MINISTRY OF EDUCATION AND TRAINING
HANOI UNIVERSITY OF MINING AND GEOLOGY

TRAN LE CHAU

RESEARCH ON METHODS FOR EXPLORING AND EVALUATING URANIUM RESOURCES IN SANDSTONES: A CASE STUDY OF THE NONG SON BASIN, QUANG NAM PROVINCE

Major: Geological Engineering
Code: 9520501

SUMMARY OF
DOCTORAL DISSERTATION IN ENGINEERING

HA NOI, 2024

The dissertation was completed at**: The Department of Exploration Geology, Faculty of Geosciences and Geo-Engineering, Ha Noi University of Mining and Geology.**

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INTRODUCTION

1. Necessity of the research

"The geological resources and minerals are not only important for the economic and social development of the country but also serve as long-term reserves that need to be properly planned, surveyed, evaluated, and explored; centrally managed and unified; sustainably, rationally, economically, and efficiently exploited and utilized. The focus should be on investigating and evaluating strategic and important minerals," as approved by the Prime Minister in Decision No. 334/QD-TTg dated April 1, 2023.

Currently, the demand for uranium in the industrial sector is highly increasing, especially in atomic energy development. Therefore, geological research, mineral potential assessment, exploration, and exploitation of uranium ore are urgent and crucial requirements for every country in the world, and Vietnam is not an exception.

Geological research results since 1954 have shown that Vietnam is one of the countries with potential for uranium, with the most promising being uranium in the late Triassic sandstone deposits distributed in the Nong Son Basin, Quang Nam province.

To date, the Nong Son Basin has been geologically mapped and mineral resources have been surveyed at scales of 1:200,000 and 1:50,000; many areas with uranium ore potential have been surveyed and evaluated; some areas have been explored and evaluated for reserves at level 122, and many in-depth research projects on uranium minerals in the Nong Son Basin sandstone deposits have been conducted. However, there are still many issues regarding the characteristics of uranium mineralization and uranium mineralogy; the conditions and types of uranium mineralization; the morphological, structural, and characteristic variations of the geological parameters of ore bodies; hence, determining the exploration and evaluation methods for uranium resources and reserves in the Nong Son basin sandstone deposits requires further detailed and comprehensive research.

Therefore, the topic: ***"Research on Methods for Exploring and Evaluating Uranium Resources in Sandstones: A Case Study of the Nong Son Basin, Quang Nam Province"*** has been conducted to meet the demands necessitated by both scientific and practical requirements, which are indeed crucial.

2. Objectives

- To investigate and clarify the variations and spatial variability of geological parameters of uranium ore bodies (morphology, size, clinostatism) in the sandstone deposits of the Nong Son Basin.

- To assess the influence of variations in industrial geological parameters of ore bodies on exploration activities; thereby selecting exploration and resource evaluation methods (with a focus on reserve/resource calculation methods) suitable for the type of uranium ore in the sandstone deposits of the Nong Son Basin, Quang Nam province.

3. Research subject and scope

The research subject is uranium in the sandstone deposits and related geological formations in the Nong Son Basin, with a scope covering approximately 3200 km^2.

4. Contents

- Collecting, synthesizing, and processing geological survey documents, and exploration data to elucidate the geological structure of mining areas or prospective areas and the controlling factors of mineralization, as well as the characteristics of uranium mineralization distribution in the sandstone deposits of the Nong Son basin.

- Clarifying the complexity of the geological structure; shape, size, clinostatism, and internal structure of the ore bodies in the areas.

- Studying the spatial variability and anisotropic characteristics of shape, thickness, U_3O_8 content, and associated elements in uranium ore bodies.

- Identifying factors influencing the selection of exploration methods and methods for assessing uranium resources/reserves in the sandstone deposits.

- Researching the selection of exploration methods and resource calculation methods for uranium in the sandstone deposits with high reliability and ensuring economic efficiency, with a focus on selecting deterministic resource calculation methods.

5. Findings

- The uranium-bearing rock layers in the late Triassic sandstone deposits of the Nong Son Basin exhibit two types depending on two lithostructural domains: (i) Bedded ore-bearing rock layers distributed in an arcuate shape along the ancient coastline belonging to the coarse-grained sandstone lithostructural domain, and (ii) Oriented parallel bedded ore-bearing rock layers belonging to the middle-grained sandstone lithostructural domain, corresponding to shallow sea or bay environments.

- Three aspects of uranium ore variability in industrial geological parameters have been elucidated in the sandstone deposits of the Nong Son Basin. The research results indicate that uranium ore bodies typically occur in layers (beds), lens-shaped bodies, or interconnected lens chains within a specific rock layer. The thickness of industrial ore bodies varies discontinuously, with internal structures ranging from simple to complex. The U_3O_8 content in industrial ore bodies follows a log-normal distribution, with uneven and particularly uneven variations. The variation in uranium content within ore bodies is more complex than thickness variations but remains stable within ore-bearing layers.

- The dissertation establishes the decisive factors in selecting exploration and resource assessment methods in the research area.

- Uranium mines in the sandstone deposits of the Nong Son Basin mainly belong to the III exploration category. The most rational exploration system involves combining excavation, vertical drilling, and geophysical methods, with a parallel line network layout, supplemented by fan-shaped or rectangular layouts with line spacings (along the strike) of 40 - 60 m and line structures (along the dip direction) of 25 - 30m.

- To enhance the reliability of uranium resource/reserve calculations in the sandstone deposits of the Nong Son Basin, the use of geostatistical block methods, combined with common Kriging methods, is necessary.

6. Scientific and Practical Significance of the Dissertation

6.1. Scientific Significance

- The novel research results on the variability of industrial geological parameters and the morphological-structural characteristics of ore bodies make significant contributions to the field of uranium exploration geology in the sandstone deposits of the Nong Son Basin, and uranium in Vietnam in general.

- The research results of the dissertation scientifically justify the geological parameters that determine the selection of exploration methods and resource/reserve calculation methods for uranium, contributing to refining exploration methodologies for uranium deposits in the sandstone deposits of the Nong Son Basin.

6.2. Practical Significance

- The research results contribute to providing a database for developing regulations on uranium exploration and enhancing the efficiency of exploration work for uranium deposits in the sandstone deposits of the Nong Son Basin.

- They provide geological production units with methods to establish mine groups, exploration networks, and methods for calculating uranium resources/reserves in sandstone deposits, which can be applied to other minerals with similar characteristics.

7. Defense Points:

Point 1: The dissertation argues that uranium ore bodies in the late Triassic sandstone deposits of the Nong Son Basin primarily exist as lens-shaped bodies, lens chains, or tabular forms, conformably situated within the surrounding rock. Industrial ore bodies exhibit complex morphology and structure, with discontinuous distribution along both strike and dip directions, unstable thickness variations, and highly heterogeneous U_3O_8 content, demonstrating significant anisotropy.

Point 2: The dissertation posits that the morphological-structural characteristics, orientation, and variability of industrial geological parameters (thickness, U_3O_8 content) are crucial determinants in selecting exploration methods and estimating uranium resources/ reserves. Uranium mines in the late Triassic sandstone deposits of the Nong Son Basin belong to the III exploration category; the most rational exploration network layout involves a parallel line configuration, supplemented by fan-shaped or rectangular patterns.

8. Structure of the dissertation

The dissertation comprises 145 pages typed on A4, including 31 figures, 23 tables, and 19 illustrative images. In addition to the introduction and conclusion, the dissertation content is presented in 4 chapters.

9. Literature and documents

- The dissertation was completed based on real documents directly researched, collected, and synthesized by the researcher during their work and participation in scientific research projects at the Geological Division for Radioactive and Rare Elements. Specifically, these include:

- Geological mapping and mineral surveys of the Nong Son Basin at various scales, along with related specialized documents published in the area of study.

- Documents from research projects, theses, journal articles, and scientific reports, both domestically and internationally, related to the topic, including specialized journals, published books, and internet resources.

- The documents of investigation, assessment, and exploration; the results of sample analysis. Especially, the newly acquired documents during the implementation of the uranium exploration project in the Pa Lua – Pa

Rong area conducted by the Geological Division for Radioactive and Rare Elements from 2010 to 2021.

- Our supplementary analysis, including analysis results of 04 thick section and 04 samples analyzed by using scanning electron microscopy equipment.

CHAPTER 1: OVERVIEW OF GEOLOGICAL AND MINERAL CHARACTERISTICS OF THE NONG SON BASIN

1.1. Overview

The Nong Son Basin is located within Nam Giang district, Quang Nam province. It is approximately 100 km southwest of Da Nang city along National Highway 14B. The study area is situated in a region characterized by medium-high mountainous terrain, with elevations ranging from 250m to 1034m. The mountain ranges extend from northwest to southeast, with common slopes ranging from 20-35 degrees.

Currently, there are various opinions regarding the tectonic position of the Nong Son Basin on the structural map of the region. Phan Van Quynh and colleagues (1992) suggest that the structure of the Nong Son Basin resembles a complex overlapping system (the Song Bung fault trending northwest-southeast and the Nong Son fault trending east-west), formed by different fault systems. Nguyen Van Trang (1986) categorizes the study area into the Nong Son zone, where Mesozoic formations play a significant role in the formation of the Nong Son zone. Tran Van Tri, Dang Vu Khuc, and colleagues (2009) divided the territory of Vietnam into three major tectonic units: Pre-Cambrian continental blocks modified during the Phanerozoic, Early Neoproterozoic - Mesozoic mountain-building systems, and Late Paleozoic - Cenozoic intraplate basins.

1.2. The history of geological and mineral research

The history of geological and mineral research in the study area involves various activities ranging from geological mapping at scales ranging from 1:500,000 to 1:50,000, mineral exploration and assessment at scales ranging from 1:25,000 to 1:10,000, to exploration activities in the Pa Lua - Pa Rong area of Nam Giang district at a scale of 1:2,000. Additionally, there have been specialized research projects focusing on uranium mineralization.

These research endeavors have provided valuable documentation for the researcher to consult and build upon, contributing to the development and resolution of the research topics addressed in the dissertation.

1.3. Geological Characteristics

- ***Stratigraphy:*** The study area comprises sedimentary rocks ranging in age from Proterozoic to Cenozoic, including the Kham Duc-Nui Vu Complex (NP_3-$Ɛ_1$ *kv*), A Vuong Formation ($Ɛ_2$-O_1*av*), Song Bung Formation (T_2a *sb*), An Diem Formation (T_3n *ađ*), Suon Giua Formation (T_3n-r *sg*), Tho Lam Formation (J_{1-2} *tl*) and Quaternary deposits (Q).

- ***Intrusions:*** Within the Nong Son Basin and adjacent areas, there are three intrusive complexes present: the Dai Loc Complex (γD_1 *đl*), Bến Giằng - Quế Sơn Complex ($\gamma\delta P_{2-3}$ *bq*) and Cha Van Complex ($\nu\sigma P_3$-T_1 *cv*).

- ***Structural Characteristics and Tectonics:***

+ *Folds and Folds:* The Nong Son Basin is a large basin divided into two sub-basins with axes nearly parallel to each other, namely the Nong Son Basin and the Song Bung Basin. Alongside these basins are secondary folds such as the Sơn Tuyền fold, Khe Cao fold, and Suon Giua fold.

+ *Structural Disruptions:* Research results have identified four main fault systems in the study area: a north-south trending fault system, a northwest-southeast trending fault system, a northeast-southwest trending fault system, and an oblique fault system.

- ***Rock Features, Paleogeography, and Distribution Patterns of Late Triassic Sediments in the Nong Son Basin:*** The Nong Son Basin resembles a half-open van-shaped basin connected to a wide sea, with Late Triassic sediments showing cyclical structures related to global sea level fluctuations. According to researchers, the area exhibits two vivid sedimentary cycles in both geological cross-sections and stratigraphic maps of the An Diem (T_3n *ađ*) and Suon Giua (T_3n-r *sg*) formations. Each sedimentary cycle corresponds to three rock formations. Therefore, these two sedimentary cycles are succinctly referred to as the An Diem cycle and the Suon Giua cycle.

1.4. Minerals: Research results suggest that the minerals in the study area consist of fuel minerals, non-metallic minerals, and metallic minerals.

1.5. Some existing limitations in previous research

- To synthesize and analyze the results of uranium investigation, assessment, and exploration in the Nong Son basin from previous studies, in order to implement the identified contents in the relevant strategies and plans related to radioactive minerals in general and uranium assessment and exploration in the Nong Son basin in particular, it is necessary to continue researching and refining some specific aspects as follows:

- The Pa Lua - Pa Rong area has been explored and reserves have been approved. However, establishing a comprehensive scientific basis to explain the variability and spatial variability of the geological parameters of uranium orebodies (morphology, size, dip) for all explored orebodies has not been completed.

- In the Nong Son basin, some areas with uranium potential in sedimentary deposits have been investigated and evaluated, requiring further exploration in the next phase. In these areas, the full range of morphological forms and structures of uranium orebodies, as well as the distribution laws of these morphological forms in relation to the structure of the Nong Son basin, have not been fully determined. Establishing a complete scientific basis to support exploration work in these areas is essential and requires further research and refinement.

- There is no comprehensive and complete work on the three aspects of uranium ore formation variation in the Nông Sơn basin, which serves as a scientific and practical basis for choosing appropriate methods for exploration and assessment of uranium resources and reserves.

- Although some studies have established mining groups and exploration networks for uranium in sedimentary deposits, the existing results do not ensure completeness and comprehensiveness. They have not yet identified the important factors that play a decisive role in grouping mines, selecting exploration methods, and assessing uranium reserves in the Nông Sơn basin.

- Currently, the Ministry of Natural Resources and Environment is implementing the project "Comprehensive Assessment of Mineral Potential in the Central Central Region to Serve Socio-Economic Development". It is expected to discover and delineate new areas with uranium potential in sedimentary deposits. Therefore, it is necessary to improve the scientific basis to support the assessment and exploration work for the newly identified areas in the above project.

CHAPTER 2: THEORETICAL BASIS AND RESEARCH METHODS

2.1. Theoretical basis

2.1.1. Basic concepts

In the thesis, several fundamental concepts are utilized, including: ore deposit, percolation (leaching) deposit, ore manifestation, ore point, endogenous mineralization, exogenous mineralization, alteration mineralization, hydrolysis, dissolution phenomenon, oxidation-reduction reaction, geochemical barrier, random

variation, non-random variation, spatial variation, three aspects of variation, exploration system, exploration network, resource assessment.

2.1.2. Overview of Uranium

In nature, uranium does not exist in a free metallic form and does not form minerals belonging to the sulfur or arsenic groups. It exists in oxidation states of [+4] and [+6]; oxidation states of [+3] and [+5] only exist in laboratory settings. In oxidizing environments, uranium exists primarily in the [+6] oxidation state, while in reducing environments (environments lacking or low in oxygen), uranium exists in the [+4] oxidation state, which is the most important form of uranium. Uranium has three isotopes: U^{238}, U^{235}, and U^{234}, accounting for 99.27%, 0.72%, and 0.01% of the atomic abundance, respectively.

2.1.3. Mineral Characteristics

Uranium typically occurs in primary uranium minerals such as uraninite, hydrated uraninite, and coffinite associated with chlorite, fine-grained pyrite, and secondary uranium minerals in alteration zones, including autunite-meta-autunite, meta-uranocircite, and uranophane. These minerals are often accompanied by goethite and hydrous oxides; rarely, early-stage uraninite may be associated with hematite and manganese oxides.

2.1.4. Classification of uranium mineral deposit types worldwide and in Vietnam

2.1.4.1. Uranium mineral deposit types worldwide

According to the classification by the International Atomic Energy Agency (IAEA) in 2009, all known uranium mines are divided into 14 types of geological-industrial mines. Among them, uranium mines in sedimentary deposits are quite common worldwide and account for a significant proportion of reserves. However, the ore grade is usually relatively low. Uranium is formed through syngenetic processes during sedimentary deposition, and uranium accumulation occurs due to the percolation and migration of fluids within the rock mass (Dahlkamp, 1994; Cuney and Kyser, 2009).

2.1.4.2. Uranium mineral deposit types in Vietnam

Similar to other minerals, uranium has been discovered in metamorphic sedimentary rocks ranging from the pre-Cambrian to Mesozoic ages, as well as in volcanic or intrusive rocks of the Cenozoic era. Uranium deposits in sedimentary formations are mainly distributed in the late Triassic sedimentary rocks in the Nong Son area (Quang Nam province). This type of deposit is considered the most promising in Vietnam at present.

2.2. Methodology

2.2.1. Approaches

The dissertation employs a systemic approach, a historical approach, a quantitative approach (or a modern approach), and an interdisciplinary approach.

2.2.2. Research methods

The dissertation employs a combination of traditional methods along with modern methods, specifically including: modeling methods (such as diagrammatic, schematic, and cross-sectional modeling); geostatistical methods including statistical methods (uni-variate statistics, bi-variate statistics), Variogram function (structural function), and spatial interpolation techniques. Additionally, for the study of uranium mineralization in sedimentary deposits, the following methods are utilized: thin section petrographic analysis of sedimentary deposits, quantitative analysis of particle size parameters on thin sections, and determination of roundness coefficient (Ro).

CHAPTER 3: CHARACTERISTICS OF URANIUM MINERALIZATION IN THE SEDIMENTS OF THE NONG SON BASIN

3.1. Geological Structure Characteristics of Mining Areas and Uranium Mineralization in the Nong Son Basin

The Nong Son Basin is primarily composed of sedimentary formations such as river deposits, marshes, and lagoons, with a structural configuration resembling a basin, divided into two secondary basins: the Song Bung Basin and the Tho Lam Basin. The main geological formations consist of the An Diem Formation, the Middle Slope Formation, and the Tho Lam series, ranging in age from late Triassic to Middle Jurassic, surrounded by metamorphosed sedimentary formations of the A Vuong Formation from early Cambrian to early Ordovician and intrusive magmatic rocks of the Dai Loc Complex to the north and southwest. The southern part of the basin is influenced by intrusive magmatic rocks of the Ben Giang - Que Son Complex.

Previous research results (surveys, assessments, explorations) have categorized mineralized areas within the Nong Son basin into regions with different characteristics of mineralization and prospects, such as: Khe Hoa - Khe Cao, Pa Lua - Pa Rong, Southeast Ben Giang, Ca Lieng - Suon Giua. Among these, the Pa Lua - Pa Rong, Khe Hoa - Khe Cao, and Southeast Ben Giang areas are considered to have more industrial prospects.

3.1.1. Stratigraphy

Characteristics of the stratigraphy and ore-bearing rock units in each area are different as follows:

- Pa Lua - Pa Rong Area: This area has been explored from 2011 to 2020. Results indicate that the Pà Lua - Pà Rong area is primarily composed of formations of the An Diem Formation, divided into two sub-formations: the Lower Sub-formation (T_3n *ađ*$_1$), consisting of three units mainly composed of conglomerates, multi-mineral cemented sands, coarse-grained sandstone containing gravel, interspersed with argillite lenses, purple-colored arkose clay cemented sands, fine-grained sands, and claystone. The average thickness is about 200m. The Upper Sub-formation (T_3n *ađ*$_2$) mainly comprises light gray fine-grained sandstone, the average thickness is over 20m. The elevation ranges from 80 - 110^0 with an average slope of 10 - 12^0.

- Khe Hoa - Khe Cao Area: Located in the eastern part of the Thanh My uplift and the western edge of the Tho Lam syncline. Gray-colored sandstone of varying sizes from small to medium is prevalent, belonging to the An Diem Formation (T_3n *ađ*) are common. Uranium is also found in claystone and coarse-grained sandstone but less commonly. The ore-bearing rocks are gray or black when fresh and turn yellow-brown, reddish-brown, or gray-white in the metamorphic zone.

- Southeast Ben Giang Area: Situated to the south of the Nong Son basin. It is surrounded to the south and west by intrusive rocks of the Ben Giang - Que Son complex, and to the north by intrusive rocks of the Cha Van complex. The uranium-bearing rocks primarily consist of sandstone from the An Diem Formation (T_3n *ađ*).

- Ca Lieng – Suon Giua Area: Located on the northeastern fringe of the Song Bung Basin, the northwestern slope of the Thanh My uplift block, and north of the Khe Hoa - Khe Cao area. The primary ore-bearing rock is fine to medium-grained sandstone, with the largest uranium concentration found in the fine-grained sandstone containing organic black material of the An Diem Formation (T_3n *ađ*). The mineral fragments mainly originate from magmatic rocks (granite, acid volcanic rocks).

3.1.2. Mamatic intrusions

- Dai Loc Complex: This is the oldest complex located at the periphery of the Nong Son Basin. It mainly consists of heavily deformed granite rocks, which are predominantly exposed at the northern fringe of the Nong Son Basin. The widespread presence of these rocks in the composition of the An Diem Formation, especially in the lower part of this formation,

indicates that the rocks of the Dai Loc Complex are an important source of material for the sedimentary formations in the Nong Son Basin.

- Ben Giang - Que Son Complex: Rocks belonging to the Ben Giang - Que Son complex are exposed to the west and south of the research area, with the western side directly overlain by formations of the An Diem Formation.

- Cha Van Complex: This complex is exposed to the west of the Nong Son Basin, forming a narrow belt. Together with the metamorphosed sedimentary formations of the Kham Duc - Nui Vu complex, it forms a structural ridge extending along the north-south axis. The main components are mafic rocks.

Currently, no young magma formations cutting through the An Diem Formation have been recorded within the Nong Son Basin, indicating that magma activities in this area were weak or ceased after the late Triassic sedimentation period.

3.1.3. Tectonic setting

3.1.3.1. Faulting

In the research areas, the phenomena of fracture and faulting are quite pronounced and comprise various types. The fracture systems exhibit diverse characteristics and typically develop into zones ranging from a few centimeters to meters in thickness, causing significant deformation and displacement of rocks on both sides.

3.1.3.2. Folding

In the Nong Son basin, the phenomenon of folding is strongly developed and plays a crucial role in forming structures shaped like basins. These folds are often complicated by high-grade folding systems oriented from northeast to southwest, and the intersection of these two-fold systems creates secondary dome and basin structures within the Nong Son basin. Additionally, smaller folds can also be observed locally in the research area, such as the Khe Cao syncline.

3.2. Uranium mineralization

Uranium ore is concentrated in arkosic or grauwacke-type sandstone, with grauwacke typically exhibiting a gray or purplish-gray color with variegations. In the An Diem area and the coal mines of Nong Son, in addition to the mentioned ore bodies, there are also occurrences of uranium mineralization within coal seams or shale layers. The ore bodies are usually concentrated in the form of lenses or elongated vein-like structures.

3.2.1. Distribution and Morphology-Structure of Ore Bodies

The ore bodies are typically concentrated in lens-like formations, vein chains, or distributed nests within specific rock layers. The morphology and structure of the ore bodies are quite complex and vary significantly along strike and dip directions (with thickness ranging from several tens of centimeters to several meters, exhibiting varying uranium concentrations). Within the ore bodies, there are often interbedded rock lenses. The boundary between the ore body and surrounding rock is not clearly defined, and is determined primarily through geological logging of drill holes and the results of uranium geochemical analysis.

Additionally, the distribution of uranium in the area is manifested by a high anomaly of radiometric geophysical field, or dispersed halos of certain elements such as V, Pb... These anomalies are considered closely related to the uranium mineralization in the region.

3.2.2. Mineral characteristics

Uranium ore exists in two forms: primary uranium ore and secondary uranium ore. Primary uranium ore is typically solid, with gray or black coloration, and has a structure that can be nodular, disseminated, or sometimes stilolitic in nature. Secondary uranium ore is less solid, sometimes brittle, and often exhibits colors ranging from light brown to yellow-red. It commonly has a stilolitic structure on remnants of disseminated or nodular structures.

3.2.2.1. Ore mineralogy

The uranium mineral group primarily exists in two forms: primary uranium minerals and secondary uranium minerals.

* *Primary uranium minerals:* Typically black or dark brown in color. Uranium minerals found here are often associated with chlorite and pyrite, indicating that the formation of uranium minerals occurs under reducing conditions.

* *Secondary uranium minerals:* These are products of alteration of primary uranium minerals and are formed under conditions of alteration, and oxidation when uranium ore bodies are exposed or fall into oxidizing environments. Secondary uranium minerals often have yellow, lemon-yellow, or greenish-yellow colors, making them easily identifiable to the naked eye.

* *Associated minerals:* These are minerals that coexist within the uranium ore alteration zone and have not undergone alteration. Their formation is closely related to the ore-controlling zone formation process. They include sulfide minerals such as pyrite, marcasite, galena, occasionally

chalcopyrite and sphalerite, gypsum and barite, goethite, hydro goethite, and less commonly hematite and manganese hydroxides.

3.2.3. Geochemistry

- *Pa Lua - Pa Rong area:* Statistical processing of U_3O_8 content from 14,563 in single samples in exploration projects shows that the highest U_3O_8 content was 5.689%, the lowest was 0.001%, and the average was 0.033% U_3O_8, with a coefficient of variation of 290%, indicating a highly uneven distribution. In ore bodies, U_3O_8 content at depth generally maintains better than in ore bodies in altered zones. Analysis of 160 ore samples with 11 parameters per sample showed that V_2O_5 content was relatively high, while As, Pb, and P content varied widely, and S content remained relatively stable in ore bodies. Uranium was closely related to V and Pb, forming associations of U - V - Pb elements.

- *Khe Hoa - Khe Cao Area:* The uranium content in uranium ore bodies ranged from 0.023% to 0.06% on average, with a distribution ranging from uneven to highly uneven (variation coefficient Vc = 90.0% to 176%).

- *Southeast Ben Giang Area:* The ore-bearing rock layers all had higher U3O8 content than the border content (Cb ≥ 0.01%). Particularly, ore-bearing rock layer 1 was noteworthy, containing not only uranium but also low levels of V, Pb, Cu, and Mo, which were not significant.

- *Ca Lieng - Suon Giua Area:* Research results indicate that U_3O_8 content in sandstone samples was higher than in coal shale. Fe^{2+} and CO_2 content in coal shale were higher than in sandstone.

3.3. Role of Factors in Uranium Ore Formation in the Sandstone Deposits of Nong Son Basin

3.3.1. Structural-Tectonic Factors

According to many previous studies, the Nong Son Basin belongs to the type of intracratonic basin connected with the sea, which formed when the continental crust experienced extensional tectonics in the late Triassic. The tectonic environment in the basin is relatively stable, so the rock layers are not metamorphosed, nor are they destroyed or tilted towards the center of the basin. Therefore, this is a favorable environment for the continuous migration of oxygen-rich groundwater from the basin margin towards the center along the slope. This is evidenced by the ore bodies in the form of "pseudo-bedded veins" and vein chains, which are relatively relaxed and stable as documented.

After ore formation, tectonic activities occurred vigorously at different geological times, resulting in the formation of high-grade folds and various-scale fault systems. Along with these fault systems are fracture zones, fault zones, and localized destruction of geological formations and pre-existing uranium mineralization, which may also alter the geochemical environment of the area to some extent.

3.3.2. Hydrological Factors

In the humid tropical climate zone, the Nong Son Basin and the surrounding hydrogeological formations always have a high groundwater level, so the thickness of the unsaturated zone is not large, which is very favorable for oxygen infiltration into the groundwater layer. This is one of the important factors contributing to the creation of oxidized and reduced zones in the arkosic, arkosic, grauwacke, and grauwacke-like conglomerate and sandstone deposits. The reducing zone is where the industrial uranium ore formation process takes place in the Nong Son Basin, with characteristic minerals such as black minerals like nasturan, cofinite associated with pyrite, marcasite, chalcopyrite, sphalerite, galena, ...

3.3.3. Climate Factors

The research area is located in a humid tropical climate zone with abundant rainfall, rich and diverse vegetation, and thick soil layers containing a lot of organic matter, so the dissolved forms of organic matter (humic acid and CO_2) can easily penetrate the aquifer along with groundwater. These combinations present in groundwater are important factors in forming the biologically zoned properties in the conglomerate, arkose, and grauwacke with high permeability of the An Diem formation; this is also a decisive factor in the rise of the oxidized-reduced zone.

3.3.4. Lithological Factors

Lithological factors and the characteristics of sedimentary rocks play a significant role in the formation of uranium deposits. In the Nong Son Basin, the layers of arkosic conglomerate, arkosic sandstone, grauwacke, and grauwacke-like conglomerate of the An Diem formation share many similarities with uranium-bearing conglomerates worldwide: they were formed in an inland basin environment connected to the sea; they have a late Triassic age and are un-metamorphosed; they are gray in color with high permeability; they are rich in organic matter and bitumen; they contain iron sulfide and other reducing agents. Additionally, these conglomerate layers are often sealed by impermeable layers or very poorly permeable layers.

3.3.5. Geochemical Factors

According to previous research results and additional findings from doctoral research, primary uranium accumulation zones within conglomerates contain ore minerals such as cofinite, nasturan, and to a lesser extent, hydrated nasturan, along with associated sulfide minerals, primarily pyrite. Pyrite is a common mineral closely associated with nasturan and cofinite. In some instances, pyrite aggregates resembling fish roe are enclosed by nasturan. This indicates that before the ore-forming period, pyrite already existed in conglomerate layers and was concentrated in various-sized nodules or "lens" structures. Research results suggest that the geochemical pattern in the Nong Son Basin is fundamentally consistent with pyrite-type geochemistry.

3.4. Overview of the Mechanism of Uranium Ore Formation in the Nong Son Basin

3.4.1. Uranium Supply Source

The Nong Son Basin was formed during the late Triassic period and continued to develop during the Jurassic, Neogene, and Quaternary periods. The basement and surrounding uplifted blocks of the Nong Son Basin consist of metamorphic rocks belonging to the Khâm Đức - Núi Vú complex, the A Vuong formation, sedimentary rocks intercalated with neutral to acidic volcanic eruptions of the Song Bung formation, and acidic to neutral intrusive magmatic rocks of the Dai Loc and Bến Giằng - Quế Sơn complexes. These geological formations constitute the source of sedimentary material and uranium for the Nong Son Basin, with particular importance attributed to the metamorphic rocks of the Khâm Đức - Núi Vú complex, the intrusive magmatic rocks of the Bến Giằng - Quế Sơn complex, and the Dai Loc complex.

3.4.2. Uranium Ore Formation Mechanism

3.4.2.1. Favorable Geochemical Types for Ore Formation

Previous research results, along with additional findings, indicate that the geochemical type in the Nong Son Basin is generally consistent with pyrite geochemistry. This geochemical type is a prerequisite for the formation of impregnated ore deposits through the oxidation-reduction process, with overlapping and spaced layers of ore veins.

3.4.2.2. Ore Formation Mechanism

During the formation period of the An Diem formation, the sedimentary material mainly consisted of weathering products from metamorphic rocks of the Khâm Đức - Núi Vú complex, the A Vuong

formation, granitic rocks of the Dai Loc complex, the Bến Giằng - Quế Sơn complex, and the Song Bung formation. These sedimentary materials typically contain fragments containing uranium minerals and uranium-bearing minerals. After the lithification stage, in a humid tropical climate, the weathering products from the hinterland continued to migrate towards the high slopes of the basin, while the groundwater level in the basin and surrounding hydrogeological blocks rose, creating favorable conditions for free oxygen to infiltrate into the groundwater with high concentrations. Under these conditions, groundwater containing uranium in the hinterland escapes through fractures, and water in the cover layer infiltrates into the top of the impregnated layers of sloping sedimentary rocks, then moves downward along the slope of the highly permeable layers of the An Diem formation.

As the oxygen-rich groundwater moves along the slope of the sedimentary layers, continuous oxidation reactions occur, leading to the depletion of oxygen, resulting in the appearance of the interface between the oxidized and reduced zones. Upon transitioning to a reducing environment, the reducing organic sulfur compounds in the water and the Eh of the water decrease sharply, accompanied by the conversion of uranium to the insoluble +4 oxidation state. Subsequently, uranium completely precipitates to form high-grade uranium ore bodies meeting industrial standards.

After the ore formation process, due to tectonic activities, both the rock units and ore bodies undergo destruction, leading to phenomena such as oxidation, migration, and localized re-deposition of uranium in favorable fractures and cavities. This phenomenon explains why the absolute ages of uranium ores fluctuate widely, ranging from 144 million years (Late Triassic - Early Jurassic) to 14 million years (Neogene - Quaternary). (Source: Nguyen Truong Giang, 2018).

CHAPTER 4: SELECTION OF EXPLORATION AND EVALUATION METHODS FOR URANIUM RESOURCES IN THE DEPOSITS OF THE NONG SON BASIN

4.1. Variations in Geological Parameters of Uranium Ore Bodies

Based on the documentation collected from exploration, assessment, and mining of uranium ores, NSC synthesizes and utilizes a combination of geological mathematical methods, incorporating variogram analysis and application of geostatistics to evaluate the variations in geological parameters of ore bodies (such as thickness, U_3O_8 grade, etc.) and their

impact on exploration methods and uranium reserves estimation in the Nong Son Basin. The focus will be on the Pa Lua - Pa Rong, Khe Hoa - Khe Cao, and Southeast Bến Giằng regions.

4.1.1. Rules and Structure of Uranium Ore Mineralization Variation

The results of modeling ore bodies using geological cross-section systems and establishing iso-grade maps (iso-grade, iso-thickness, and iso-grade thickness) of ore body 1, block A - Pa Lua - Pa Rong area conducted by Lê Quyết Tâm and Nguyễn Tiến Phú in 2021, allow for the following observations:

- Ore bodies tend to plunge northeastward (45 to 55°) with dip angles ranging from 5 to 15°, occasionally up to 20°, with some nearly horizontal positions. Overall, the ore bodies have tabular forms with some high-angle folds developed on them.

- The morphology and structure of ore bodies are relatively complex, with industrial bodies appearing as chains of lenses and unclear bulges. The thickness of industrial ore bodies in the Pa Lua - Pa Rong area varies discontinuously and irregularly, with no apparent pattern; internal structures range from simple to complex (containing few to multiple layers of interbedded rock).

- The thickness and U_3O_8 grade of ore bodies 1 and 2 (TQ1 and TQ2) are closely correlated (Rxy = 0.7 for TQ1 and Rxy = 0.6 for TQ2). Industrial ore bodies are concentrated and relatively stable in the central area, decreasing gradually northward and southward (along strike) in both thickness and grade.

- Industrial uranium ores are distributed in lens-like chains and are interconnected within a certain ore-bearing rock layer, with lengths along strike ranging from 35m to 250m, averaging from 60 to 110m; along dip, they vary from 25 - 35m to 120 - 130m, with an average of 50 - 100m. The spacing between industrial uranium lenses ranges from 20m to 100m.

4.1.2. Variability in Thickness and U_3O_8 Content in Ore Bodies

The degree of variation in thickness and U_3O_8 content is fundamental in determining the choice of exploration methods and estimating mineral reserves, particularly for uranium. To model and assess the variability in ore body thickness parameters, we utilize one-dimensional statistical models.

4.1.2.1. Ore Body Thickness

- The thickness of uranium ore bodies (both industrial and geological ore bodies) varies widely, ranging from 0.5 to 19.1 meters, with an average of 1.15 to 3.27 meters. These ore bodies are predominantly concentrated in

the range of 1.0 to 2.7 meters (constituting 50 to 70%), categorized as thin to moderate thickness ore bodies, with some exceptions having lenses that are very thick.

- The statistical distribution characteristics of the thickness of industrial ore bodies can be described by a standard logarithmic distribution. The variability in thickness is classified as unstable to very unstable (Vm from 43.0% to 100.3%). Specifically, the thickness of industrial ore bodies (Pa Lua - Pa Rong) exhibits more complex variations compared to geological ore bodies (in other areas).

4.1.2.2. U_3O_8 content

The statistical processing results of U_3O_8 content in ore bodies (both industrial and geological) in the research areas show:

- In the Pa Lua - Pa Rong, Khe Hoa - Khe Cao, and Southeast Ben Giang regions, the uranium ore grade in the ore-bearing rock layers varies from 0.001% to 5.689% U_3O_8, with an average of 0.033%. The distribution follows a standard logarithmic form. The U_3O_8 content in different types of rocks all falls under the category of particularly unstable.

- In the coarse-grained conglomerate, the U_3O_8 content is higher compared to medium and fine-grained conglomerates, and the distribution is more complex. Additionally, the research results also indicate that coarse-grained conglomerates are more favorable for uranium ore formation than medium and fine-grained conglomerates due to their larger pore sizes and higher organic matter content.

- In industrial ore bodies, the uranium ore grade varies from 0.01% to 5.689% U_3O_8, with an average of 0.041%. The U_3O_8 content in industrial ore bodies can be described by a standard logarithmic statistical distribution, with uneven to particularly uneven distribution (V_C = 82.7 - 186.96%). The variability in uranium grade in ore bodies is more complex than thickness but more stable within ore-bearing layers.

- The variability in thickness and uranium grade exhibits a significant correlation, with thickness generally positively correlated with uranium grade. Bivariate analysis of thickness and uranium grade for the three ore bodies (TQ.1, TQ.2, TQ.3a) in the Pa Lua - Pa Rong area delineates thicker ore bodies typically having higher uranium grades and vice versa.

4.1.3. Anisotropic Characteristics of Uranium Mineralization

Various geological mathematical methods are used by exploration geologists to assess the anisotropic properties of mineralization, which is crucial in determining the mineral exploration network. For uranium in the

Nong Son basin conglomerates, several studies have employed variogram analysis (structural function) to experimentally study some ore bodies in block A in the Pa Lua - Pa Rong area. The research results show that for block A ore body 1, the highest variability coincides with the dip direction of the ore body (500), with an influential zone size of 30 m; the smallest variability coincides with the strike of the ore body.

Based on the research results of these studies, we conducted modeling in two basic directions (along the dip and strike of the ore bodies), with a rotation angle around each direction of ±22.50 for the thickness and grade (U_3O_8) of ore bodies TQ1, TQ2, and TQ2b in block G2 in the Pa Lua - Pa Rong area, ore body 4 in the Khe Cao area in the Khe Hoa - Khe Cao region, and ore body 1 in the Southeast Ben Giang area for further investigation.

The synthesized results determining the influential size (H) and anisotropy factor (A) of the characteristic ore bodies TQ1, TQ2, and TQ2b in block G2 in the Pa Lua - Pa Rong area, ore body 4 in the Khe Cao area in the Khe Hoa - Khe Cao region, and ore body 1 in the Southeast Ben Giang area are presented in the following table:

Area	**Ore bodies**	**The size of the influencing zone H(m) corresponds to the thickness**		**The anisotropy index A corresponds to the thickness**	**The influence zone size H(%) corresponding to U_3O_8 content**		**The anisotropy index A corresponds to U_3O_8 content**
		Strike	**Dip**		**Strike**	**Dip**	
Pa Lua – Pa Rong	TQ1 – Block A (The results of exploration)				125	30	4,16
	TQ1 – Block G2	79,1	46,9	1,68	85,0	47,0	1,81
	TQ2 – Block G2	83,0	43,8	1,89	83,0	44,6	1,86
	TQ2b – Block G2	80,0	44,1	1,81	86,0	44,6	1,93
Khe Cao	TQ4	91,3	46	1,98	90,0	45,0	2,0
Southeast Ben Giang	TQ1	88,0	45,8	1,92	78,0	45,0	1,7

Based on the calculated data shown in the table, it is evident that:

- The parameters of thickness and grade in the industrial ore bodies within the research area exhibit distinct directional characteristics; however, the U_3O_8 grades within the ore bodies demonstrate more complex variations than their thicknesses.

- For selecting the exploration grid, it is advisable to utilize a linear grid pattern, aligned parallel to the dip direction of the ore bodies, with a spacing between lines approximately 2 to 4 times the spacing between drill holes along the line.

4.2. Exploration Method Selection

In solid mineral exploration, the selection of exploration methods primarily focuses on addressing four main aspects: establishing exploration target groups, projects and their systems, exploration project networks, and reserve estimation methods.

4.2.1. Exploration Groups

Based on geological-mineral maps, exploration, and research endeavors, as well as findings from other studies and research conducted, uranium in the Nong Son basin sedimentary formations originates from infiltration and is formed through oxidation-reduction processes. Additionally, uranium mine sites exhibit complex structures due to post-ore formation tectonic activities, particularly fault systems. Upon comparison with the criteria for dividing exploration groups outlined in Circular No. 60/2017/TT-BTNMT dated December 8, 2017, issued by the Ministry of Natural Resources and Environment, and referencing the division of uranium exploration target groups by former Soviet scientists (Kajdan A.B, 1982), it is evident that most research areas (uranium mines in the Nong Son basin sedimentary formations) fall into exploration group III and require exploration to achieve a reserve of 122 level.

4.2.2. Exploration Projects and Infrastructure

Uranium in the Nong Son basin sedimentary formations originates from infiltration, thus exhibiting distinct characteristics compared to other types of minerals. We establish criteria for selecting exploration projects and infrastructure, including: the shape and size of ore bodies, the relationship of ore bodies with geological structural factors, topographic conditions, and the relationship of ore bodies with the surface terrain, and radiation characteristics. Based on these four criteria, combined with the exploration of uranium in the Pa Lua – Pa Rong region, we select exploration projects and infrastructure, including: surface excavation projects (trenches, exploration wells) combined with drilling projects, vertical core sampling, and geophysical methods. However, in cases where a detailed study of deep ore formation and technological sampling is necessary, the crosscut method may be used.

4.2.3. Exploration Network

Based on uranium exploration and survey results, key criteria for selecting a uranium exploration project network, including: the shape, size, and orientation of ore bodies; the variability of ore body thickness and U_3O_8 content; and the ore mineralization anisotropy. The best choice for an exploration project network is to apply a parallel linear network. In specific

blocks, a rectangular network may be applied, with the exploration line (horizontal line) aligning with the slope direction and the distance between lines is 2-4 times the distance between projects on the line; the maximum distance between projects along the slope (on the line) is about 30m.

Orientation of the exploration network

Exploration Group	Exploration Project Types	Reserve (122)		Resorces (333)	
		Strike (m)	Dip (m)	Strike (m)	Dip (m)
III	Drilling	50 - 60	25 - 30	100 - 120	50 - 60
	Excavation	25 - 30		50 - 60	

When conducting exploration work, it is necessary to allocate a contingency volume ranging from 10 to 15% of the total estimated volume for the entire exploration project. Contingency works are primarily focused on areas where the ore body has sharp abrupt edges or within ore bodies with complex morphology or structure, and in areas near faults.

4.3. Method Selection for Resource Evaluation

4.3.1. Determined Resources

For uranium in the Nong Son basin sandstone deposits, based on exploration documents and surveys of the Pa Lua - Pa Rong mine, key criteria that influence the selection of resource estimation methods, including the shape and size of ore bodies, ore body positioning, ore body thickness, and exploration network. Based on these four criteria, combined with survey results from the Pa Lua - Pa Rong area, applying the geological block method for uranium resource estimation is reasonable and suitable for the type of uranium deposit in the Nong Son basin sandstone deposits. Additionally, in specific cases, the Kriging method can be applied with specialized software to validate resource estimation results obtained through the geological block method.

In the exploration report approvaled in 2021, geologists from the Geological Division for Radioactive and Rare Elements applied the Kreiging interpolation method in the SURPAC software package to estimate the uranium reserves in the Pà Lừa - Pà Rồng area. The results of estimating uranium ore reserves using the traditional geological block method and the results using the commonly used Kreiging method in the SURPAC software package showed a difference of 2.7%. This result confirms that the methods chosen to estimate uranium reserves are suitable for the characteristics of ore mineralization and the exploration system conducted in the Pa Lua - Pa Rong area and can be applied to other areas in the Nong Son basin with similar uranium mineralization characteristics as the research area.

4.3.2. Undetermined Resources

Evaluating undetermined mineral resources is an extremely important and necessary task when establishing future development plans and providing geological survey managers with scientific grounds for developing geological survey plans and uranium exploration in the future. Based on practical summaries from uranium ore formation research since 1990, the following methods can be applied to forecast uranium resources in the Nong Son basin sandstone deposits as follows:

- Direct estimation methods based on ore formation parameters;
- Mineralization area analogy methods (similar to geological methods).

Geologists from the Geological Division for Radioactive and Rare Elements have used these methods in their surveys and evaluations to compare and estimate unconfirmed uranium resources in the Nong Son basin sandstone deposits.

4.3.3. Requirements for Exploration Work

To determine an appropriate exploration program for the type of uranium deposit in the Nong Son basin sandstone deposits, it is necessary to consider the complexity of the geological structure, morphological characteristics, size, ore body positioning, and resource scale. During exploration, to obtain reliable data and improve economic efficiency, it is essential to proceed sequentially through the following steps: Conduct exploration with the required volume according to the 333-level grid network as the basis for preparing a feasibility study report. Then, conduct exploration according to the designed grid network after concluding that the economic value of the exploration area and investment are reasonable and economically efficient.

To achieve the above objectives, exploration work needs to meet requirements for geodetic surveying; geological mapping; construction of exploration facilities; sample collection, processing, and analysis; geological and economic evaluations; and resource estimation work.

CONCLUSIONS AND RECOMMENDATIONS

I. Conclusion

1. The Nong Son basin has a semi-closed fan-shaped basin connected to the sea. The results of lithological and structural geological studies indicate the existence of two sedimentary cycles from the An Diem (T_3n *ad*) and Suon Giua (T_3n-r *sg*) formations in the Nong Son basin. Uranium-bearing rock layers in the late Triassic deposits of the Nong Son basin occur in two

forms depending on two structural systems: (i) Layers of lens-shaped ore distributed in a fan-shaped coarse-grained sandstone structural system with small fan-shaped subaqueous deltaic grains along the shore; (ii) Layers of lens-shaped ore oriented parallel to the sandstone structural system, with small subaqueous deltaic grains in shallow marine bays.

2. The composition of sedimentary filling in the Nong Son basin primarily consists of weathered rocks from uranium-bearing formations, predominantly from the metamorphic rocks of the Khanh Duc - Nui Vu structural system, granitic rocks of the Ben Giang - Que Son structural system, and the Dai Loc structural system. Synthesizing, analyzing, and processing existing documents allows for the elucidation of the characteristics of uranium mineralization and related controlling factors. It identifies geochemical characteristics related to the concentration process and the formation of uranium ore bodies in the Nong Son basin.

3. Uranium ore bodies are typically concentrated in the form of layers, lens-shaped ore bodies, parallel-oriented lens chains, or fan-shaped arcs and are interconnected within a certain rock layer. Lens-shaped ore bodies oriented parallel to the sandstone structural system primarily concentrate in the middle and small grain marine bays, while lens-shaped ore bodies distributed along the coastline occur in fan-shaped coarse-grained sandstone structural systems with small fan-shaped subaqueous deltaic grains along the shore. The thickness of industrial ore bodies varies irregularly and discontinuously, with internal structures ranging from simple to complex. The U_3O_8 content in industrial ore bodies is unevenly distributed, ranging from uneven to extremely uneven. U_3O_8 content variations are more complex than variations in thickness but are more stable within ore-bearing layers. This factor poses difficulties in exploration work and significantly affects the reliability of resource estimation and uranium resources in the Nong Son basin sandstone deposits.

4. Based on the complexity of the geological structure of mining areas and the variability of industrial geological parameters, uranium mining areas in the Nong Son basin sandstone deposits mainly belong to exploration group III. For group III areas, exploration requirements to support the investment project must achieve a resource level of 122. The most reasonable exploration network system is to use a parallel line grid network. In specific blocks, a rectangular grid network or a fan-shaped grid network can be used, with line spacing not exceeding 50 - 60m and construction spacing not exceeding 25 - 30m for resource level 122 blocks. During exploration, it is necessary to have a reserve volume of exploration work

ranging from 10% to 15% of the total estimated volume for the entire exploration project. Reserved works mainly focus on ore bodies with sharp, abrupt edges or within ore bodies with complex morphologies and structures.

5. On the basis of previous research results and practical documentation summarized during the exploration process in the Pa Lua - Pa Rong area, the most reasonable method for estimating uranium resources in the Nong Son basin sandstone deposits is to use the geological block method combined with common Kriging methods for validation. These methods are suitable for the morphological and structural characteristics of ore bodies and the proposed exploration system in the thesis.

II. Recommendations

1. Detailed and deeper research is needed on the ore formation process to provide a comprehensive analysis of various ore body shapes. For uranium-bearing sandstone deposits, not only include lens-shaped ore bodies, but also Rol-shaped ore bodies. These ore bodies have complex winding shapes on both cross-sections and maps, significantly impacting the efficiency of exploration work and resource estimation.

2. In the future, we should accelerate the application of informatic technology and artificial intelligence with the assistance of specialized software to enhance the quality of estimating reserves and mineral resources, especially for uranium, rare earth minerals, and precious metals. This is to meet the requirements for innovation and creativity, serving the socio-economic development of Vietnam.

Hanoi, day month year 2024

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