thus, this comment can be considered as an advice for the future work.

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*

Reviewer: Dr. Irina Bayuk