MINISTRY OF EDUCATION AND TRAINING
HA NOI UNIVERSITY OF MINING AND GEOLOGY

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PETROGENESIS AND MINERALIZATION ASSOCIATED WITH MUONG LAT GRANITIC COMPLEX IN NORTHWEST VIETNAM

MAJOR: **GEOLOGICAL ENGINEERING**
CODE: **9520501**

PhD. DISSERTATION SUMMARY

Ha Noi - 2020

The thesis is executed at **Department of Prospecting and Exploration, Faculty of Geology, Ha Noi University of Mining and Geology**

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INTRODUCTION

1. The necessity of the project

The petrogenesis research plays an important role in elucidating tectonic-magmatic activities, material composition, mantle-crust interaction, and initial material source of the rocks exposed in on the Earth's surface. Besides, it contributes to understanding the formation processes of igneous mineralization and to assessing their mineralization potential.

According to current documents (Tri and Khuc, 2009; Tam et al. 2010), Northwest Vietnam shows quite abundant granitoids from Chieng Khuong, Muong Lat, Dien Bien, Song Ma, and Phia Bioc complexes. The granitoids have not systematically and synchronously been studied by the modern and quantitative method in terms of material composition, emplacement age, igneous origin, tectonic setting, and regional geological implication. Granitoids from the Muong Lat complex haven't been investigated in detail. The geodynamic process, material source, emplacement ages, and potential mineralization of the Muong Lat complex is still controversial. Moreover, the relationship between the Muong Lat granite and surrounding rocks on the geological framework of Northwest Vietnam is also a matter of debate.

In this case, the thesis: "*Petrogenesis and mineralization associated with Muong Lat granitic complex in Northwest Vietnam*" has been studied in detail.

Material composition, distribution, emplacement age, igneous origin, and associated potential mineralization from the Muong Lat granitic complex place important constraints on the evolution history and geodynamic process of the study area.

2. Research scope and subject

- Research scope: The Muong Lat complex in NW Vietnam;

- Research subject:

+ The granitoids from the Muong Lat complex;

+ mineralization associated with the granitoids from the Muong Lat complex.

3. Objectives

Clarifying geological structural characteristics, petrography, geochemistry, and isotopic composition of the Muong Lat granitoid. Determining emplacement age, tectonic setting, igneous origin, and potential mineralization associated with the Muong Lat granitoid in northwest Vietnam.

4. Main research content

- Studying geological characteristics, and the material composition of granitic formations in the study area: spatial distribution, petrography, and representative mineral assemblage from the granitoids. Establishing a geological map and detailed geological section showing their relationships with other geological formations in the study area.

- Studying mineralizations associated with granitic formations. Determining preliminarily potential mineralization. Clarifying ore composition, distribution, existence form, emplacement age (pre-, syn-, and post-ore) with geological objects.

- Based on the above results, interpreting the evolutionary history of Earth's crust in the study area and providing accurate information of formation origin.

- Connecting and comparing the evolutionary history of the research objects with the surrounding areas (Yangtze, South China, and Western Indochina) to form structural - tectonic model based on Plate Tectonics.

5. Main points

- Main point 1: Mineralogy and geochemistry of the 251-235 Ma Muong Lat granitoid show the characteristic of S-type granite. The Muong Lat granitoid was produced by partial melting of crustal source rocks and was related to the South China-Indochina collision along the Song Ma suture.

- Main point 2: The Muong Lat granitoid is characterized by rare-metal minerals as well as W and Sn mineralization potential.

6. New points

- Determining characteristics of S-type granite and crustal source from the Muong Lat granitic complex based on the geochemical and isotopic analysis.

- Determining the emplacement age of the Muong Lat granitoid ranging from 251 Ma to 230 Ma based on LA-ICP-MS U-Pb zircon analysis.

- Providing the additional information of the syn-collision and collision of the Northern Vietnam-South China and Indochina blocks during the Indosinian orogeny

- Establishing geochemical indicators of the Muong Lat granitoid on W and Sn mineralization potential.

7. Scientific significance and practical significance

- Scientific significance: the results of the thesis determines granitic assemblages, LA-ICP-MS U-Pb age, magmatic origin, and tectonic setting, and contributes to shedding light on the geological growth history of Muong Lat complex in Northwest Vietnam in particular and Asia in general. At the same time, the research results contribute to determining the mineralization potential of the Muong Lat formation.

- Practical significance: the research results of the thesis can be used in the measurement, adjustment of geological maps, and studies on petrology, petrogenesis, and mineralization. They also are new premises of the mineralization investigation. They provide a valuable document that can be used in professional education and guiding scientific research in universities and research institutes. They are the database of scientific articles and monographs in the geological field.

8. Data

The thesis is based on the author's documents collected from field trips. The new research data is mainly analyzed by the author.

- 100 petrographic samples; 10 mineralographic samples; 10 chemical samples of minerals; 15 major and trace element samples (including REEs) earth); 06 LA-ICP-MS U-Pb zircon age samples; 3 Hf isotopic samples on zircon grains. 5 Rb - Sr isotopic samples on whole-rock; 5 Sm-NdNd isotopic samples on whole-rock at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGG CAS).

Besides, the PhD. student consulted more documents of Moc Chau sheet group at 1:50.000 scale (Do Van Thanh, 2015) by the students themselves participating in the fieldwork and other published documents as well as resource data storage.

9. The thesis structure

Instead of introduction, conclusion and reference, the thesis consists of 4 chapters:

Chapter 1. Overview of the study area.

Chapter 2. Theoretical foundations and research methods.

Chapter 3. Geological characteristics and geochemistry of the granitoids from the Muong Lat complex.

Chapter 4. Origin and related mineralization of the Muong Lat complex.

RESEARCH CONTENT

Chapter 1

OVERVIEW OF THE STUDY AREA

1.1. Location of the study area

The NW Vietnam is limited by geographical coordinates: 19°31'58"N to 22°38'57"N and 102°02'40"E to 106°00'00"E. Three are high fragmented mountainous, tropical climate, sparsely population, difficult economy and low socio-cultural life.

1.2. Geological history

The Muong Lat complex has been studied at a basic level in the Indochina geological map at 1:2.000.000 scale in 1952. On Vietnam geological map at 1:1.000.000 scale, Tri and Tung classified Muong Lat complex into Caledonian Orogeny with early Paleozoic age. Thuc et al. (1995) in Vietnam geology, part of II: Magma, the Muong Lat complex shows 285 Ma and 295 Ma. In the geological mapping of Muong Lat sheet group at 1:50.000 scale, (Dinh Cong Hung 2003) and Moc Chau sheet group at 1:50.000 scale (Do Van Thanh 2015), the Muong Lat granitoid is belong to S-type granite with $^{87}Rb/^{86}Sr$ isotopic ages of 257± 2.6Ma.

1.3. Geological setting

1.3.1. Zoning metamorphosed arch of the Muong Lat intrusion

From the center of the intrusion to surrounding rocks, there are transformation zones: the molten granite; sillimanite; staurolite; granite; biotite, and chlorite. They are caused by dynamothermal metamorphism in the study area.

1.3.2. Stratigraphy

Huoi Hao formation (NP*hh*); Nam Ty formation (NP*nt*); Nam Co formation (NP_3*nc*); Suoi Lat formation (NP_3*sl*); Song Ma formation (ε_2*sm*); Ham Rong formation (ε_3-O_1*hr*); and Ban Pap formation($D_{1\text{-}2}$*bp*).

1.3.3. Magmatic intrusions

Nui Nua complex (σPZ_1*nn*): harzburgite, dunite peridotite.

Bo Xinh complex (υPZ_1*bx*): gabbro-amphibolite.

Chieng Khuong complex ($\gamma\delta PZ_1$*ck*): hornblende biotite tonalite, biotite granodiorite.

Cam Thuy complex (βP_3*ct*): basalt, amygdaloidal basalt.

Dien Bien complex (P_3-T_1*đb*): gabbro, gabbro-diorite, diorite, granodiorite, hornblende granodiorite, hornblende quartz diorite, quartz hornblende monzodiorite, granite, biotite granite, medium- to coarse-grained hornblende granite, aplite granite, pegmatite granite.

Muong Lat (γT_2*ml*): biotite granite, medium- to coarse-grained two-mica granite, muscovite granite, fine-grained light two-mica granite, aplite granite, pegmatite granite.

Song Ma complex (γT_2*sm*): Phase 1: biotite granite, porphyritic biotite granite, hornblende granite, granodiorite biotite, hornblende, quartz diorite; Phase 2: aplite granite

1.4.1. Petro-tectonic assemblage in the study area (THTKT)

THTKT late Neoproterozoic ancient continental crust, THTKT early Paleozoic ancient oceanic crust (ophiolite) and related mineralization (Ni, Cr, gemstone); TKTKT Paleozoic passive continental margin and related mineralization (W); TKTKT late Permian – Triassic magmatic arc and related mineralization (Pb); TKTKT late Permian – Triassic collision and related mineralization (W); THKTKT Late Permian – Triassic intra-continental rift and related mineralization (building materials).

1.4.2. Characteristics of major fault activities

The research area of the thesis has identified three fault systems: northwest-southeast fault, sublatitude fault, and eastnorth-westsouth fault. In particular, the northwest-southeast fault system has a long development history, playing a major role in creating a regional geological structure.

1.5. Mineral characteristics of the study area

In the study area, 5 points of mineralization manifestations have been recorded. There are 2 W (Au) mineralization manifestations in Ban Nga and Ta Lao. There is 1 Sn (Au) mineralization manifestation in Ban Phat. There is 1 W (Au) mineralization manifestation in Ban Lat. There is 1 Ni mineralization manifestation in Suoi Bo.

Chapter 2
THEORETICAL FOUNDATIONS AND RESEARCH METHODS

2.1. Theoretical foundations

2.1.1. Concept

- **Granitoid:** a wide range from diorite to granite, containing more than 5% quartz and SiO_2> 60% (Pearce, 1996; J. Winter, 2001).

- **Manhetite granite series** (corresponding to I-type granite): Crystallized from magma with high Fuga oxygen and high temperature: manhetite content (0,1 - 2%), containing ilmenite, hemantite, pyrite, and sphene. High oxidation ($Fe_2O_3/(FeO + Fe_2O_3)$)> 0.35) is mainly related to Cu-Mo ore (Ishihara, 1977).

- **Ilmenite granite series** (corresponding to S-type granite). Formed by the partial flow of sedimentary rocks with low oxygen Fuga, low temperature, with the following main characteristics: ilmenite content of nearly 0.1%, containing pyrite, pyrite, graphite, and muscovite. Small oxidation ($Fe_2O_3/(FeO+Fe_2O_3)$) <0.35, is mainly related to Sn - W ore (Ishihara, 1977).

- **Major elements:** The major elements consist mainly of Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, P in all rock analysis.

- **Trace elements:** Trace element is characterized by less than 0.1% weight, meaning less than 1 part per million (ppm) weight unit.

2.1.2. Petrogenesis of granite

Petrogenesis of granite is the primary material source from mantle or crust, providing directly or indirectly material source for the formation of magmatic intrusions.

2.1.3. Classification of granite According to mineral composition

- Calc-alkaline granite and alkaline granite

According to the chemical composition

Magmatic rock is classified and named based on the percentage of oxides from major elements (Si, Ti, Al, Fe, Mn, Ca, Na, K, and P).

2.1.4. Division of granite series

Granite is divided into three series: tholeiite, calc-alkaline, and alkaline

2.1.5. Classification of granite types

2.1.5.1. Types of granite backgrounds

According to Chappel and White (1974) and Loiselle and Wones (1979) granite is divided into four types: I-type granite, S-type granite, M-type granite and A-type granite.

2.1.5.2. Tectonic setting of granite

Pearce (1984) divides the tectonic setting of granite into ocean ridge granite (ORG), within plate granite (WPG), volcanic arc granite (VAG), and collisional granite (COLG), syn-collisional granite (syn-COLG), and post- collisional granite (post-COLG).

2.1.6. The mineralization relationship related to granitic types

Granitic types and related mineralization (Condie 2003; Pohl 2011):

- M-type granite: Cu - Au porphyry mineralization and Au hydrothermal mineralization;

- I-type granite: U - REE mineralization, Cu - Mo porphyry mineralization, Mo - W - Cu Skarn mineralization, Pb – Zn mineralization and sometimes Au- Ag hydrothermal mineralization;

- S-type granite: Sn, W, Ta hydrothermal mineralization;

- S-type granite: related mineralization:

+ high-K granite:

Sn, W, Pb, Zn, CaF_2 in internal greisen, pegmatite, porphyry stockwork or dykes from surrounding rocks;

+ high-Na granite:

Nb, U, REE, and little Sn in albite

2.2. Research Methods

2.2.1. Research method in the field

Field survey and detailed analysis of geological crop.

2.2.2. Methods of collecting and synthesizing documents

Collecting, analyzing, and synthesizing documents, and results from previously geological studies.

2.2.3. Petrographical method

The rock samples were made for the thin section and analyzed under polarized microscopy to determine texture, structure, composition, mineral characteristics, and replacement and alteration processes.

2.2.4. Mineralographic method

Mineralographic analysis is to determine exactly ore-forming names, correlations, and ore-forming order.

2.2.5. Geochemical method

The major and trace elements are analyzed from whole-rock.

Analytical samples are sent to reputable analysis facilities in foreign countries by XRF, ICP - MS method.

The sample was analyzed at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGG CAS).

2.2.6. Isotopic component methods

In this study, using an isotopic component is to determine the petrogenesis and emplacement age of rocks.

- Zircon structure method: zircon is characterized by the highest closing temperature (> 9000°C). Besides, it is one of the minerals with stable physical and chemical characteristics. It is not affected by a low metamorphic degree. U

-Pb zircon is said to be the crystalline age of magmatic intrusions. Hence, zircon is considered a useful tool in isotopic age.

- Determining the Hf isotopic model age by MC - LA - ICP MS method on zircon grains.

- Determining the Rb - Sr and Sm-Nd isotopic model age by TIMS method on whole-rocks.

- U - Pb isotopic zircon age method is based on the U nucleus decay giving Pb.

2.2.7. Geochemical specialization and magmatic mineralization

** Geochemical specialization:*

The geochemical specialization (mineralization) of magma are behavioral characteristics of the elements, or compounds (metals) in rocks when their average contents exceed Clark contents many times.

Geochemical specialization types of the magmatic complex are related to the petrochemical characteristics of the original magma due to anabolism and fractional crystallization process.

** Relationship between magma and mineralization:*

To determine this relationship for any mine in a certain area is often based on conditions: geological structure; petrography; and geochemistry.

Based on this relationship, scientists show relative origin, related symbiotic patterns and spatial relationship between ore and magmatic rocks.

** Dividing denudation level of granitoid*

Current magmatic is divided into four denudation levels: hidden magmatic intrusions, top-exposed magmatic intrusions, exposed magmatic intrusions and foot-exposed magmatic intrusions.

2.2.8. Processing analytical results

The results of petrography, geochemistry and isotopic age were processed on specialized computer software (Excel, Minpet, Igpetwin, Isoplot 3, Coreldraw 12).

Chapter 3

GEOLOGICAL CHARACTERISTICS AND GEOCHEMISTRY OF THE GRANITOIDS FROM THE MUONG LAT COMPLEX

3.1. Geological characteristics

The Muong Lat complex, situated in Song Ma suture, belongs to the NW Vietnam, including the Muong Lat and Sam Son intrusions. The Muong Lat intrusion occupies the largest area of the Muong Lat complex. In this study, the researcher focused on the Muong Lat intrusion. In this

study, the author focuses on the Muong Lat intrusion, which is located in the south of the Song Ma suture, in Thanh Hoa province. The Muong Lat intrusion has an area of about 300 km^2, extending an approximate 30 km long and 6-16 km wide belt in the direction of sub-latitude. It is mainly characterized by two-mica granite and consists of several phases: Phase 1- coarse- to medium-grained porphyritic two-mica granite and Phase 2- fine-grained gray-white two-mica granite. It also has tourmaline- muscovite granite, and aplite as well as pegmatitic dykes. The Muong Lat granite intruded and metamorphosed adjacent rocks. At western, northern and southern boundaries, the Muong Lat granite intruded the quartz-mica granat schists and microline gneiss of Nam Co formation with Proterozoic age. In the west, it intruded into the Paleozoic Song Ma formation.

3.2. Petrography

The Muong Lat granitoid consist of 2 phases:

Phase 1 ($\gamma T_2 ml_1$) has 2 facies

Coarse-grained facies: biotite granite and coarse- to medium-grained gray two-mica granite.

Fine-grained facies: muscovite granite and fine-grained white two-mica granite.

Phase 2 ($\gamma T_2 ml_2$) shows white aplite granite and pegmatite granite.

3.2.1. Coarse-grained two-mica granite

Coarse-grained two-mica granite occupies the main bodies in the mineral assemblage of the Muong Lat complex. It indicates coarse- to medium-grained rocks. The rocks are characterized by light to gray color, massive structure, coarse- to medium-grained texture and subhedral in shape. The mineral arrangement is not oriented.

3.2.2. Biotite granite

Biotite granite is less common in the Muong Lat complex. It is characterized by gray color, massive structure, coarse- to medium-grained texture, and subhedral in shape. The mineral arrangement is not oriented.

3.2.3. Muscovite granite

Muscovite granite is quite common in the Muong Lat complex. It is characterized by light-colored rocks, massive structure, and subhedral in shape.

3.2.4. Fine-grained two-mica granite

Fine-grained two-mica granite is quite common in the Muong Lat complex. It is characterized by fine-grained texture, subhedral in shape and massive structure. The mineral arrangement is not oriented.

3.2.5. Aplite granite

Aplite granite is less common in the Muong Lat, having several 1-20 cm veins. It is characterized by fine-grained texture and low oriented structure. It changes anhedral texture to low lepidoblastic texture

3.2.6. Pegmatite granite

Pegmatite granite is less common than aplite granite, and has 20 - 25cm cm veins. the size of feldspar and mica crystal particles is quite large (0.5 - 1cm^2).

3.3. Mineral composition characteristics

The granite from the Muong Lat complex is characterized by gray to light in color. The texture varies from coarse- to medium-grains

with large K-feldspar phenocryst (20% - 30%), quartz (25% - 35%), biotite (<10%), muscovite, microline (<5%)) and sillimanite (<1%). K-feldspar mainly indicates pertite texture. At the edge of the large feldspar, there are usually euhedral biotite and euhedral plagioclase. Plagioclases are oligoclase and albite that shows albite twinning texture. Quartz forms anhedral grains and indicates deformation features. Biotite in two-mica granite is yellowish-brown or dark brown, and partial fading. Commonly secondary muscovites replace biotite. Muscovite varies from 3 to 5 mm in size. Primary muscovite usually crystallizes together with biotite and displays enhedral grains. Secondary muscovite usually replaces primary biotite. Moreover, muscovites are distributed along feldspar cleavage. Microcline shows tartan twinning grains and often replaces partial or complete orthoclase. Sillimanite occurs as long-prismatic crystals and is displayed together with biotite. Accessory minerals mostly contain tourmaline, zircon, sillimanite, and ilmenite.

3.4. Geochemical characteristics

3.4.1. Major element characteristics

SiO_2 content ranges from 67.07 to 74.06 wt%, Al_2O_3 from 13.72 to 15.25 wt %, and $K_2O + Na_2O$ from 6.74 to 9.85 with K_2O/Na_2O ratio > 1. On the rock classification diagram (Wilson, 1989), all samples fall into the granite field. They almost indicate peraluminous characteristics (Peccerillo and Taylo, 1976).

The A/CNK ratio ranges from 0.97 to 1.29 (average 1.14). This shows that the Muong Lat granitoid belongs to the peraluminous series, suggesting the characteristic of S-type granite. Moreover, on the granitic diagram all analytical samples fall into the S-type granite field (Whalen et al., 1987; Chappell and White, 1974; 1992).

The research samples all have low TiO_2 (0.08- 0.56 wt%), MgO (0.21 – 0.68 wt %), CaO (0.51-1.88 wt %), MnO (0.03 – 0.09 wt %), Na_2O (2.76 – 5.04 wt %), and Fe_2O_3 (0.05 – 0.46 wt %) components. The Fe^{3+}/Fe^{2+}ratio indicates approximately equal values of about 0.11.

Very high Al_2O_3 components range from 13.72 wt% to 15.25 wt%.

On Harker diagrams, Al_2O_3, $Fe_2O_3^t$, MgO CaO, Na_2O, and K_2O decline with increasing SiO_2, showing that fractional crystallization occurs during the crystallization process.

3.4.2. Trace element characteristics

The total heavy rare earth elements (∑REEs) range from 11.42 ppm to
161.90 ppm and show the medium to high fractional crystallization of heavy rare earth elements (HREEs) and light rare earth elements (LREEs). The strong Eu anomalies are expressed in Eu/Eu* ratio (0.19 to 0.90). The ratio of (La/Yb)n and (Tb/Yb)n ranges from 2.15 to 23.77 and from 1.73 to 4.55, respectively; The ratio of Rb/Sr ranges from 7.497 –
28.65 (average of 17.73).

The distribution characteristics of trace elements in the Muong Lat granite are in the primitive mantle-normalized composition (Sun and McDonough, 1989). The Muong Lat granite shows negative Ba, Nb, Sr, and Ti anomalies but positive Rb, U, K, and Pb anomalies. The geochemical characteristics of the Muong Lat granite are similar to those of ancient continental crust (Harris et al., 1986; Chappell and White 1992; Bea et al., 2011).

On the tectonic classification diagram: type granite classification diagram by tectonic setting (Pearce, 1984); R1-R2 diagram (Batchelor and Bowden, 1985). R1 = 4Si - 11 (Na + K) - (Fe + Ti) and R2 = 6Ca + 2Mg + Al. Most of the samples fall into syn - collision and volcanic arc field.

3.5. Emplacement age

3.5.1. Sampling location

PhD. student collected 06 representative samples from the Muong Lat complex to separate zircon for U-Pb zircon age analysis.

3.5.2. Analytical results

a. Cathodoluminescence image

The zircon crystals were selected from the Muong Lat granite. They are pale pink to colorless and transparent. The zircon grains are

mainly prismatic, euhedral in shape and clear oscillatory zoning showing a magmatic origin. The zircon grains have a length of 100–300 μm with length-to-width ratio varies from 2:1 to 3:1.

Some zircon remnant grains in the center contain ancient crustal material remnants such as analytical points 7, 8, 13, 20, and 16 from MLT34 sample, and an analytical point 16 from MLT09 sample.

The inherited zircon components indicate heterogeneous structure with the surrounding zircon and often have a different color than that of formed zircon in the Muong Lat formation stage.

b. U-Pb zircon age

The Th/U ratios from analyzed zircon grains of the sample MLT08 show an average of 0.37 (>0.1), indicating a magmatic origin (Corfu et al., 2003). 17 grains yielded concordant U-Pb ages with an average $^{206}Pb/^{238}U$ age of 251 ± 3 Ma (n=17, MSWD=2.6), which is understood as the emplacement age of the sample MLT08.

A total of 20 zircon grains were analyzed for their U-Pb isotopic compositions. 13 grains yielded concordant U-Pb ages with an average $^{206}Pb/^{238}U$ age of 247.4 ± 2.8 Ma (MSWD = 0.66, n = 13), which is understood as the emplacement age of the sample MLT09. One zircon grain shows an old age of 1758 Ma, corresponding to Paleoproterozoic

The Th/U ratios from analyzed zircon grains of the sample MLT34 show an average of 0.40 (>0.1), indicating a magmatic origin (Corfu et al., 2003). A total of 20 zircon grains were analyzed for their U-Pb isotopic compositions. 14 grains yielded concordant U-Pb ages with an average $^{206}Pb/^{238}U$ age of 242 ± 2.6 Ma (MSWD = 0.79, n = 14), which is understood as the emplacement age of the sample MLT34. 6 zircons plot in $^{206}Pb/^{238}U$ ages in 1597, 759, 755, 705, 661 and 328 Ma, corresponding to late Mesoproterozoic - early Paleoproterozoic, Neoproterozoic, and late Carboniferous.

The Th/U ratios from analyzed zircon grains of the sample MLT42 show an average of 0.32 (>0.1), indicating a magmatic origin (Corfu et al., 2003). 19 grains yielded concordant U-Pb ages with an average $^{206}Pb/^{238}U$ age of 235 ± 3.1 Ma (MSWD = 1.9, n = 19), which is understood as the emplacement age of the sample MLT42. This age is quite concentrated and inherited zircon component.

A total of 20 zircon grains of the sample MLT42a were analyzed for their U-Pb isotopic compositions. The results of the $^{206}Pb/^{238}U$ age concentrated on 217 - 238 Ma. Mainly analysis points concentrated on 230 ± 7 Ma. Moreover, zircons plot in $^{206}Pb/^{238}U$ ages in 1597, 759, 755, 705, 661 and 328 Ma, corresponding to late Mesoproterozoic - early Paleoproterozoic, Neoproterozoic, and late Carboniferous. The older age values were concentrated on about 2.8 Ga, 2.4 Ga, 1.8 Ga, 850 Ma, and 400 Ma.

A total of 20 zircon grains of the sample MLT02 were analyzed for their U-Pb isotopic compositions. The older age values were concentrated on about 1.2-1.6 Ga, 582-985 Ma, and 400 Ma.

In this study, we selected 06 representative samples from the Muong Lat intrusion to determine the U-Pb zircon age by LA - ICP - MS method. Their age concentrated from 251 Ma to 230 Ma. These ages are understood as the emplacement age of the Muong Lat complex (Early- middle Triassic). Thus, it can be seen that the Muong Lat complex was formed in about 20 Ma.

Chapter 4

ORIGIN AND RELATED MINERALIZATION OF THE MUONG LAT COMPLEX

4.1. Origin and forming process of Muong Lat granitoid

4.1.1. Hf isotope composition in zircon grain

Lu-Hf isotope composition from three samples MLT09, MLT34, and MLT42 were measured on the same zircon crystals performed for their U- Pb age. More than fifty spots were analyzed on particles zircons. All analyzed zircons have the $^{176}Lu/^{177}Hf$ ratios (0.003373-0.000447) and $^{176}Hf/^{177}Hf$ ratios (0.282283-0.282223). The age of 240 Ma obtained from this study was used to determine the initial $^{176}Hf/^{177}Hf$ ratios. $\varepsilon_{Hf(t)}$ values are from –12.7 to –7.3, and Hf model ages (T_{DM2}) are 1872 a to 2077 Ma.

4.1.2. Rb-Sr and Sm-Nd isotope composition of whole-rock

Whole-rock Rb-Sr and Sm-Nd isotope composition are from the five samples of the Muong Lat granite (MLT02, MLT08, MLT09, MLT34 and MLT42). Initial Nd and Sr isotopic ratios were calculated

using 240 Ma. 5 samples have $^{147}Sm/^{144}Nd$ ratio of 0.1260 to 0.11511, and very high $^{87}Sr/^{86}Sr$ ratio of 0.71391 to 0.745680 (average of 0.72633> 0.71). They
indicate negative $\varepsilon_{Nd(t)}$ values of -13.1 to -9.4 with T_{DM2} model age (1.8 Ga to 2.1 Ga). The $\varepsilon_{Nd(t)}$ values and T_{DM2} model age on whole-rock are quite similar to those on Hf zircon grains. The Sm-Nd isotopic characteristics indicate generation through partial melting of a Paleoproterozoic crustal source.

4.1.3. The process of forming granitoid of Muong Lat complex

4.1.3.1 Discussion of type S granite

Based on the petrochemical results in chapter 3, and the conditions of I-, S-, M-, and A-type granite classification (Chappel and White, 1974; Loiselle and Wones 1979), the Muong Lat granitoid is consistent with type S granite:

- The geochemical composition of the Muong Lat granitoid includes biotite granite, muscovite granite, fine- to coarse-grained two-mica granite, aplite granite, and light pegmatite granite with low massive structure, orientation and subhedral to euhedral texture. Major rock- forming minerals are plagioclases, quartz, feldspar, muscovite and biotite. Accessory minerals contain zircon, tourmaline, sillimanite, apatite and ore-forming minerals (ilmenite and so on).

- *Geochemical characteristics:*

+ Based on major elements, SiO_2 values range from 67.07 to 74.06 wt.%, Al_2O_3 from 13.72 to 15.25 wt%, and $K_2O + Na_2O$ from 6.74 to 9.85 (average of 8.21) with K_2O/Na_2O ratio (average of 1.18) > 1. The A/CNK ratios range from 0.97 to 1.29 (average of 1.14). Hence, the Muong Lat granite indicates peraluminous characteristics and the typical feature of S- type granite. In addition, relatively low CaO content ranges from 0.51 to
1.88 wt%. Basically, Al_2O_3, $Fe_2O_3^t$, MgO CaO, Na_2O and K_2O decline
with increasing SiO2, showing that fractional crystallization occurs during the crystallization process.

+ In addition, very high $^{87}Sr/^{86}Sr$ ratio ranges from 0.71391 to

0.745680 > 0.71.

The Muong Lat granite shows negative Ba, Nb, Sr and Ti anomalies but positive Rb, U, K, and Pb anomalies. The geochemical characteristics of Muong Lat granite are similar to those of ancient continental crust (Harris et al., 1986; Chappell and White 1992; Bea et al., 2011)

Based on the above data, the Muong Lat granites display the typical feature of S-type granite

4.1.3.2. Petrogenesis

Aluminium-rich minerals such as muscovite and sillimanite are relatively common in the Muong Lat granite. Geochemically, the A/CNK ratios range from 0.97 to 1.29 > 1.1. SiO_2, $Na_2O + K_2O$, và Zr contents from Muong Lat granite.

The Muong Lat granite contains some ancient inherited zircons with a round in shape, which is possibly the remnants of surrounding rocks due to incomplete melting. Isotopically, the Muong Lat granite has high initial $^{87}Sr/^{86}Sr$ ratios (0.71391 to 0.745680). The Hf isotope composition from the Muong Lat granite is within the evolutionary line of the continental crust (Chen and Jahn., 1998; Wang et al, 2010, 2012; Xu et al., 2015).

Zircon $\varepsilon_{Hf(t)}$ and whole-rock $\varepsilon_{Nd(t)}$ values range from -14.4 to -6.6 as well as Hf-Nd model ages range from 1.6 Ga to 2.1 Ga.

Moreover, on Rb/Sr vs Rb/Ba diagram (Sylvester, 1998) and Al_2O_3/TiO_2 vs CaO/Na_2O (Sylvester, 1998) diagram compared with granites in Yangtze and Cathaysia blocks, initial material source of the Muong Lat granite can be rich in clay and saturated aluminum, which is quite similar to those early Paleozoic rocks in Yangtze, South China.

Based on field observations, the Muong Lat granite contained metasedimentary xenolith from the Nam Co Formation, which has a dominantly detrital zircon age of 1.7-1.8 Ga (Zhang et al. 2014). These are xenolith melting materials when the Muong Lat granite was formed (Hau and Thanh, 2016). The youngest sediments from Nam Co formation are about Neoproterozoic. These ages are quite similar to the xenolith materials in the Muong Lat granite.

Based on petrographic and geochemical characteristics, the Muong

Lat granite is quite similar to S-type granite, formed by partial melting of a Paleoproterozoic crustal source.

4.1.3.3. Tectonic setting

The Muong Lat granitoid is the characteristic of S-type granite and is derived from partial melting of Paleoproterozoic crustal source (Pearce et al. 1984; Batchelor and Bowden1985) as follows:

The Na_2O+K_2O content (6.74 - 9.85%) in the samples is high while the Lacroix-LI index (1993) from K_2O/Na_2O of 0.76 to 1.58 shows the Muong Lat granitoid is quite close to the common high alkaline granite series.

Moreover, the strong Eu/Eu* anomalies range from 0.19 to 0.90. The ratio of (La/Yb)n and (Tb/Yb)n ranges from 2.15 to 23.77 and from 1.73 to 4.55, respectively. The Muong Lat granite shows negative Ba, Nb, Sr and Ti anomalies but positive Rb, U, K, and Pb anomalies. The geochemical characteristics of the Muong Lat granite are similar to those of ancient continental crust (Harris et al., 1986; Chappell and White 1992; Bea et al., 2011).

On the tectonic classification diagram (Pearce, 1984), the Muong Lat samples fall into syn-collision and volcanic arc field.

On the tectonic classification based on R1-R2 diagram (Batchelor and Bowden, 1985), the Muong Lat samples fall into the volcanic arc and
syn-collision field (VAG + syn-COLG).

The Muong Lat granitoid indicates peraluminous characteristics and the typical feature of S-type granite with common muscovite và biotite (two-mica granite). These characteristics identify the Muong Lat complex associated with a continent-continent collision by partial melting of the crust.

4.1.3.4. Overview of the formation process of Muong Lat granitoid

The previous studies many Vietnamese and foreign geologists suggested that the Indochina block was formed by welding of continental and microcontinental plates such as South China, Sibumasu and Simao that separated from the Gondwana supercontinent (Lan et al. 2000; Hoa et al. 2008; Shu et al. 2008; Liu et al. 2012, Faure et al.

2014, Hieu et al. 2013, 2017). The suture between the South China block and the Indochina block is thought of as the Song Ma zone (Hutchison 1989; Findlay and Trinh 1997; Lepvrier et al. 1997, 2008; Metcalfe 2013). The presence of Nui Nua and Bo Xinh ultramafic rocks are considered as the fragments of former Paleotethys oceanic lithosphere before the two-block collision (Thanh et al. 2011). The time for collision is often considered as Triassic (Lepvrier et al. 2008; Nakano et al. 2008; Faure et al. 2014, Hieu et al. 2017). However, an older age of Early Paleozoic is reported by Usuki et al. (2009) when they studied amphibolites at the Kontum massif. Carter and Clift (2008) argued that the collision of South China and Indochina blocks happened before the Devonian, and the Indosinian orogeny during the Triassic was an event of thermo-tectonic reactivation. The Song Ma suture, NW Vietnam was made up of foliated greenschist and amphibolite facies of the Nam Co Formation, metabasalt, lenses of serpentinized peridotite, gabbro, and granitoid of the Song Ma, Chieng Khuong and Muong Lat complexes. Field observation showed that the Nam Co Formation is foliated and intruded by granitic plutons, which are dated at about 255-230 Ma. Amphibole, biotite and muscovite minerals separated from the rocks of the Nam Co Formation yielded $^{40}Ar/^{39}Ar$ ages from 240 Ma to 266 Ma (Lepvrier et al. 2004). These provide the evidence of a tectonic-thermal event between 230 Ma and 260 Ma along the Song Ma region. This is also supported by the presence of eclogite and garnet-mica schist in the zone which showed monazite chemical U-Th-Pb and SHRIMP U-Pb zircon age values of 230.5 ± 8 Ma (Zhang et al. 2013), and 243 ± 4 Ma (Nakano et al. 2010), respectively. The eclogite rocks are evidence of a subduction-collision event that appeared in the Song Ma suture.

The author's study demonstrated that the Muong Lat granites are S- type granite and crystallized at 251-230 Ma. This data supports the subduction-collision of the Indochina-South China block that took place during the late Permian-early Triassic. This is in agreement with the conclusion of Faure et al. (2014) that the Indochina-South China collision can be simply represented as the result of the Paleotethys ocean closure in the middle Triassic. Hence, the Muong Lat granite of

late Permian to early Triassic resulted from the collision of South China and Indochina blocks

4.2. Related mineralization of the Muong Lat complex

4.2.1. Related mineralization of the Muong Lat complex based on the results of petrology and geodynamic environment

The Muong Lat granite has SiO_2 values (67.07-74.06wt.%), Al_2O_3 (3.72-15.25 wt%), and K_2O+Na_2O (6.74-9.85, an average of 8.21) with K_2O/Na_2O ratio > 1. All the samples fall into the high K field (calc-alkaline) (Meinert 1995) with related mineralization such as Sn, W, and low Ca. The Muong Lat granite contains muscovite and has A/CNK ratios

> 1.1. Hence, the Muong Lat granite indicates peraluminous characteristics and the typical feature of S- type granite.

The material origin of the Muong Lat granitoid was derived partial melting of crustal sedimentary rocks due to the collision of the South China and Indochina blocks.

Thus, based on the petrology and geodynamic environment described above, compared with granite type and related mineralization (Condie, 2003; Pohl, 2011), the Muong Lat granitoid is characterized by the Sn, W mineralization potential.

4.2.2. Related mineralization of the Muong Lat complex based on the results of geochemistry

4.2.2.1. Redox properties and mineralization specialization of minerals by accessory minerals

* Using FeO*-log(Fe_2O_3/FeO) diagram to determine the oxidation- reduction environment, the Muong Lat granitoid is mainly concentrated on a reduction environment, which has Sn, W mineralization potential (Blevin, 2003).

* Using the Fe_2O_3/(FeO+Fe_2O_3)-SiO_2 oxidation diagram, the Muong Lat granitoid plots in reduction field with Sn, W mineralization potential (Meinert, 1995).

*Based on Rb-Sc and V-Ni diagram (Meinert, 1995) and Fe_2O_3/FeO- Rb/Sr oxidation diagram (Blevin, 2003; Cook, 2012) to discuss mineralization, the Muong Lat granitoid is quite suitable for W, Sn ± W mineralization ability.

* Based on K^{+}-Mg^{+2}, Na^{+}-Mg^{+2} correlation diagram (Sattran 1977), the Muong Lat granitoid is related to Sn mineralization.

* Based on the relationship diagram of sodium, potassium, and calcium in ore-bearing granite (V. Pokalov), the Muong Lat granitoid is suitable for producing Sn mineralization.

4.2.2. Trace elements

According to trace elements results of the Muong Lat granitoid compared with Clark values (Vinogradov, 1962), the ore-forming elements are lower or equal to Clark value.

According to a classification table related to wolfram mines with magmatic activity (Ishihara, 1977), mines of Sn, W, Mo and W are always present with accompanying Cu, Pb, Zn and so on elements. Compared with magmatic formations that are closely related to the mineralization indicator elements (Cu, Pb, and Zn), the Muong Lat granite could be related to Sn and W mineralization.

Results of Rb and Sc elements on trace elements in W-Mo skarn mines show that these elements of the Muong Lat granitoid are also quite suitable (Lawrence and Meinert, 2005).

4.2.3. Related mineralization of the Muong Lat complex based on the geochemical modules

Calculation results based on the major elements:

Silic value: q = 0.7 - 0.81, alkaline value: α = 0.72 - 0.88, calcium valuse: c = 0.04 - 0.08, iron value: f = 0.92 - 0.98, and alkaline type value: n = 0.41 - 0.65 match with the geochemical modulus in Zabaican ore complex (former Soviet Union) corresponding to magmatic assemblage VI related to Sn and Sn-W mineralization.

4.2.3. Related mineralization of the Muong Lat complex based on mineralogical geochemistry

- Based on thin-section analysis and field research, K-feldspar, muscovite, biotite, sillimanite, ilmenite, meta-sedimentary xenolith and so on are in the Muong Lat granitoid. In comparison with granite type and related mineralization (Condie, 2003; Pohl, 2011), the Muong Lat granitoid has Sn-W mineralization potential.

- According to collected data in the study area, there are placer dispersion rings and Sn, W, Cu, Pb, and Zn sediments.

- In the study area of the thesis, there are W mineralization manifestations in Ban Nga, Tan Xuan commune, Van Ho district, Son La province. W ores exist in the disseminated form of sheelite or small loaves in veins, quartz lenses, marble and quartz - biotite shale.

4.2.4. Related mineralization of the Muong Lat complex based on forming depth and denudation level

- The Muong Lat intrusion has an area of about 300 km2, and a large depth difference (250m-1300m). The surrounding rocks have a large steep slope angle. Besides, based on 2 cross-sections, the rim of the intrusion is mainly composed of medium- to coarse-grained rocks up to over 2 km thickness after fine-grained rocks are little exposed.

- Plagioclase clearly shows oscillatory zoning.

- The Nb/V ratio ranges from 0.015 to about 2, but most samples are less than 1 (Amshinski, 1970). The granitic formations have been deeply eroded up to more than 4.5 km, with only ore manifestations and poor mineralization.

Thus, the Muong Lat granitoid has Sn, W related mineralization, existing ore manifestations and is eroded up to more than 4.5 km.

* Thus, related mineralization of the Muong Lat granite based on the results of petrology and geodynamic environment; geochemistry;
mineralogical geochemistry; and the forming depth shows that the Muong Lat granitoid is related to Sn and W mineralization.

4.2.5. Prospecting premise and forecasting signs for Sn and W in the study area

The study area is related to Sn and W ore as following specific prospecting premise and forecasting signs:

- Prospecting premise includes magmatism, stratigraphy, and structure- tectonics.

- Forecasting signs are mineral-element dispersion rings, direct ore- exposed points, excavation works, geophysical and geomorphological anomalies.

CONCLUSION AND RECOMMENDATION

1. Conclusion

(1) The Muong Lat complex located in Song Ma suture, NW Vietnam consists of Muong Lat, Sam Son and Lang Bong intrusions. The Muong Lat intrusion occupies the largest area of the Muong Lat complex about a quarter of the area. The Muong Lat granites intruded the quartz-mica granat schists and microline gneiss of Nam Co formation (PR_2-$€_1nc$) and intruded the Paleozoic Song Ma formation ($€sm$).

(2) The composition of the Muong Lat granite includes biotite granite, medium- to coarse-grained two-mica granite and fine-grained two-mica granite as well as aplite granite and pegmatite granite. Major rock- forming minerals are quartz (25-30%), plagioclase (28-45%), K-feldspar (22-36%), biotite (1-10%), and muscovite (1-10%). Plagioclase is mainly albite and oligoclase. K-feldspar is mainly microline. Accessory minerals include zircon, sillimanite, turmaline and ore.

(3) The Muong Lat granitoid has high SiO_2, Al_2O_3 and K_2O+Na_2O, but low TiO_2 and MgO. A/CNK ratios indicate the typical feature of S-type granite. $^{87}Sr/^{86}Sr$ ratios range from 0.71391 to 0.74568, low $\varepsilon_{Nd(t)}$ values range from -13.1 to -9.4 and Nd model ages range from 1.8 Ga to
2.1 Ga. Zircon $\varepsilon_{Hf(t)}$ values range from -12.7 to -7.3. These characteristics are evidence of partial melting a crustal source.

4) The emplacement age of the Muong Lat granite in this study by the LA-ICP-MS U-Pb zircon method ranges from 251 Ma to 230 Ma, corresponding to late Permian - early Triassic. The Muong Lat complex was formed by the collision of South China and Indochina blocks during a period of about 25 Ma.

(5) Whole-rock Sm-Nd, whole-rock Rb-Sr, and zircon Hf isotopic components suggest that the material origin of the Muong Lat granitoid was derived partial melting of crustal sedimentary rocks. The Muong Lat granite was produced by the partial melting of the Paleoproterozoic crustal sedimentary source.

6) Based on the results of primary geochemistry; petrology; geodynamic environment; mineralogical geochemistry; forming depth and denudation level, the Muong Lat granite is characterized by Sn and

W related mineralization.

2. Recommendation

1) Petrological research is synchronous, and modern methods need to be was performed on a wider scale.

2) Sheelite ore exposed in Ban Nga in the study area should be further investigated and evaluated in more detail on the spatial and temporal relationship with the Muong Lat granitoid.

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