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THE STUDY OF GEOLOGICAL AND HYDROLOGICAL PROCESSES OF ROLL-FRONT TYPE DEPOSITS GENESIS

ANNOTATION

Dissertation for the degree
Doctor of Philosophy (PhD) in specialty
6D060300 – "Mechanics"

General Description of the Work. The dissertation is dedicated to conducting numerical experiments of the rollfront deposits genesis in order to determine mechanisms influencing their geometry and content, as well as creating a new geostatistical method to achieve highly accurate geological models of such formations.

Relevance of the Work.

Kazakhstan is the 2nd largest country by uranium reserves, accounting for as much as 12% of World's uranium resources. Approximately 40% of all uranium produced in the World can be attributed to Kazakhstan. Uranium is one of those resources where extraction volumes greatly exceed new discoveries through exploration. Until now, Kazakhstan has focused on developing deposits with a cost-effective uranium concentration (less than $80 per kilogram), however, over the past years, the number of such resources has declined by a 43%, reaching a total of 2.1 million tons. Based on the projected uranium mining capacity, a shortage of cost-effective uranium resources has been anticipated by 2020. This deficit inevitably results in reduced profitability for the uranium industry in Kazakhstan.

Rollfront deposits are significant for the mining industry, particularly in the uranium sector. Rollfront deposits is a mineralization that form at redox fronts in permeable rocks. Effective production of minerals through the ISL depends on a comprehensive analysis of mineral distribution, grade values and overall profitability of the extraction. In other words, the performance of any selected technique of production in terms of cost of drilling and further operation, highly depends on the accuracy of geological exploration techniques. Enhancing the comprehension of reactive transport and chemical processes implicated in the formation of rollfront deposits would lead to safer and more economical utilization of ISL methods for exploiting rollfront deposits. Rollfront deposits contain various minerals, including rare earth minerals such as selenium, molybdenum, rhenium, vanadium, scandium and yttrium.

Currently, the demarcation of economically viable ores in the uranium industry is primarily performed manually, relying on established methodological recommendations, or alternatively utilizing geostatistical methods. Nonetheless, these employed techniques fail to consider the hydrodynamic and chemical factors that influence the formation of deposits. Conversely, studying the mechanisms behind rollfront deposit formation, would allow discerning certain patterns in ore distribution within the reservoir. Consequently, this knowledge can contribute to the development

of an enhanced geomodelling method for the ore body, yielding improved accuracy. As a result, several benefits can be attained, including cost reduction in exploration and development by minimizing the number of wells required, increased precision in reserve estimations, and enhanced recovery rates during the production process.

Based on the aforementioned considerations, **the goal of the work** is to establish the formation mechanisms of rollfront mineral deposits with the purpose of constructing mathematical and numerical models that accurately depict their formation. Additionally, leveraging the acquired findings, the work aims to devise a new geostatistical method for precise geomodelling and reserve estimation of such formations.

The tasks of the work.

1) numerical reproduction of an empirical experiment on rollfront formation process;

2) development of an appropriate quantitative model of the formation mechanism of the rollfront that can be applied for various bedded geometries;

3) to propose a technique to produce synthetic deposits, based on numerical simulation of hydrodynamics and chemical kinetics of precipitation/dissolution of mineral complexes during the deposit genesis;

4) to propose a new geostatistical method with some modifications/improvements of conventional algorithms by honoring hydrodynamic constraints that govern fluid flows in ore bearing layers;

5) to test the performance of conventional methods as well as a proposed method in terms of accuracy of resource estimation and geological model generation.

The research methods are numerical simulation of the processes of transport, dissolution and precipitation of mineral containing solutions in porous media, as well as geostatistical methods for geomodelling and reserve estimation.

The scientific novelty of the problem. Current methods for constructing geological models of infiltration type deposits rarely take into account the hydrodynamic and geochemical processes that influence the formation of such deposits. Moreover, at present, constructing the contour of the ore body and calculating the reserves of uranium deposits in Kazakhstan is carried out manually based on methodological recommendations developed independently in each of the mining industries. Accordingly, the accuracy of the constructed geological models highly depends on the qualifications of a particular expert and can vary greatly from expert to expert. The original research lies in replicating a laboratory experiment numerically in order to broaden the understanding of rollfront genesis mechanisms from geological, hydrodynamic and chemical perspectives. Additionally, these experiments have contributed to the creation of a quantitative model for the numerical generation of synthetic rollfront deposits to acquire data necessary for verification of various geological modeling techniques or for potential utilization in the training of AI-based technologies, such as Physics-Informed Neural Networks. A novel geostatistical method has been created specifically intended for infiltration type deposits, accounting for the hydrodynamic characteristics inherent in their formation processes. Computational Fluid Dynamics methods within the newly proposed method has led to an increase in the accuracy of current geostatistical approaches when implemented for

rollfront deposits. The effectiveness of this method has been substantiated through appropriate verification procedures detailed within the current research.

The scientific positions proposed for defense include.

1) reactive transport simulation employed to investigate the formation of rollfront deposits, facilitating the determination of the relationship between various characteristics and the geometry and content of these deposits;

2) mathematical model and a tool for generating synthetic rollfront fields for verification of geostatistical models;

3) a new geostatistical method, utilizing streamlines, devised to construct a geological 3D model of the deposit with increased accuracy;

4) software tool for geological modeling and reserve estimation of rollfront deposits.

The main results of the research.

1) Based on laboratory experiments, a mathematical and computational model for the formation of deposits in the form of rollfronts has been developed.

2) Modeling has established that the elongated “tongue” known for roll-front uranium deposits in sandstones arises due to changes in the degree of permeability of the formations.

3) Convection and the regime during the precipitation and dissolution of uranium are the mechanisms for the formation of fronts, and the velocity coefficient directly affects the extension of the front along the direction of groundwater flow.

4) A number of synthetic fields have been created for verification and comparison of modern and/or new geostatistical methods.

5) Results show that a geostatistical method that account for hydrodynamic properties of the rollfront deposits, can produce geological of higher quality and qualititevely more accurate results of resource estimation of such deposits.

Scientific novelty of the obtained results.

Two models have been devised through the research: quanititative model of rollfront genesis and a new geostatistical method to construct geological models of rollfront deposits.

Quanititative model can potentially be used to generate synthetic data for deposits formed via infiltration of minerals through porous medium and redox chemical reactions, to test and verify any prospective modelling techniques based non-deterministic approaches.

A new geostatistical method provided geological models of infiltration type depostis with higher accuracy, which would lead to decrease of exploration costs.

Practical significance of the work.

The model of rollfront geneis can be used to verify the accuracy of any interpolation technique applied to contour the ore body and resource estimation. Relationship between filtration velocity and deposit propogation through permeable media due to redeposition has been determined. This can lead to discoveries of new deposits at macro scale.

A new geostatistical method is significantly more accurate as compared to conventional methods, which will reduce costs of exploration. This will be achieved

through fewer exploratory wells necessary to construct a geological model with sufficient accuracy.

Software modules based on the results of conducted research have been deployed at deposits developed by subsidiaries of JSC NAC Kazatomprom.

The connection of the work with state scientific programs. Some parts of this dissertation were conducted within the framework of the following projects:

– BR05236447 "Intelligent control and decision-making systems for the development of uranium and oil deposits" targeted program funding for scientific research from the Ministry of Education and Science of the Republic of Kazakhstan, 2018 – 2020, project number GR 0118RK01275

– AP08051929 « The study of the mechanisms of ore genesis and development of high accuracy digital technology to contour ore bodies in rollfront type mineral deposits », grant funding for scientific research from the Ministry of Education and Science of the Republic of Kazakhstan, 2020-2022, project number GR 0120PK00058.

– **The individual contribution of the doctoral candidate to the preparation of articles.** The author of the dissertation took part in formulating the problem, developing the methods/models, writing codes, conducting calculations, as well as writing the article itself in all of the following papers. First author in all of them.

– Aizhulov, D., Tungatarova, M., & Kaltayev, A. (2022). Streamlines based stochastic methods and reactive transport simulation applied to resource estimation of roll-front uranium deposits exploited by in-situ leaching. Minerals, 12(10) doi:10.3390/min12101209. T

– Aizhulov, D. Quantitative model of the formation mechanism of the rollfront uranium deposits / D. Aizhulov, N. Shayakhmetov, A. Kaltayev // Eurasian chemico-technological journal. – 2018. – № 3. – С. 213-221. (Scopus, SJR 0.157).

– Aizhulov D.Y., Kurmanseiit M.B., Tungatarova M.S. Application of geostatistical methods for reconstruction of lithological and mineralogical structure of uranium deposit by interpolating well data // Казахский Национальный Университет имени Аль-Фараби, Вестник КазНУ, серия математика, механика, информатика - №3 (91) -2016. -С.53-58.

– Aizhulov, D. 2022 и Tungatarova, M. Comparison of geostatistical methods for modeling infiltration-type uranium deposits. // "Physical and mathematical sciences." 79, 3 (June. 2022). DOI: https://doi.org/10.51889/2022-3.1728-7901.401 .

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– Aizhulov D.Y., Kaltayev A., Study of geological and hydrological mechanisms of formation of deposits in the form of roll fronts // Current problems of the uranium industry: Materials of the VIII international scientific and practical conference, August 3-5: Collection of proceedings - Astana, Republic of Kazakhstan: P. 120-121, 451 p.

– Айжулов Д.Е. Калтаев А., Құрмансейіт М. Б., Кульджабеков А. Б., Интерполяция и построение 3D модели на основе скважинных данных, Конференция"VII международной научно-методической конференции "Математическое моделирование и информационные технологии в образовании и науке", посвященной к 70-летию профессора Е.Ы. Бидайбекова и 30 летию школьной информатики. 1-2 октября 2015 г. Министерство образования и науки РК. Казахский Национальный педагогический Универси", уровень Международный, КАЗАХСТАН, Алматы, 01.10.2015-02.10.2015.

– Айжулов Д.Е., Калтаев А., The study of rollfront properties and formation mechanisms by examining uranium deposits in Tianshian megaprovince, Конференция"27th Conference Drilling-Oil-Gas", уровень Международный, ПОЛЬША, Krakow, 08.06.2016-10.06.2016

– Айжулов Д.Е. Калтаев А., Application of geostatistical methods for reconstruction of lithological and mineralogical structure of uranium deposit by interpolating well data, Конференция"3 международная научно-методическая конференция «Математическое моделирование механических систем и физических процессов» посвященная 75-летию юбилея и 55-летию научно-педагогической деятельности академика НАН РК, академика НИА РК, лауреата Государственной премии РК в области науки и техники, доктора технических наук,", уровень Международный, КАЗАХСТАН, Алматы, 18.11.2016-19.11.2016

– Айжулов Д.Е., Калтаев А., Тунгатарова М.С., Шаяхметов Н. М., Құрмансейіт М. Б., Шаяхметов Н. М., Интеллектуальные системы управления и принятия решений для разработки месторождений урана, Круглый стол "Цифровизация промышленности-основа четвертой промышленной революции", уровень Республиканский, КАЗАХСТАН, дата начала: 20.04.2018

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– Aizhulov D., Kaltayev A. Stochastic modeling of uranium roll-front deposits based on stream-line simulation / D. Aizhulov, A. Kaltayev // International Scientific and Practical Conference on “Actual Problems of Informatics, Mechanics and Robotics. – Almaty, 2018

– Айжулов, Д. Е.Цифровая методика оконтуривания рудного тела пластово-инфильтрационных месторождений на основе линий тока / Д.Е. Айжулов, А. Калтаев // В трудах международной конференции: рациональное использование минерального и техногенного сырья в условиях Индустрии 4.0. – Алматы, 2019. – С. 465 – 467

In addition to this, within the dissertation 10 copyright certificates were obtained for various software modules, that are successfully being used in the industry. Author of the dissertation has been main speaker at all conferences listed in the dissertation thesis.