

Jury Member Report – Doctor of Philosophy thesis.

Name of Candidate: Nadezhda Khaustova

PhD Program: Petroleum Engineering

Title of Thesis: Uranium accumulation in marine source rocks: role of redox conditions and correlation with productivity

Supervisor: Professor Mikhail Spasennykh

Co-supervisors: Professor Yuri Popov

Dr. Elena Kozlova

Name of the Reviewer: Ksenija Stojanović

I confirm the absence of any conflict of interest ■

Date: 14-09-2022

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

Reviewers report should contain the following items:

- Brief evaluation of the thesis quality and overall structure of the dissertation.
- The relevance of the topic of dissertation work to its actual content
- The relevance of the methods used in the dissertation
- The scientific significance of the results obtained and their compliance with the international level and current state of the art
- The relevance of the obtained results to applications (if applicable)
- The quality of publications

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

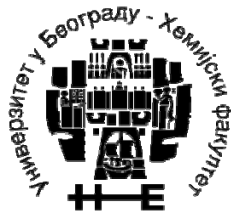
Please see the Report bellow Table, since I could not insert it into the Table.

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



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SKOLKOVO INSTITUTE OF SCIENCE AND TECHNOLOGY Doctoral Program in Petroleum Engineering

Belgrade, September 14, 2022

Dear Colleagues,

First of all I would like to thank you very much to select me as a referee of the work of Nadezhda Khaustova, PhD candidate of highly respectable the Skolkovo Institute of Science and Technology. For me it is a great pleasure and honour.

After reviewing the work of Mrs. Khaustova, I submit to the Doctoral School in Petroleum Engineering of the Skolkovo Institute of Science and Technology, the following:

REPORT

A) Preview of the doctoral dissertation content

The doctoral dissertation of the candidate Nadezhda Khaustova is written on 174 pages, A4 (font 12), with 66 figures and 37 tables (34 in the main text and 3 in the Appendix A). The doctoral dissertation is written in English, and contains five chapters. After the first chapter, the **Introduction** (2 pages) there is the second chapter, **Review of literature** (17 pages). This is followed by **Uranium accumulation in marine sediments under different redox conditions on the example of the White, East Siberian and Black Seas, as well as the Laptev Sea** (56 pages) which is divided into five subchapters, representing *Regional settings, Materials and methods, Results of bottom sediments investigations, Behavior of uranium in bottom sediments under reducing conditions in the example of Black Sea and Discussion*. Third, fourth and fifth subchapter includes several sections. Chapter 4, **Distribution of uranium (U) and uranium/TOC (U/TOC) ratios in the unconventional reservoir on the example of the Bazhenov Formation**, is written on 28 pages and contains 7 subchapters: *Objectives of research, Methods of research, The high-resolution analysis results of variations TOC and uranium concentrations in the Bazhenov Formation, Role of redox conditions in uranium accumulation in source rocks, Relationship of uranium content, total organic carbon, mineral composition and productivity of source rocks, Classification of productive intervals by uranium content and U/TOC ratio and Summary*. The chapter **Conclusion** is presented on 11 pages. The last chapter, **References**, contains 101 citations, given on 6 pages. In addition, the doctoral dissertation

contains: Acknowledgements; List of tables and figures; Abstract; a Table of contents; List of publications and Declaration of originality.

B) A brief description of the thesis and achieved results

The uranium (U) concentration and its combining with content of total organic carbon (TOC), content of other micro (trace) and certain major elements, mineralogical data, isotopic signatures, as well as other indicators of source, depositional environment and maturity of sedimentary organic matter can be useful for understanding of geochemical cycle of uranium in different environments, as well as for prediction of properties of prolific petroleum production areas. However, using of uranium data for studies of unconventional reservoirs and source rock productivity remains limited and mainly has been applied for identification of source rock lithological boundaries, well-to-well log correlation, as well as for core-to-log data integration. One of the main reasons for such lack of application is insufficient knowledge of factors that determine uranium accumulation during deposition of sediments and further geological history.

The current work represents very comprehensive study of significance of uranium contents in marine environments, including modern sediments (Arctic Seas and the Black Sea) and petroleum source rocks (Bazhenov Formation). Numerous up to date techniques were applied and interpretation have been done on large sample sets.

The results from study of modern sediments showed that higher content of uranium in reducing conditions in comparison to oxidizing settings could be explained by the difference in solubility of uranium in the water-bottom layers contacting with sediments and in the water saturating the upper part of sediments. However, reducing conditions observed in sediments located deeper than 0.5 m in Arctic Seas (example on the White Sea), did not lead to an increase in the accumulation of uranium because the amount of uranium that can be precipitated from the pore water of sediments is much lower in comparison with uranium content in the inorganic part of sediments that originated from continental run-off.

The study of uranium content in 13 wells of the Bazhenov source rock Formation revealed the considerable role of redox conditions, as expected (enhanced uranium content under reducing settings). Although redox conditions at sedimentations stage play a leading role in uranium accumulation in rocks, it was observed that the presence of phosphate minerals and high maturity of organic matter may considerably increase uranium content in source rocks.

The particular novelty of the thesis (**the relevance of the obtained results to applications**) is attained comparing uranium concentration and Rock-Eval data in the Bazhenov Formation. It was observed that the intervals with the maximum oil saturation index are characterized by uranium content in the range of 1-20 ppm. These intervals should be considered promising for development using multi-stage hydraulic fracturing technologies applied to the low-permeability reservoirs. Intervals with intermediate uranium contents from 20 to 40 ppm should be considered conditionally productive. Greater maturity of organic matter and higher U/TOC ratios can be considered as factors enhancing oil recovery potential. The intervals with uranium content above 40 ppm and high TOC are characterized by low productivity index and low oil saturation index. Therefore these intervals are classified as non-promising for oil production. Nevertheless, these intervals may be promising for the production of hydrocarbons generated from kerogen using thermal methods of oil recovery, particularly in case of low organic matter maturity. According to P_2O_5 contents in studied samples, it was noticed that the discussed above uranium-based productivity criteria cannot be directly applied to the classification of the phosphorite intervals, which can have high oil saturation for high uranium concentrations (from 20 to 100 ppm). The obtained results provide the criteria for identifying the productive intervals within the Bazhenov Formation cross-section according to logging data on the

uranium content in rocks and neutron logging data (using Lithoscanner) and their classification in terms of the methods for oil production. These results may be useful on global scale for interpretation of other marine prolific petroleum production areas of similar lithology and maturity of organic matter.

Answers to the specific questions:

- The relevance of the topic of dissertation work to its actual content
- The relevance of the methods used in the dissertation

In my opinion, the scientific research presented in this dissertation is in line with modern trends in Geosciences and represents a scientific contribution to the field.

The thesis is well organized, written and illustrated. The interpretation is documented by data. It is clear and well done. Discussion is consistent and supported by numerous citations. The technical quality of thesis is good. Numerous up to date relevant laboratory techniques were applied and interpretation have been done on large sample sets.

All objectives defined in current research project were achieved. However, the candidate, in the manner of experienced scientist, recognized certain new questions that arise from the obtained results, and made good guidelines for future research.

C) Significance of the candidate's results (The scientific significance of the results obtained and their compliance with the international level and current state of the art)

A total of ten scientific publications have resulted from this research. Three of them are published as the original scientific papers in international journals (two manuscripts are published in journals that have impact factor, and one of them in highly recognized journal Marine and Petroleum Geology), one patent for invention (documenting novelty and quality of the thesis) and six contributions to scientific conferences.

D) Conclusion and recommendation

Based on all previous statements, it can be concluded that in the submitted dissertation entitled "URANIUM ACCUMULATION IN MARINE SOURCE ROCKS: ROLE OF REDOX CONDITIONS AND CORRELATION WITH PRODUCTIVITY", the candidate NADEZHDA KHAUSTOVA, successfully answered to all tasks defined in current research project.

I suggest very few technical corrections:

1. Table of content – please uniform the style:

Capitalize the first letter in all words in titles of chapters (e.g. Review of the Literature, Materials and Methods, etc.) or capitalize the first letter in the first word only (e.g. Objects of research, Role of redox conditions in uranium accumulation in source rocks, etc.) and of course names of seas and formation, as it has been already performed.

2. Page 80; Line 8 from the top: carbon instead of carbom

3. Page 93; Line 5 from the top: Braduchan и др., 1986 should be replaced by Braduchan et al., 1986.

4. Page 112; Line 15 from the top: Formula of pyrolusite is MnO_2 . Therefore you should correct the sentence: Increased uranium content is associated with uranium concentration by phosphate minerals (represented by P_2O_5 content) and manganese (represented by MnO). Analogically the word "pyrolusite" should be removed from line 18 at the same page.

5. Appendix A; Table 36; the first row and the first column: epth should be corrected into Depth.

In my opinion, the scientific research presented in this dissertation is in line with modern trends in Geosciences and represents a scientific contribution to the field.

In this regard, with a great pleasure, I propose to the Thesis Committee to issue the authorization for the defense of the doctoral dissertation.

Kind regards,
Sincerely,

Ksenija Stojanović, PhD
Full Professor
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Faculty of Chemistry
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11000 Belgrade
Serbia