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Chemical compositions of amphiboles and their references to formation conditions of granitoids from Nam Rom and Song Ma massifs, Northwest Vietnam

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ABSTRACT

In this paper, the mineralogical and geochemical characteristics of amphiboles and plagioclases of granitoids from the Nam Rom and Song Ma massifs have been investigated to understand their formation conditions. The Nam Rom amphibole and plagioclase are subhedral to euhedral fine- to medium-grained crystals. Whereas, the Song Ma amphibole and plagioclase are anhedral to subhedral fine-grained crystals. Geochemical compositions of amphiboles suggest that Nam Rom and Song Ma amphiboles are edenite and ferro-edenite, respectively. Nam Rom edenite has higher contents of basic constituents (Mg and Ca) and lower contents of felsic constituents (Na and K) compared with the Song Ma ferro-edenite. On the other hand, Si-(Na+K) and Si-Ca apfu ratios of the Nam Rom edenite and the Song Ma ferro-edenite and Al/(Na+K)-Al/(Ca+Na+K) atom per formula unit (apfu) ratios of the Nam Rom edenite and andesine and the Song Ma ferro-edenite, andesine and oligoclase are similar. Formation conditions of the Nam Rom and Song Ma granitoids were calculated using amphibole-plagioclase geobarometer. The Nam Rom granitoid was formed at 3.07-5.32 kbar (10.1-17.6 km under paleo-surface) and 750-785°C. The Song Ma granitoid was formed at 1.04-3.08 kbar (3.4-10.2 km under paleo-surface) and 715-745°C. Therefore, Nam Rom and Song Ma granitoids are thought to be crystallized from the same magma. The former was formed from the immature and more basic stage of magma; the latter was formed from the mature and more felsic stage of magma.

Keywords: Nam Rom; Song Ma; amphibole; plagioclase; geobarometer.

1. Introduction

Dien Bien and Song Ma granitoids are the significant Permian-Triassic magmatic rocks in the northwest segment of the Truong Son Fold Belt in both Vietnam and Laos territories. While the Dien Bien granitoid is located to the north along the Dien Bien-Lai Chau and Song Ma faults, the Song Ma granitoid is situated to the south along the Song Ma fault. In the Sam Nua Zone (Fig. 1A), the Dien Bien granitoid, Song Ma granitoid and Dong Trau volcanic rocks form a felsic intrusive-effusive magmatic group. The rock facies vary from the medium through fine-grained crystalline rocks to tuff

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breccia rocks. Close distribution of these rocks suggests a possibility that they were formed in the different stages of a magmatic event. The modern technologies on the isotopic ratios and dating are the appropriate techniques to elucidate the origin and timing of the magma. However, these techniques are expensive and difficult to approach. Despite, conventional techniques such as mineralogy and geochemistry of minerals are easier to approach, and the data could provide information about the evolution of magma. Approaching from the mineralogical and geochemical characteristics of the amphibole and plagioclase of the Dien Bien and Song Ma granitoids have been studied to clarify the formation conditions of these rocks due to modeling their forming procedure.

2. Outline of the geology of the Dien Bien and Song Ma complexes

The Dien Bien complex consists of Nam Rom (formerly Dien Bien), Nam Meng, Muong Tung, and Muong Luan massifs and several small intrusions. They distribute along the Dien Bien-Lai Chau fault (Dovzhikov et al., 1965; Tran et al., 1977; Nguyen and Tran, 1992; and Dao and Huynh, 1995). Petrology of the Dien Bien complex was classified into 3 phases. Phase 1 (early stage) consists of gabbroic diorite and diorite. Phase 2 (intermediate stage) consists of granodiorite and quartz diorite. Phase 3 (later stage) consists of biotite-amphibole granite and leucogranite (Figs. 1A-C; Dao and Huynh, 1995). The Dien Bien granitoid intruded into Neoproterozoic Nam Co quartz-mica-cordierite schist, garnet-mica-quartz schist, quart-sericite schist, sericite-chlorite schist and quartzite; and is covered by Late Triassic Suoi Bang conglomerate, sandstone, siltstone, and claystone (Tran, 2005). The isotopic datings of the Dien Bien granitoids are 272 ±3.2 Ma (U-Pb; Tran and Nguyen, 2006) and 252-266 Ma (K-Ar; Dao and Huynh, 1995). Based on the rock facies, geochemical data, and age dating, the Dien Bien granitoid is believed to form during the Indosinian orogenic magmatism and in an active continental margin environment (Tran et al., 2008).

The Song Ma complex consists of four elongated intrusions. They distribute along the Song Ma fault from Northwest to Southeast. Petrology of the Song Ma complex was classified into two phases. Phase 1 (early stage) consists of porphyritic biotite granite and biotite-amphibole granite. Phase 2 (later stage) consists of porphyritic granodiorite and quartz diorite (Figs. 1A, 1C, and 1E; Dao and Huynh, 1995; Phan, 2005). The Song Ma complex is closely related in space and origin to Middle Triassic felsic effusive of the Dong Trau Formation. Its rocks are overlain unconformably by coal-bearing beds of the Suoi Bang Formation, the basal conglomerate of which contains pebbles from granitoids of the Song Ma complex. The isotopic dating (Rb-Sr) of the Song Ma complex was 232 ±11 Ma (Dao and Huynh, 1995; Phan, 2005). The Song Ma granitoid and Dong Trau rhyolite co-magmatic association are thought to form in a post-collisional environment.

3. Petrographical characteristics of the Nam Rom and Song Ma massive

Representative samples of Dien Bien and Song Ma granitoids had been collected from the Nam Rom and Song Ma massifs, respectively (Figs. 1A-1E).

The Song Ma biotite-amphibole granite (sample SM-11; Fig 1E) comprises of large amounts of plagioclase, K-feldspar and quartz with lesser amounts of amphibole and biotite. Song Ma amphibole is granular, dark green color, anhedral to subhedral, small-grained. The grain size of the Song Ma amphibole is less than 1 mm in diameter. The Song Ma amphibole is commonly replaced by later minerals and partially to completely chloritized. There are two types of plagioclase in the Song Ma biotite-amphibole granite. Type 1 is isometrically, twinning and less altered plagioclase. The size of the Song Ma plagioclase type 1 is from 0.5 to 1.5 mm in diameter. Type 2 is tabular in shape and highly altered plagioclase. The size of the Song Ma plagioclase type 2 is less than 1 mm in diameter (Fig. 3).

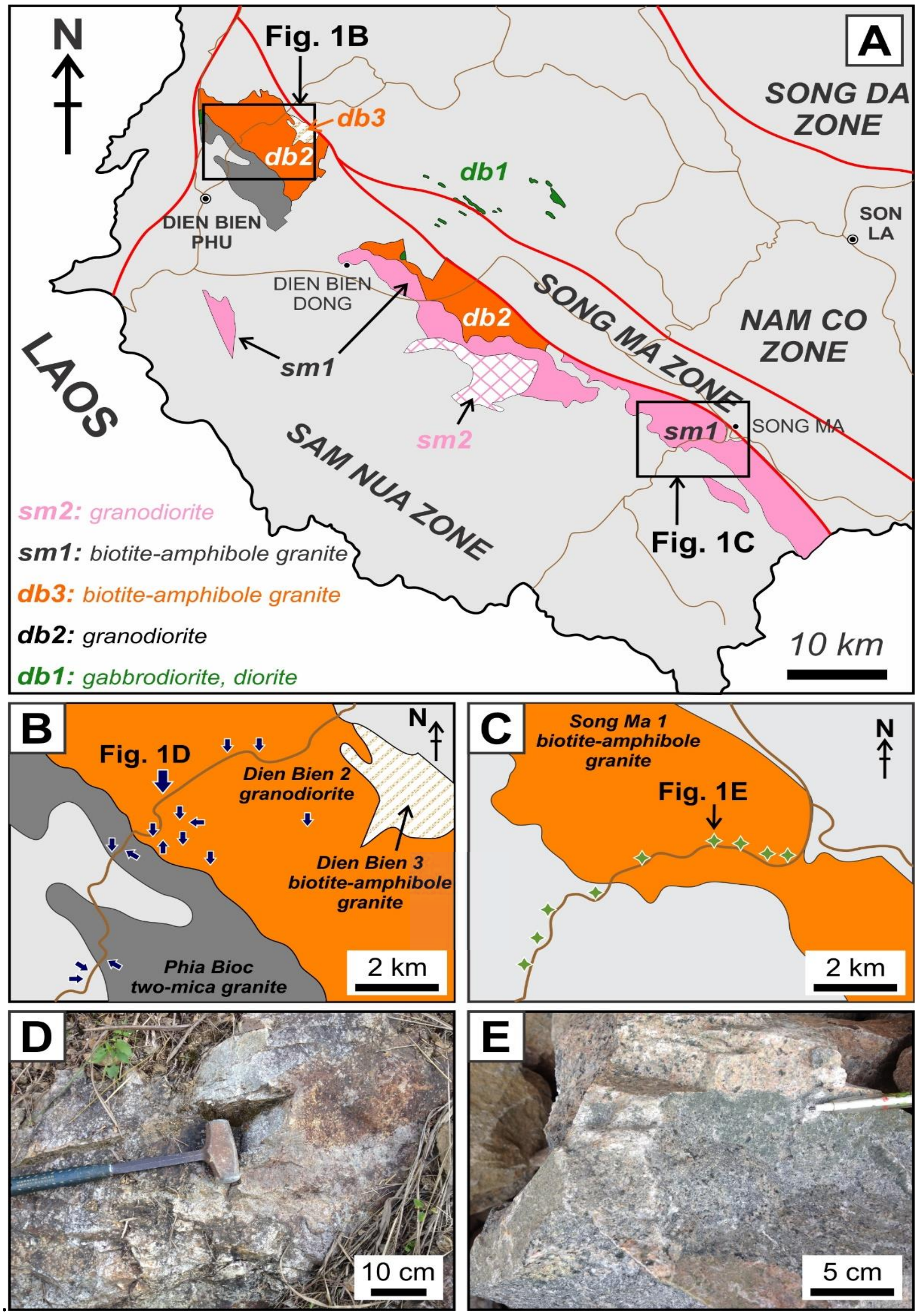

Figure 1. Simplified geological map shows the distribution of the Bien Dien and Song Ma granitoid and investigated locations

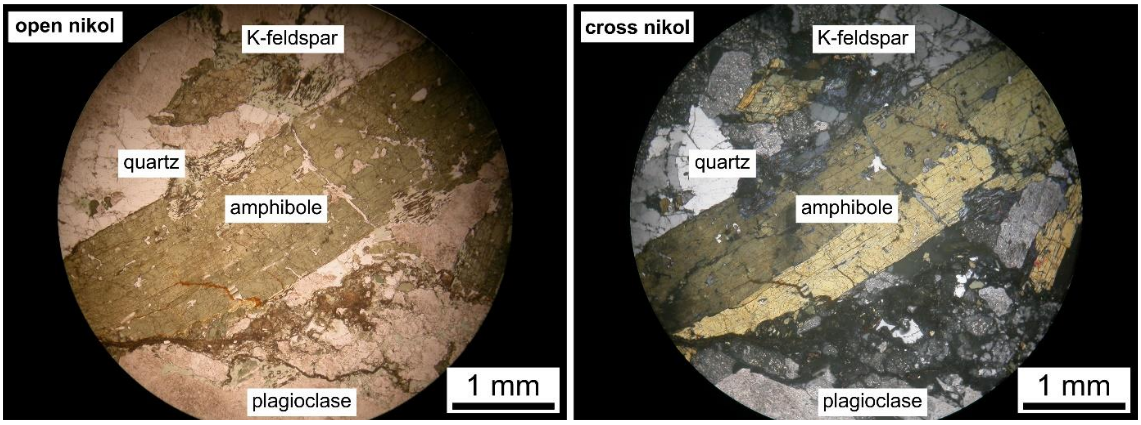

Figure 2. Photomicrograph of a thin section of the Nam Rom granodiorite

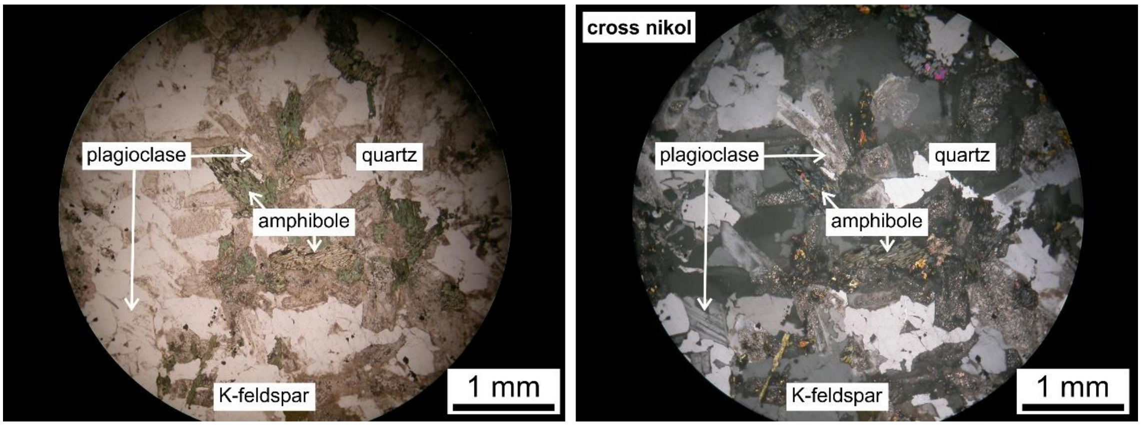

Figure 3. Photomicrograph of a thin section of the Song Ma amphibole-biotite granite

Based on the petrographical characteristics, the Nam Rom granodiorite is thought to be formed in a deeper and steady condition. On the other hand, the Song Ma biotite-amphibole granite is thought to be formed in a shallower and unsteady condition.

4. The chemical composition of amphibole and plagioclase

The chemical composition of amphibole and plagioclase was determined using a JEOL Superprobe JXA 8230 at the Institute of Geology and Mineralogy, Siberian Branch-Russian Academy of Sciences (IGM SB RAS). Quantitative analysis was conducted with an accelerated voltage of 20 kV, a beam current of 10 nA, count time for 10s and a beam diameter of 1 µm. The characteristic X-rays for measurement were F Kα, Na Kα, Mg Kα, Al Kα, Si Kα, Cl Kα, K Kα, Ca Kα, Ti Kα, Mn Kα, Fe Kα. The standards for Si, Al, and Na was albite; Mg and Ca was diopside; K was orthoclase; Mn and Fe were MnO-Fe_2O_3; Fe and Cl was phlogopite. All the data was corrected with a ZAF-oxide matrix.

4.1. The chemical composition of amphibole

The chemical compositions of amphiboles of the Nam Rom and Song Ma massifs are shown in Table 1. The structural formulas of amphiboles were calculated on the basis of 23 oxygen numbers. The ferric/ferrous correction followed the procedures introduced by Schumacher (1991), Leake et al. (1997), and Hawthorne et al. (2012). Since all data have $Ca_B > 1.5$ and $(Na + K)_A > 0.5$ (Table 1), the amphiboles of the Nam Rom and Song Ma massifs are edenite and ferro-edenite, respectively (Fig. 4; Leake et al., 1997; awthorne et al., 2012).

Table 1. Chemical compositions of amphiboles from the granitoids of the Nam Rom and Song Ma massifs

Locations	Nam Rom						
Results	1	2	3	4	5	6	7
SiO_2	43.7	42.3	44.3	43.4	43.6	42.7	43.8
TiO_2	1.31	1.32	1.14	1.24	1.25	1.23	1.21
Al_2O_3	9.8	9.7	8.7	9.4	9.7	9.5	9.2
FeO	18.3	18.4	17.8	17.8	18.2	18.1	17.9
MnO	0.44	0.47	0.48	0.46	0.48	0.47	0.43
MgO	10.2	10.1	10.7	10.6	10.2	10.3	10.7
CaO	11.5	11.5	11.6	11.5	11.5	11.5	11.5
Na_2O	1.59	1.55	1.39	1.47	1.67	1.66	1.62
K_2O	1.32	1.28	1.03	1.16	1.23	1.22	1.16
F	0.38	0.41	0.41	0.31	0.30	0.42	0.38
Cl	0.19	0.17	0.13	0.14	0.19	0.19	0.16
Total	98.7	97.1	97.7	97.4	98.2	97.4	98.1
Atomic number on the basis of 23 oxygen, Fe^{3+}/Fe^{2+} based on stoichiometric balance							
Si	6.562	6.452	6.673	6.565	6.569	6.505	6.592
Ti^{4+}	0.148	0.152	0.130	0.141	0.141	0.141	0.136
Al^{IV}	1.290	1.396	1.197	1.294	1.290	1.354	1.272
Sum T	*8.000*	*8.000*	*8.000*	*8.000*	*8.000*	*8.000*	*8.000*
Al^{VI}	0.438	0.352	0.349	0.373	0.429	0.353	0.365
Fe^{3+}	0.287	0.465	0.388	0.416	0.299	0.404	0.369
Mg	2.278	2.301	2.411	2.386	2.290	2.342	2.396
Fe^{2+}	1.997	1.878	1.852	1.824	1.982	1.897	1.870
Mn	0.000	0.004	0.000	0.000	0.000	0.004	0.000
Sum C	*5.000*	*5.000*	*5.000*	*5.000*	*5.000*	*5.000*	*5.000*
Mg	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe^{2+}	0.011	0.000	0.001	0.007	0.009	0.000	0.014
Mn	0.056	0.057	0.062	0.058	0.062	0.057	0.055
Ca	1.858	1.879	1.866	1.860	1.848	1.878	1.852
Na	0.076	0.065	0.072	0.075	0.081	0.065	0.079
Sum B	*2.000*	*2.000*	*2.000*	*2.000*	*2.000*	*2.000*	*2.000*
Na	0.388	0.394	0.334	0.355	0.407	0.425	0.395
K	0.254	0.250	0.198	0.224	0.236	0.237	0.222
Sum A	*0.641*	*0.644*	*0.531*	*0.579*	*0.643*	*0.663*	*0.616*
$Fe^{3+}/(Fe^{3+}+Fe^{2+})$	0.13	0.20	0.17	0.19	0.13	0.18	0.16
$Mg/(Mg+Fe^{2+})$	0.53	0.55	0.57	0.57	0.53	0.55	0.56

Table 1 (cont.)

Locations	Nam Rom			Song Ma			
Results	8	9	10	11	12	13	14
SiO_2	42.7	44.1	43.9	44.1	45.2	44.1	44.3
TiO_2	1.29	1.15	1.23	1.55	1.21	1.70	1.57
Al_2O_3	9.8	8.7	9.2	6.8	5.9	7.0	6.9
FeO	18.2	17.9	17.8	26.3	25.0	25.9	25.9
MnO	0.48	0.48	0.47	0.49	0.61	0.55	0.54
MgO	10.1	10.6	10.4	6.3	7.3	6.4	6.4
CaO	11.5	11.5	11.5	9.6	9.7	9.8	9.8
Na_2O	1.70	1.47	1.59	2.36	2.05	2.43	2.49
K_2O	1.30	1.06	1.18	0.56	0.72	0.54	0.49
F	0.45	0.31	0.39	0.90	0.83	0.79	0.90

Cl	0.20	0.14	0.12	0.30	0.39	0.32	0.28
Total	97.7	97.4	97.8	99.2	98.9	99.5	99.5
Atomic number on the basis of 23 oxygen, Fe^{3+}/Fe^{2+} based on stoichiometric balance							
Si	6.493	6.663	6.622	6.845	6.981	6.811	6.849
Ti^{4+}	0.147	0.131	0.140	0.181	0.140	0.198	0.183
Al^{IV}	1.359	1.205	1.239	0.974	0.879	0.991	0.968
Sum T	*8.000*	*8.000*	*8.000*	*8.000*	*8.000*	*8.000*	*8.000*
Al^{VI}	0.391	0.339	0.405	0.262	0.191	0.281	0.285
Fe^{3+}	0.344	0.379	0.296	0.325	0.350	0.270	0.244
Mg	2.284	2.398	2.352	1.459	1.687	1.480	1.475
Fe^{2+}	1.976	1.883	1.947	2.953	2.772	2.970	2.996
Mn	0.005	0.000	0.000	0.000	0.000	0.000	0.000
Sum C	*5.000*	*5.000*	*5.000*	*5.000*	*5.000*	*5.000*	*5.000*
Mg	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe^{2+}	0.000	0.003	0.009	0.129	0.106	0.103	0.111
Mn	0.056	0.061	0.060	0.064	0.080	0.072	0.070
Ca	1.879	1.861	1.853	1.589	1.605	1.628	1.616
Na	0.064	0.074	0.079	0.217	0.209	0.197	0.203
Sum B	*2.000*	*2.000*	*2.000*	*2.000*	*2.000*	*2.000*	*2.000*
Na	0.437	0.358	0.388	0.493	0.404	0.532	0.544
K	0.252	0.203	0.228	0.111	0.141	0.106	0.097
Sum A	*0.688*	*0.561*	*0.616*	*0.604*	*0.546*	*0.638*	*0.641*
$Fe^{3+}/(Fe^{3+}+Fe^{2+})$	0.15	0.17	0.13	0.10	0.11	0.08	0.07
$Mg/(Mg+Fe^{2+})$	0.54	0.56	0.55	0.32	0.37	0.33	0.32

Table 1 (cont.)

Locations	Song Ma						
Results	15	16	17	18	19	20	21
SiO_2	45.1	44.2	44.0	44.5	44.2	44.5	44.5
TiO_2	1.38	1.68	1.37	1.62	1.61	1.48	1.66
Al_2O_3	6.2	7.0	6.5	6.7	7.0	6.7	6.8
FeO	27.1	26.3	26.6	26.5	26.6	26.0	26.0
MnO	0.50	0.51	0.64	0.38	0.50	0.46	0.54
MgO	5.8	6.0	6.0	6.4	5.8	6.2	6.4
CaO	9.2	9.8	9.6	9.6	9.7	9.9	9.7
Na_2O	2.24	2.34	2.18	2.20	2.44	2.34	2.31
K_2O	0.59	0.55	0.78	0.47	0.62	0.51	0.62
F	0.84	0.74	0.54	0.87	0.86	0.75	0.82
Cl	0.25	0.33	0.44	0.27	0.33	0.31	0.33
Total	99.2	99.4	98.5	99.5	99.8	99.1	99.7
Atomic number on the basis of 23 oxygen, Fe^{3+}/Fe^{2+} based on stoichiometric balance							
Si	7.001	6.849	6.875	6.865	6.846	6.894	6.866
Ti^{4+}	0.162	0.195	0.162	0.188	0.187	0.172	0.193
Al^{IV}	0.838	0.956	0.964	0.947	0.967	0.934	0.941
Sum T	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al^{VI}	0.304	0.315	0.241	0.269	0.313	0.298	0.295
Fe^{3+}	0.235	0.220	0.325	0.367	0.206	0.211	0.249
Mg	1.337	1.386	1.390	1.468	1.349	1.441	1.461
Fe^{2+}	3.124	3.079	3.043	2.896	3.131	3.049	2.995
Mn	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Sum C	5.000	5.000	5.000	5.000	5.000	5.000	5.000
Mg	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe^{2+}	0.154	0.108	0.103	0.146	0.116	0.109	0.114
Mn	0.066	0.066	0.085	0.050	0.065	0.061	0.071

Ca	1.535	1.629	1.601	1.584	1.616	1.640	1.609
Na	0.245	0.196	0.211	0.220	0.203	0.191	0.207
Sum B	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Na	0.428	0.507	0.451	0.439	0.529	0.513	0.483
K	0.116	0.109	0.156	0.092	0.122	0.102	0.121
Sum A	0.544	0.617	0.608	0.531	0.651	0.615	0.604
$Fe^{3+}/(Fe^{3+}+Fe^{2+})$	0.07	0.06	0.09	0.11	0.06	0.06	0.07
$Mg/(Mg+Fe^{2+})$	0.29	0.30	0.31	0.33	0.29	0.31	0.32

Nam Rom edenite are characterized by higher concentrations of Al_2O_3 (8.7-9.8 wt. %), MgO (10.1-10.7 wt. %), CaO (11.5-11.6 wt. %), and K_2O (1.03-1.32 wt. %) and lower concentration of SiO_2 (42.3-44.3 wt. %), FeO (17.4-18.4 wt. %), and Na_2O (1.39-1.70 wt. %) compared to those of Song Ma ferro-edenite (SiO_2 = 44.2-45.2 wt. %; Al_2O_3 = 5.9-7.0 wt. %; FeO = 25.0-27.1 wt. %; MgO = 5.8-7.3 wt. %; CaO = 9.2-9.9 wt. %; Na_2O = 2.05-2.49 wt. %; and K_2O = 0.47-0.78 wt. %) (Table 1; Figs. 4-7).

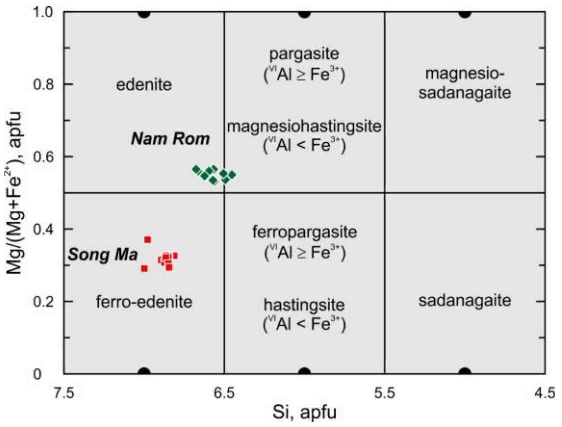

Figure 4. Classification of calcic amphiboles (Leake et al., 1997). Diagram parameters: $Ca_B \geq 1.50$; $(Na+K)_A \geq 0.50$; Ti < 0.50. apfu: Atoms per formula unit

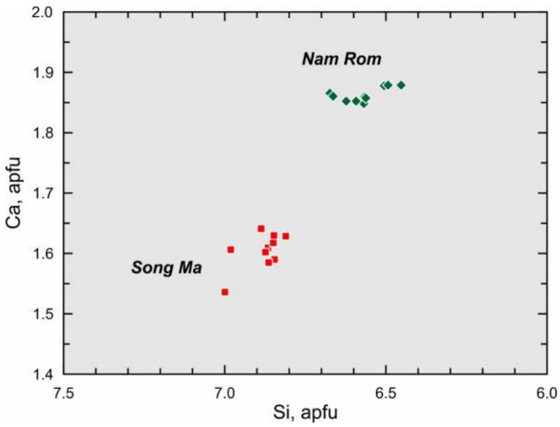

Figure 5. Correlation between Si and Ca (apfu) in the Nam Rom and Song Ma amphiboles

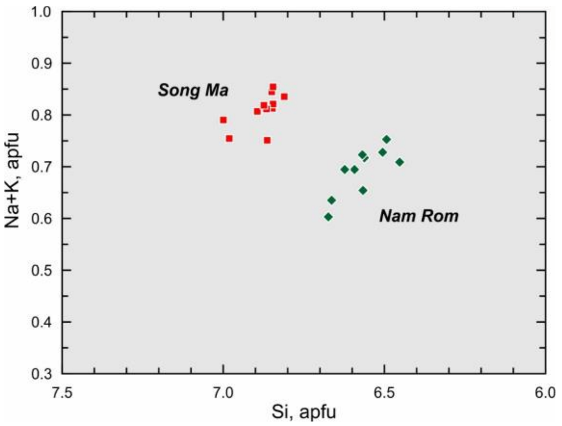

Figure 6. Correlation between Si and Na+K (apfu) in the Nam Rom and Song Ma amphiboles

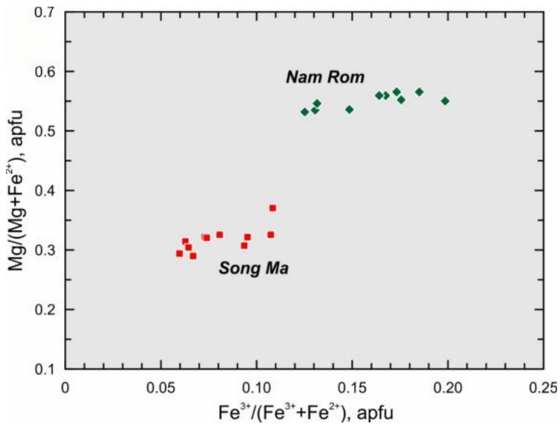

Figure 7. Correlation between $Fe^{3+}/(Fe^{3+}+Fe^{2+})$ and $Mg/(Mg+Fe^{2+})$ (apfu) in the Nam Rom and Song Ma amphiboles

Total concentrations of Na_2O+K_2O of the Nam Rom edenite and Song Ma ferro-edenite are similar (2.42-3.00 wt. % and 2.67-3.05 wt. %, respectively). However, Na+K (apfu) of the Song Ma ferro-edenite are higher than those of the Nam Rom edenite (Table 1; Fig. 6). In contrast, Ca (1.85-1.88 apfu), $Mg/(Mg+Fe^{2+})$ (0.53-0.57 apfu), and $Fe^{3+}/(Fe^{3+}+Fe^{2+})$ (0.13-0.20 apfu) of the Song Ma ferro-edenite are lower than those of Nam Rom edenite (1.54-1.64, 0.29-0.37, and 0.06-0.11 apfu, respectively) (Table 1; Fig 7).

H_2O contents had not been determined so it is difficult to interpret volatile components of the amphibole. However, based on the results of F, Cl and total measured components (Table 1), it is roughly said that the Nam Rom edenite has higher F+Cl+H_2O concentrations and lower (F+Cl)/H_2O ratios than those of the Song Ma ferro-edenite.

4.1. The chemical composition of plagioclase

The chemical compositions of plagioclases of the Nam Rom and Song Ma massifs are shown in Table 2. The structural formulas of plagioclases were calculated based on 8 oxygen numbers. Nam Rom plagioclases are restricted in an andesine component (Table 2; Fig. 8). Song Ma plagioclases are equally distributed in andesine and oligoclase (Table 2; Fig. 8). Both chemical compositions of the Nam Rom and Song Ma plagioclases show crystallization differentiation tendencies from andesine to oligoclase (Fig. 8).

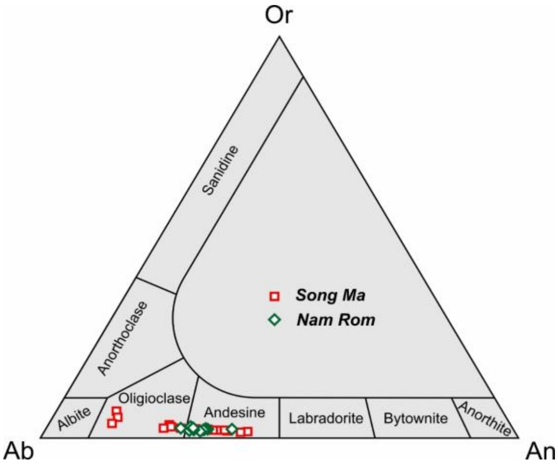

Figure 8. The Ab-An-Or ternary diagram shows compositions of the Nam Rom and Song Ma plagioclases

Table 2. Chemical compositions of plagioclase of the granitoid of the Nam Rom and Song Ma massive

Location	Nam Rom									
Results	1	2	3	4	5	6	7	8	9	10
SiO_2	59.3	59.7	59.2	59.5	58.8	59.0	59.1	57.3	60.0	59.4
Al_2O_3	25.0	24.5	24.5	25.3	25.3	25.3	25.4	26.2	24.8	25.2
FeO	0.13	0.17	0.18	0.15	0.13	0.17	0.17	0.18	0.12	0.05
CaO	6.83	6.42	6.77	7.45	7.48	7.58	7.49	8.68	6.84	7.24
Na_2O	8.49	8.72	8.35	8.01	8.10	7.87	7.96	7.25	8.44	8.07
K_2O	0.34	0.45	0.54	0.42	0.36	0.40	0.43	0.41	0.38	0.31
Total	100.1	99.9	99.5	100.8	100.3	100.4	100.6	100.0	100.6	100.3
Atomic number on the basis of 8 oxygen										
Si	2.657	2.675	2.668	2.646	2.634	2.639	2.637	2.579	2.670	2.652
Fe^{IV}	0.005	0.006	0.007	0.006	0.005	0.006	0.007	0.007	0.005	0.002
Al^{IV}	0.338	0.318	0.325	0.349	0.361	0.355	0.357	0.414	0.325	0.347
Al^{VI}	0.979	0.977	0.975	0.978	0.976	0.979	0.980	0.978	0.977	0.981
Ca	0.328	0.308	0.327	0.355	0.359	0.363	0.358	0.419	0.326	0.346
Na	0.737	0.758	0.729	0.691	0.703	0.682	0.688	0.633	0.729	0.698
K	0.019	0.026	0.031	0.024	0.021	0.023	0.024	0.024	0.022	0.018
Feldspar proportion										
Ab	68.0	69.4	67.1	64.6	64.9	63.9	64.3	58.9	67.7	65.8
An	30.2	28.2	30.1	33.2	33.1	34.0	33.4	39.0	30.3	32.6
Or	1.8	2.4	2.8	2.2	1.9	2.1	2.3	2.1	2.0	1.6

Table 2 (cont.)

Location	Nam Rom		Song Ma							
Results	11	12	13	14	15	16	17	18	19	20
SiO_2	59.8	59.7	61.2	64.4	58.8	55.3	57.5	56.5	57.2	57.0
Al_2O_3	24.9	24.8	23.8	21.8	25.0	26.9	25.4	25.9	25.9	26.0
FeO	0.12	0.18	0.20	0.24	0.21	0.33	0.25	0.24	0.23	0.30
CaO	6.98	6.90	5.62	3.15	7.04	9.34	7.54	7.98	7.99	8.39
Na_2O	8.29	8.29	8.69	10.32	8.18	6.75	7.93	7.58	7.87	7.44
K_2O	0.37	0.48	0.57	0.96	0.42	0.27	0.38	0.35	0.36	0.34
Total	100.5	100.4	100.1	100.8	99.6	98.8	99.0	98.5	99.5	99.4
Atomic number on the basis of 8 oxygen										
Si	2.667	2.666	2.727	2.839	2.647	2.525	2.613	2.582	2.589	2.582
Fe^{IV}	0.005	0.007	0.007	0.009	0.008	0.013	0.010	0.009	0.009	0.012
Al^{IV}	0.329	0.327	0.266	0.152	0.345	0.462	0.378	0.409	0.402	0.407
Al^{VI}	0.978	0.978	0.987	0.978	0.981	0.986	0.981	0.984	0.978	0.981
Ca	0.333	0.330	0.269	0.149	0.340	0.457	0.367	0.391	0.387	0.407
Na	0.716	0.718	0.751	0.883	0.714	0.598	0.698	0.672	0.690	0.653
K	0.021	0.028	0.032	0.054	0.024	0.016	0.022	0.020	0.021	0.020
Feldspar proportion										
Ab	66.9	66.7	71.4	81.3	66.3	55.8	64.2	62.1	62.8	60.5
An	31.	30.7	25.5	13.7	31.5	42.7	33.8	36.1	35.3	37.7
Or	2.0	2.6	3.1	5.0	2.2	1.5	2.0	1.8	1.9	1.8

Table 2 (cont.)

Locations	Song Ma								
Results	21	22	23	24	25	26	27	28	29
SiO_2	55.9	59.3	56.6	63.0	64.5	59.7	58.1	61.6	56.0
Al_2O_3	26.5	24.0	26.2	21.5	21.2	24.3	25.2	23.7	26.7
FeO	0.33	0.20	0.21	0.15	0.22	0.18	0.21	0.30	0.31
CaO	9.12	5.75	8.48	2.97	2.92	6.34	7.57	5.60	9.39
Na_2O	6.99	8.74	7.32	10.30	10.25	8.59	7.76	9.13	6.78
K_2O	0.25	0.49	0.31	0.67	1.27	0.45	0.36	0.44	0.27
Total	99.1	98.5	99.1	98.6	100.4	99.6	99.2	100.7	99.4
Atomic number on the basis of 8 oxygen									
Si	2.547	2.692	2.572	2.837	2.857	2.684	2.629	2.731	2.541
Fe^{IV}	0.012	0.008	0.008	0.006	0.008	0.007	0.008	0.011	0.012
Al^{IV}	0.440	0.300	0.420	0.157	0.135	0.309	0.363	0.258	0.448
Al^{VI}	0.981	0.986	0.982	0.981	0.974	0.979	0.981	0.979	0.982
Ca	0.445	0.280	0.413	0.143	0.139	0.305	0.367	0.266	0.457
Na	0.617	0.769	0.645	0.899	0.880	0.749	0.681	0.785	0.597
K	0.014	0.028	0.018	0.038	0.072	0.026	0.021	0.025	0.016
Feldspar proportion									
Ab	57.3	71.4	59.9	83.2	80.7	69.3	63.7	73.0	55.8
An	41.4	26.0	38.4	13.3	12.7	28.3	34.3	24.7	42.7
Or	1.3	2.6	1.6	3.5	6.6	2.4	2.0	2.3	1.5

5. Formation conditions of the Nam Rom granodiorite and Song Ma biotite-amphibole granite

5.1. The evolution of the granitoids

The Nam Rom plagioclases are large, iso-dimension and isometric crystals. Their chemical compositions are narrow variation and mostly andesine. It suggests that the Nam Rom plagioclases were crystallized in a deep and stable magma chamber. The Song Ma plagioclases consist of large, iso-dimension intermediate plagioclase and small, tabular sodic plagioclase. They correspond to andesine and oligoclase, respectively. It suggests that the Song Ma plagioclases were crystallized in two environments: early is deeper and stable and later is shallower.

5.2. Chemical compositions of magmas

Major constituents of granitoid are amphibole, biotite, muscovite, plagioclase, K-feldspar, and quartz (Streckeisen, 1973; Le Bas and Streckeisen, 1991). Among the minerals, amphibole and intermediate plagioclase are of initial crystallization (Bowen's reaction series, Bowen, 1956). Therefore, the chemical compositions of amphibole and intermediate plagioclase reflect the initial composition of the magma.

The Nam Rom edenite has higher contents of basic constituents (Mg and Ca) and lower contents of felsic constituents (Na and K) than those of the Song Ma ferro-edenite. It suggests that the Nam Rom granitoids were crystallized from a more basic magma than the Song Ma granitoids. However, both amphiboles have a similar correlation between Si and Na+K, and Si and Ca (Figs. 5-6).

On the Ab-An-Or ternary diagram, all the data of the Nam Rom and Song Ma plagioclase are plotted on one line. On the Al/(Na+K)-Al/(Ca+Na+K) binary diagram, all the data of Nam Rom and Song Ma amphiboles and plagioclases are also plotted on two parallel lines (Fig. 9). The higher volatile contents and H_2O proportions in volatile correspond with higher ferric/ferrous ratios in the Nam Rom amphibole. All the above data suggest that the Nam Rom and Song Ma granitoids were crystallized from magmas that have a similar origin. The Nam Rom magma was immature while the Song Ma magma was mature and differentiated.

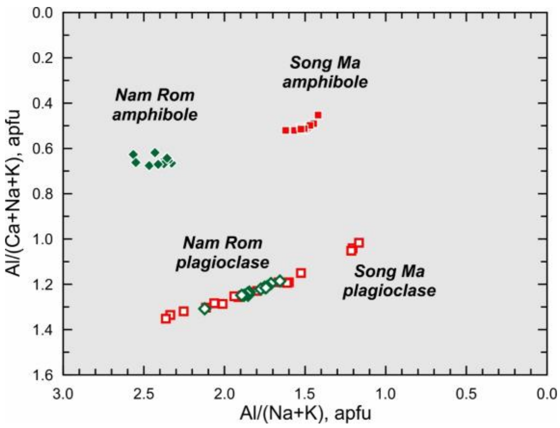

Figure 9. Correlation between Al/(Na+K) and Al/(Ca+Na+K) (apfu) in the Nam Rom and Song Ma amphiboles and plagioclases

5.3. Formation conditions of the Nam Rom and Song Ma massifs

Experimental studies (Hammarstrom and Zen, 1986; Hollister et al., 1987; Johnson and Rutherford, 1989; Schmidt, 1992) suggested that solidification pressure of calc-alkaline plutons could be calculated from Al^{total} in hornblende (Table 3). Based on the above procedures, crystallization pressure of the Nam Rom edenite and the Song Ma ferro-edenite were calculated at 3.07-5.32 kbar and 1.04-3.08 kbar, respectively. They correspond with 10.1-17.6 km and 3.4-10.2 km under paleo-surface. The deeper of Nam Rom magma chamber than the Song Ma magma chamber appropriate with the morphology of their plagioclase.

By reference to the procedure proposed by Blundy and Holland (1990), amphibole-plagioclase equilibrium temperature is estimated as follow:

$T = (0.677P - 48.98 + Y)/(-0.0429 - 0.008314 \ln K)$ and $K = (Si-4)/(8-Si)\ XPlAb$

Where Si is the number of apfu in amphiboles, with P in kbar and T in K, Y = 0 for $X^{Pl}_{Ab} > 0.5$ and $Y = -0.86 + 25.5(1-X^{Pl}_{Ab})^2$ for $X^{Pl}_{Ab} < 0.5$.

The formation temperature of the Nam Rom and Song Ma amphiboles was estimated to be 750-785°C and 715-745°C.

Table 3. Empirical correlation between the estimated pressures of crystallization of calc-alkaline plutons and the total Al content of hornblende

Equation (kbar)	Deviation	Error (kbar)	Reference
$P = 5.03Al^{total} - 3.92$	$r^2 = 0.80$	± 1	Hammarstrom and Zen, 1986
$P = 5.64Al^{total} - 4.76$	$r^2 = 0.97$	± 1	Hollister et al., 1987
$P = 4.23Al^{total} - 3.46$			Johnson and Rutherford, 1989
$P = 4.76Al^{total} - 3.01$	$r^2 = 0.99$	± 0.6	Schmidt, 1992

6. Summaries

The formation conditions of the Nam Rom and Song Ma granitoids are summarized as follows (Fig. 10).

Nam Rom and Song Ma granitoids were crystallized from the same magma. The Nam Rom magma was more basic and immature while the Song Ma magma was more felsic and matured. The Nam Rom magma was relatively higher oxidation state than the Song Ma magma.

The Nam Rom granitoid was formed at 3.07-5.32 kbar (10.1-17.6 km under paleo-surface) and 750-785°C. The Song Ma granitoid was formed at 1.04-3.08 kbar (3.4-10.2 km under paleo-surface) and 715-745°C.

There was possibly additional magma supply to a deeper Nam Rom crystallization chamber, that caused initially differentiated Nam Rom magmas to rise, forming shallower Song Ma crystallization chambers where initial magmas became matured.

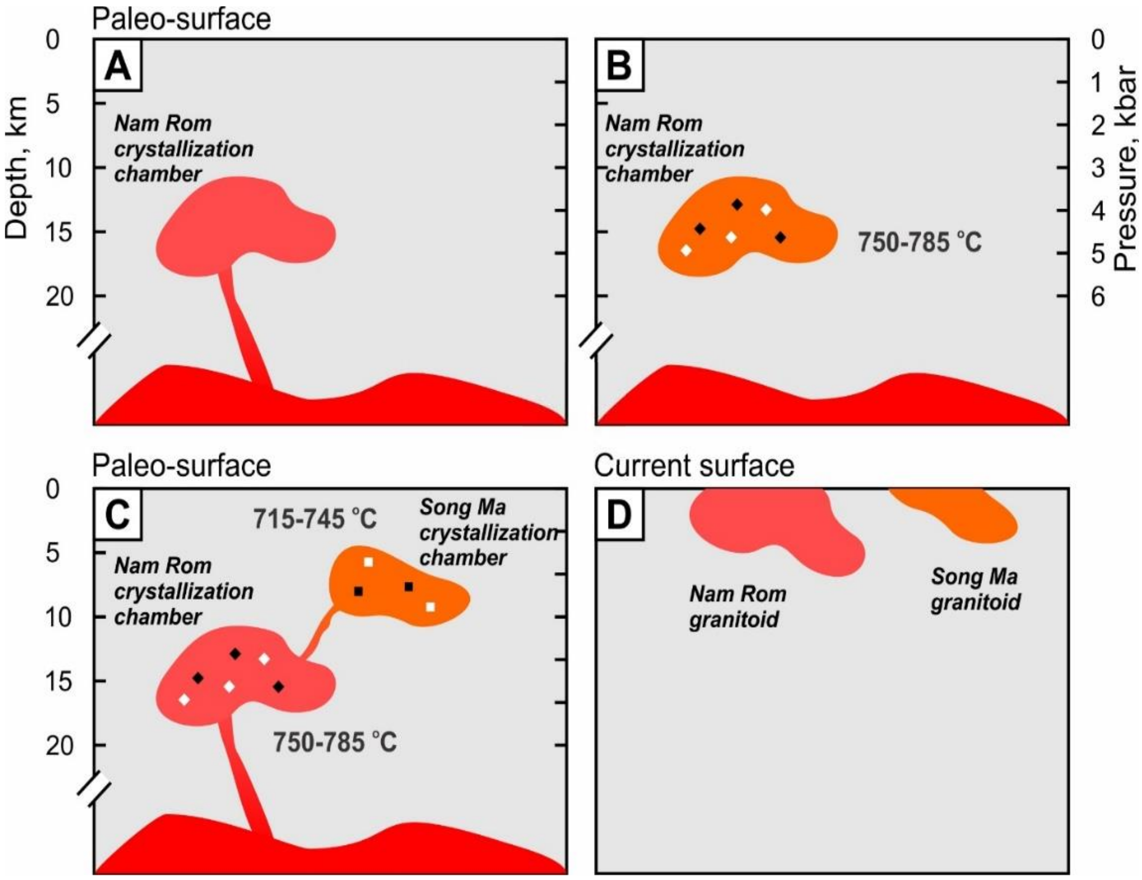

Figure 10. llustration showing the formation mechanism of the Nam Rom and Song Ma granitoids

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