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Petrographic and geochemical characteristics of the Nui Chua pegmatoid mafic-ultramafic series, Northern Vietnam: Significance in petrogenesis and Fe-Ti-V metallogenesis

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ABSTRACT

The pegmatoid intrusions of the Nui Chua complex are one of the important mafic-ultramafic intrusive series associated with Fe-Ti-V ores in northern Vietnam. These intrusions consist of plagiowebsterite, clinopyroxenite, melanogabbronorite, mesogabbro, gabbronorite, and leucogabbronorite. The Fe-Ti oxide ores being massive or disseminated appear layered or veined in pegmatoid rocks. The geochemical characteristics of pegmatoid rocks are rich in Fe, Ti, V and poor Mg; their HREE are higher than LREE, with $[La/Yb]_N$ of 0.49 to 0.91 (average: 0.67), showing negative anomalies at Nb, Ta, Th, U, Sr, Zr and positive anomalies at Cs, Ti, and K. The chemical composition and distribution characteristics of trace and rare earth elements of mafic and ultramafic rocks show that they share the same magma source. Having the same geochemical tendency of intrusive formations, Fe-Ti oxide ores are magmatic origin associated with intrusive pegmatoid rocks. The pegmatoid rocks of the Nui Chua complex and Fe-Ti oxide ores are formed as a product of the fractional crystallization of Fe-Ti-rich residual melts after crystallization of the layered rocks.

Keywords: Mafic-ultramafic, pegmatoid rocks, Fe-Ti oxide ore, Nui Chua intrusive complex, Northern Vietnam.

1. Introduction

Mafic-ultramafic intrusive formations are of interest to many geologists, especially mafic-ultramafic formations of the Nui Chua complex in northern Vietnam. The information includes the status of the mantle, the geodynamic context, and especially the information on how a series of valuable minerals such as Cr, Cu, Ni, platinum element group (PGE), Fe, Ti, and V related to these formations are formed (Polyakov et al., 1996, 1999; 2009; Hoang H.T. et al., 2004; Tran T.H. et al., 2008).

Many detailed studies of the petrology, mineralogy, and geochemistry have divided the mafic-ultramafic intrusions of the Nui Chua complex into layered and pegmatoid series (Polyakov et al., 1996, 1999; 2009; Tran T.H.

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et al., 2008). The layered intrusive rocks are related to Cu, Ni, and PGE mineralization, and the pegmatoid series are related to Fe, Ti, and V ores. The layered intrusions have been studied on the origin and formation mechanism as well as the relationship with Cu, Ni, and PGE minerals (Polyakov et al., 1996, 2009; Tran TH et al., 2008; Tran Q.H. et al., 2010). In contrast, the pegmatoid intrusion of the Nui Chua complex and Fe-Ti-V oxide minerals have not been well studied although Fe-Ti oxide ores have been exploited for a long time. Among the mines, the Cay Cham titanium ore deposit is proposed to be the largest primary titanium ore mine in Vietnam with 4.6 million tons reserves of ilmenite and 2.4 million tons TiO_2 (Explanation of the geological and mineral map at 1:200,000 scale of Tuyen Quang sheet).

In this paper, we present the results of detailed geological, petrological, and geochemical characteristics of pegmatoid mafic-ultramafic rocks and Fe-Ti oxide ores of the Nui Chua complex in order to better understanding the origin and forming mechanism of pegmatoid rocks and Fe-Ti oxide ore bodies as well as their relation.

2. Geological background

Northern Vietnam is part of the Yangtze craton, which is separated from the Indochina block by the Song Ma suture zone (Fig. 1). Northern Vietnam is divided into Northwest and Northeast Vietnam with its boundary being the Red River shear zone (Fig. 1). Northeast Vietnam was subdivided into Song Hien, Lo Gam - Phu Ngu, and An Chau tectonic domains (Fig. 1).

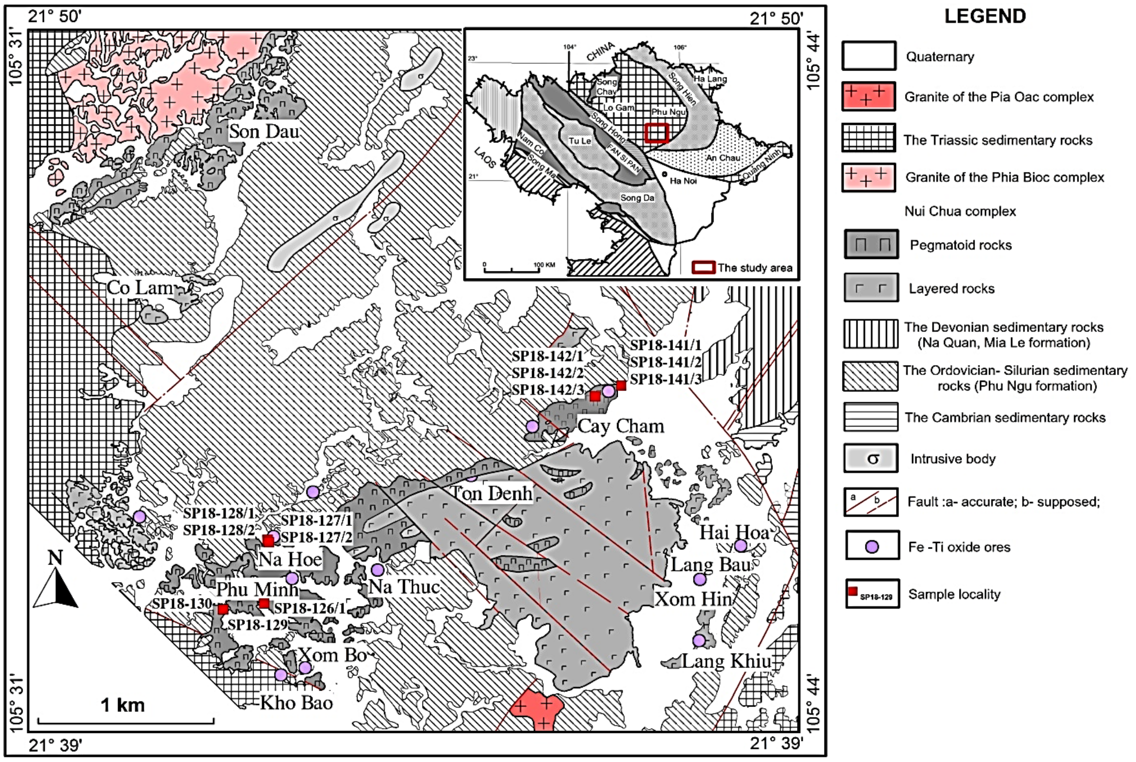


Figure 1. Geological scheme and survey locations of pegmatoid rocks of Nui Chua complex (modified from Polyakov et al., 1996; 2009)

The Nui Chua complex is located in the Phu Ngu tectonic domain, including main massifs as Nui Chua, and Khao Que, Son Dau (in Thai Nguyen province) and a number of small bodies in the Phu Luong, Phu Ninh, Nui Hong (Thai Nguyen province), Cho Ra and Ba Be lake (in Bac Kan province). All these massifs have concentric zonation, layering, and periodicity characteristics, such as the rhythm of variously grain-sized, and dark-, light-colored gabbroid. The gabbroid rocks have a close spatial relationship with the high aluminum granite of the Phia Bioc complex (Polyakov et al., 2009). The intrusive formations in the complex are usually divided into layered intrusive rocks (including olivinite, lherzolite, wehrlite, troctolite, olivine gabbro) and pegmatoid rocks (including variable pyroxenite and gabbronorite (Polyakov et al., 2009). The two series are distinguished by the presence of olivine in the layered series and almost absent in the pegmatoid series (Polyakov et al., 2009).

The Nui Chua massif is a representative intrusion of the Nui Chua complex that has been studied in detail. According to the geological and mineral map of the 1: 200,000 scale by Pham Dinh Long (2001), Nui Chua massif located in the south of the Phu Ngu tectonic domain as an oval shape extending in the W-E direction (Fig. 1) within the metamorphic sedimentary rocks of the Phu Ngu formation (Ordovician - Silurian age). To the Northeast and Southeast, the massif cut by the Song Cong fault and the QL-3 road. The Northeast contact is Devonian sedimentary formations composed of limestone, sandstone, quartz schist-sericite, and sericite. The westernmost part is overlain by molasses of Late Triassic Van Lang formation composed of sandy clay, clay - lime, conglomerate, and coals. The massif was separated by the Northeast and some by the Northwest faults to form 5 small blocks, of which the eastern one has the largest outcrop, accounting for over 50% of the massif's area. This massif is best outcropped and has the most representative geochemical compositions, including a full range of different rock types of the series, from dark- to light-colored gabbro-pegmatite common in the Nui Chua massif. U-Pb age dating on zircon by SHRIMP for the gabbro in Nui Chua massif yielded ca. 251 Ma (Tran T.H. et al., 2008), corresponding to the Late Permian - Early Triassic.

3. Petrographic characteristics

The pegmatoid series of Nui Chua complex composes of plagiowebsterite, clinopyroxenite, melanogabbronorite, mesogabbro, gabbronorite, leucogabbronorite.

Clinopyroxenite is dark-gray color, coarse-grained exposing in Khao Que and Nui Chua massifs. The main rock-forming mineral is dark- blue clinopyroxene (70-80 %), plagioclase (10-30%) and a few ore minerals. Clinopyroxene is typically euhedral and up to 2-5 cm in length, creating a pegmatite texture. The minerals often fractured, amorphous, and slightly altered (Figs. 2a, b), some is amphibolized. Plagioclase occurs in small- to medium-grained, sometimes with large-grained size, clear twins, and generally quite fresh. There are also a few red-brown amphibole and biotite grains. Ore minerals account for about 2-3 modal %, mainly titanomagnetite and ilmenite that are often evenly distributed in the rocks (Figs. 2e, f). Found also is a small number of sulfide ores distributed in aggregates.

Pegmatite-formed gabbroid: The characteristic petrographic composition and textural feature of this rock type are that they have large pyroxene mosaic crystals surrounding euhedral plagioclase crystals. Pyroxene often has an eroding texture, orthopyroxene often includes clusters of a pine branch-, worm-, sheet- or nest-shaped clinopyroxene together with magnetite and ilmenite. Plagioclase is labrador (An61-65), clinopyroxene is diopside (f_{CPx} = 29.6%), and orthopyroxene is hypersthene (f_{OPx} = 43%) in composition.

Gabbro-pegmatoid: This rock is quite common in the west of Nui Chua, far from the center of the stratified series, usually has a trachytic texture, containing quartz and biotite. The characteristic of these rocks is plagioclase with a low base component, while dark minerals have higher iron content as compared with those of the stratified series (f_{CPx} = 29.5%; f_{OPx} = 65.5%; f_{Ol} = 37%). Pyroxene often has a corrosive texture; "pine skin" texture is observed in orthopyroxene with thin diagonal sheets of diopside. Gabbro-pegmatoid is quite rich in ore minerals such as magnetite, titanomagnetite, ilmenite, sometimes apatite, and sulfide.

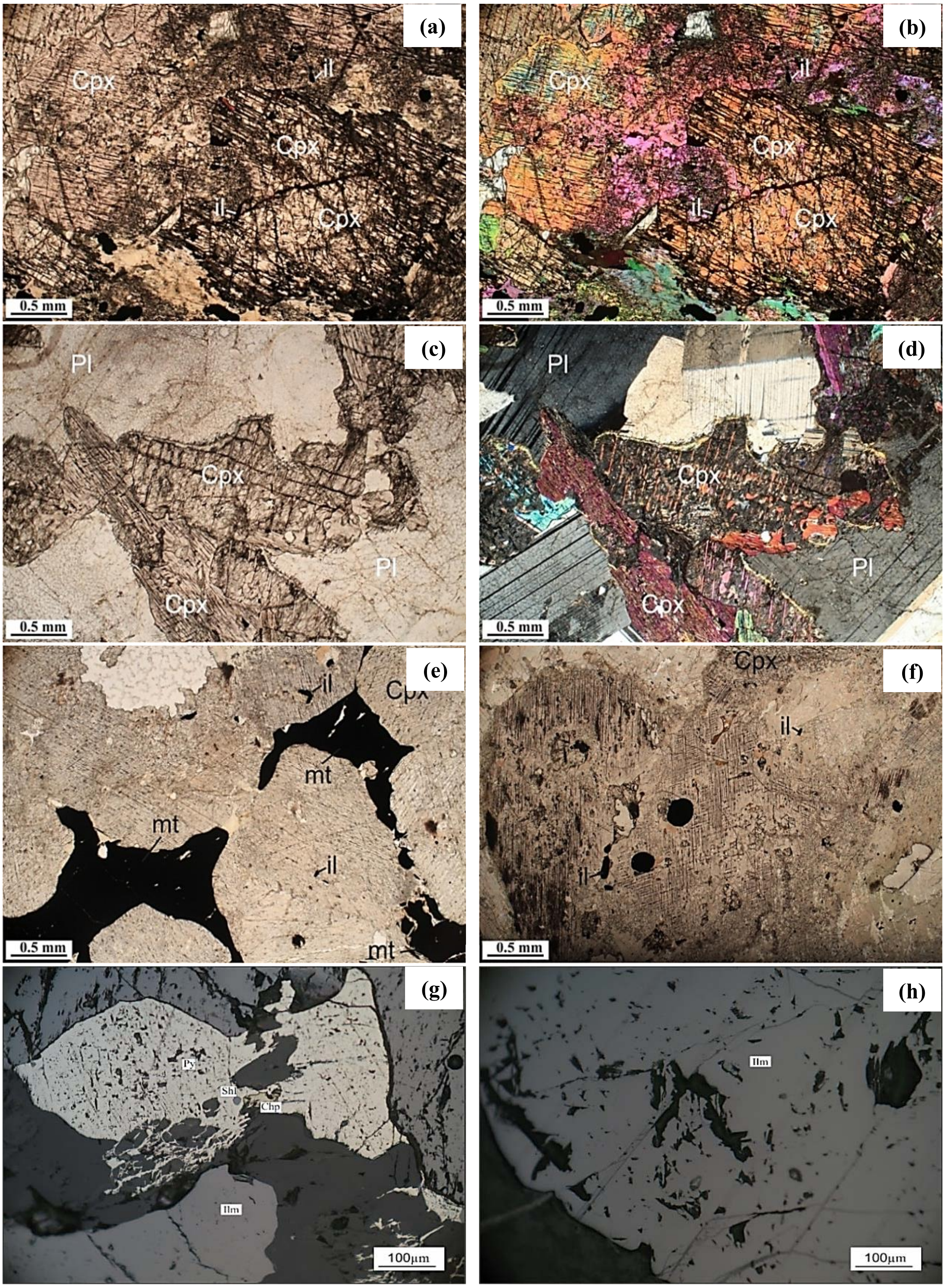
Plagiowebsterite and melanogabbronorite: These two rock types have quite a similar mineral composition, except only in the content of dark pyroxene and light plagioclase. In plagiowebsterite, the amount of colored minerals is from 70 to 85%, while in melanogabbronorite they account for about 55 to 70%. Pyroxene in both rocks is large, from 1 to 3 cm, sometimes up to 5-6 cm, making pegmatite texture of the rock. Pyroxene is often decomposed, in orthopyroxene often contains small clinopyroxene grains. Plagioclase is usually small, euhedral and fresh, and is distinctly twining. Ore minerals are fewer, about 1-2 vol.%.

Mesogabbroid (normal gabbro): This is an olivine-free magma, quite common in the pegmatoid series. The rock-forming minerals are similar to that of the dark-colored magmas consisting of plagioclase, two pyroxenes, and the oxide ore mineral. Of which, gabbro has only plagioclase and clinopyroxene, while gabbronorite contains also orthopyroxene, but usually less than clinopyroxene. Plagioclase accounts for about 60-65%, often having lower bases (An_{55-60}) than similar rocks in stratified series. Pyroxene is similar to that of dark-colored rock types in pegmatite series, having a higher iron content as compared to those in stratified rocks, with clinopyroxene at f_{Cpx} = 29.6% and orthopyroxene at f_{Opx} = 43%. The clinopyroxene often has the same decomposing texture as in the dark-colored rocks (Figs. 2c, d). Ore minerals are mainly magnetite, titanomagnetite, and ilmenite.

Light-colored gabbro (leucogabbro): has a mineral composition that is similar to that of the same rock types in the pegmatoid series, with the light-colored mineral being plagioclase accounting for 70 to 80%. Sometimes a few small grains of biotite and apatite are also discovered. Ore minerals are mainly magnetite, titanomagnetite, ilmenite with varying content of about 2-3%, or can be up to 6-7% in ore-bearing rocks. The composition of the rock-forming minerals is similar to those in the pegmatoid series, with plagioclase being a low base component and pyroxene being high iron content.

4. Oxide mineralization

The ore bodies associated with gabbro of the Nui Chua complex concentrate mainly in the north of Dai Tu district and southwest of Phu Luong district, Thai Nguyen province. Ore bodies of thick seam form or lens are distributed inside or along the edge of intrusive bodies. Rich ores accumulating types are found in Cay Cham (Phu Luong district) and Na Hoe deposits (Dai Tu district) in Thai Nguyen province. The ore bodies of this type are usually no more than 1000 m long, from a few meters to more than 100 m thick, beveled gradually along with the depth. The ilmenite content in ores usually reaches 30-70 wt.%. At the remaining sites, ores are disseminated or lumpy in pegmatoid rocks. The disseminated ore bodies are large, sometimes several kilometers long, from 10 to 100 meters thick. Ore minerals are mainly ilmenite, secondary are magnetite, pyrrhotine, pyrite, chalcopyrite, sphalerite (Figs. 2g, h). In the oxide ores, the ore minerals are interstitial to the main rock-forming minerals (Figs. 2 e-h), suggesting that they crystallized at a late stage. The ilmenite content in ores usually reaches 2-3 wt.% to more than 10 wt.% (Average 4-5 wt.%). The ore zones are disseminated in weathering crust and even in gabbro rocks, where ilmenite content is enriched. Weathered crust thickness varies from a few meters to over 20 m. The remnant weathered ore bodies have favorable mining conditions. Although its content is not high, the ilmenite potential is huge.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← *Figure 2*. Microphotographs of pegmatoid rocks of Nui Chua complex. a-b: Clinopyroxenite, sample SP18-128, ilmenite exsolution lamellae in Clinopyroxene; c-d: gabbro, sample SP18-126; e-f: clinopyroxenite with disseminated Fe-Ti oxides, sample SP18-130 and SP18-115, respectively; g: Ilmenite and secondary pyrite in intergrowth with chalcopyrite and sphalerite, sample SP18-141/5; h: Ilmenite with exsolved lamellae of titanomagnetite (sample SP18-142/3). a-f: Polarized light (a, c, e, f: plane - polarized light; b, d: crossed - polarized light); g-h: reflected light. Abbreviations: Cpx- Clinopyroxene, Pl-Plagioclase, K-fels- K-feldspar, Bt-Biotite, il, ilm -ilmenite; mt- magnetite; Py- pyrite; Chp- chalcopyrite; Shl: sphalerite

5. Analytical methods

Major element concentrations were determined by X-ray fluorescence (XRF) method at the Analytical Center for Multi-element and Isotope Research, Siberian Branch, Russian Academy of Science in Novosibirsk, Russia. The standard samples for the analysis were MU-1, MU-3, MU-4, SA-1, SCHT-1, SCHT-2, SDO-1, SDU-1, SG-1A, SG-2, SG-3, SGD-1, SGD-2, SGX-1, SGX-5, SGXM-2, SGXM-3, SI-1, SI-2, SNS-1, SNS-2, SOP-1, ST-1, and accuracy of the analysis is about ±2% for all oxides.

Trace element analysis was performed at the Activation Laboratories Ltd. (Actlabs), Ancaster, Ontario, Canada. Trace elements were measured using Multi-method Package Ultratrace 3 including Instrumental Neutron Activation Analysis (INAA) and multi-acid total digestion inductively coupled plasma spectrometry (TP-ICP) combined with Inductively coupled plasma mass spectrometry (TD-ICP-MS). Major oxide and trace element data are given in Table 1, 2.

Table 1. Major element compositions (wt%) of pegmatoid series of Nui Chua complex

Sample	SP18-126/1	SP18-128/1	SP18-128/2	SP18-129	SP18-130	SP18-141/1	SP18-141/2	SP18-141/3
	Na Hoe deposit			Route 264, Thai Nguyen		Cay Cham deposit		
	1	2	3	4	5	6	7	8
SiO_2	50.27	43.46	48.48	53.86	44.03	33.34	34.20	34.33
TiO_2	0.62	4.75	1.08	3.85	4.97	16.37	14.98	16.15
Al_2O_3	14.02	5.16	20.39	11.09	13.76	1.83	3.77	1.32
Fe_2O_3T	12.23	25.31	8.03	16.56	19.53	28.65	25.93	26.31
MnO	0.25	0.57	0.21	0.47	0.35	0.63	0.50	0.50
MgO	8.91	10.73	5.22	2.64	4.47	8.98	8.70	9.40
CaO	11.52	9.68	12.83	8.14	9.84	9.63	10.93	12.10
Na_2O	1.82	0.15	2.05	1.73	1.94	0.11	0.36	0.11
K_2O	0.12	0.04	0.13	0.44	0.25	0.37	0.11	0.19
P_2O_5	0.04	0.02	0.06	0.66	0.46	0.13	0.38	0.11
LOI	0.03	1.05	0.88	0.27	0.23	0.43	0.48	0.89
Total	99.82	100.93	99.39	99.70	99.81	100.47	100.35	101.40

To be continued

Sample	SP18-141/4	SP18-141/5	SP18-142/1	SP18-142/2	SP18-142/3	SP18-127/1	SP18-127/2
	Cay Cham deposit					Ore in Na Hoe deposit	
	9	10	11	12	13	14	15
SiO_2	49.71	27.42	47.68	36.71	49.90	0.69	1.22
TiO_2	0.53	17.99	3.05	13.51	0.55	43.59	38.95
Al_2O_3	15.37	4.04	5.34	2.33	15.79	0.27	0.30
Fe_2O_3	10.76	29.13	18.86	25.54	10.66	54.73	57.24
MnO	0.30	0.66	0.44	0.51	0.23	0.60	0.54
MgO	7.63	6.41	11.30	10.21	7.68	1.42	1.37
CaO	13.66	10.84	12.30	11.52	11.75	0.04	0.05
Na_2O	1.79	0.29	0.71	0.24	2.02	0.06	0.05

Sample	SP18-141/4	SP18-141/5	SP18-142/1	SP18-142/2	SP18-142/3	SP18-127/1	SP18-127/2
	Cay Cham deposit					Ore in Na Hoe deposit	
K_2O	0.07	0.48	0.13	0.07	0.22	0.02	0.02
P_2O_5	0.02	3.06	0.07	0.05	0.03	0.01	0.02
LOI	0.13	0.67	0.35	1.27	0.51	2.16	0.79
Total	99.97	101.00	100.24	101.96	99.36	103.58	100.55

Remark: 1-3, 9, 11, 13: ore-bearing gabbronorite, 4-5: monzogabbro, 6-8, 10: pyroxenite, 12- ore-bearing websterite, 14-15: ore

Table 2. Trace element compositions (ppm) of pegmatoid series of Nui Chua complex

Sample	SP18-128/1	SP18-141/2	SP18-141/3	SP18-141/4	SP18-141/5	SP18-142/1	SP18-142/2	SP18-142/3	SP18-127/1	SP18-127/2
Location	Na Hoe deposit	Cay Cham deposit							Na Hoe deposit	
Rock type	2	7	8	9	10	11	12	13	14	15
Sc	39.96	46.38	67.19	42.95	62.03	67.72	60.88	34.47	48.44	45.04
V	252.18	256.81	345.00	318.22	171.66	302.39	314.60	301.65	1200.05	1079.47
Cr	98.29	144.32	165.28	167.24	238.43	206.37	141.84	94.36	743.92	900.95
Co	51.53	49.16	75.98	31.87	92.09	55.03	71.86	45.35	51.03	67.74
Ni	61.18	31.48	34.05	34.91	71.26	42.40	31.29	19.30	40.93	73.06
Cu	41.80	48.45	62.56	21.42	111.79	34.68	68.60	23.31	139.88	348.70
Zn	129.73	89.20	112.40	81.04	144.03	113.54	107.11	90.51	421.23	181.56
Rb	1.59	6.13	2.61	1.40	5.63	8.69	4.82	10.21	0.22	0.40
Sr	75.21	63.50	9.36	178.86	7.71	9.73	12.68	132.37	0.59	0.70
Y	9.32	17.22	18.34	9.11	14.65	17.71	15.67	10.58	1.53	6.19
Zr	7.61	9.21	16.61	5.62	22.66	19.84	15.28	10.47	66.88	66.53
Nb	0.12	0.02	0.12	0.19	0.07	0.04	0.21	0.55	4.49	4.35
Cs	0.41	0.80	0.62	0.41	1.19	1.67	0.66	1.22	0.06	0.04
Ba	12.01	28.39	10.35	45.38	21.26	24.28	19.15	36.23	2.77	3.32
La	0.94	2.45	1.48	0.77	1.93	2.21	1.45	0.85	0.63	2.30
Ce	2.35	5.91	4.47	1.84	5.67	6.48	3.87	2.07	0.83	2.51
Pr	0.36	0.87	0.78	0.30	0.85	0.98	0.61	0.32	0.19	1.03
Nd	1.86	4.24	4.23	1.67	4.16	5.00	3.20	1.69	0.74	4.36
Sm	0.68	1.44	1.58	0.72	1.39	1.78	1.23	0.61	0.26	1.19
Eu	0.42	0.49	0.26	0.74	0.19	0.24	0.24	0.73	0.02	0.20
Gd	0.86	1.80	2.16	0.99	1.78	2.12	1.75	0.94	0.09	1.11
Tb	0.18	0.36	0.42	0.19	0.34	0.41	0.34	0.20	0.02	0.20
Dy	1.43	2.70	3.10	1.40	2.38	2.98	2.63	1.46	0.20	1.36
Ho	0.31	0.56	0.61	0.30	0.49	0.59	0.52	0.33	0.04	0.25
Er	0.94	1.64	1.87	0.91	1.47	1.80	1.58	1.00	0.18	0.77
Tm	0.15	0.26	0.29	0.14	0.22	0.28	0.25	0.15	0.03	0.12
Yb	1.18	1.91	2.05	0.81	1.70	1.89	1.76	1.23	0.43	1.04
Lu	0.18	0.28	0.33	0.12	0.26	0.29	0.28	0.18	0.08	0.17
Hf	0.24	0.35	0.63	0.19	0.74	0.62	0.58	0.29	1.62	1.51
Ta	0.04	0.01	0.05	0.06	0.04	0.04	0.06	0.07	0.49	0.38
Pb	0.84	1.32	0.97	6.98	2.37	1.29	1.13	2.09	0.88	1.89
Th		0.06	0.07	0.03	0.25	0.11	0.31	0.05	0.23	
U	0.01	0.11	0.04	0.02	0.08	0.12	0.16	0.05	0.14	
$(La/Yb)_N$	0.56	0.91	0.51	0.68	0.80	0.83	0.58	0.49	1.04	1.57
Cu/Ni	0.68	1.54	1.84	0.61	1.57	0.82	2.19	1.21	3.42	4.77

6. Results

6.1. Major elements

Pyroxenite rocks have SiO_2 content ranging from 27.42-36.71 wt.%, Al_2O_3 ranges from 1.32-4.04 wt.%, High Fe_2O_3 and TiO_2 content, respectively, 25.54-29.13 wt.% and 13.51-17.99 wt.%. Pyroxenite is poor in MgO (6.41-10.21 wt.%), Na_2O (from 0.11-0.36%), K_2O (0.07-0.48%), and CaO varies in a narrow range from 9.63 to 12.10 wt.%). SiO_2 in grabbronorite ranges from 43.46-50.27 wt.%, Al_2O_3, TiO_2, Fe_2O_3T, MgO and Na_2O fluctuate in a wide range, in which Fe and Ti are quite high compared to conventional gabbro series (Al_2O_3 = 5.16-20.39%, TiO_2 = 0.53-4.97%, Fe_2O_3T = 8.03-25.31%, MgO = 4.47-11.3%, Na_2O = 0.15-2.05%), the content of K_2O (0.04-0.48%), CaO (8.14-12.83%) vary slightly. Al_2O_3, (Na_2O + K_2O) and Mg# are positively correlated with SiO_2; In contrast, MgO, Fe_2O_3, TiO_2, and P_2O_5 are inversely correlated with SiO_2, with CaO almost unchanged (Fig. 3). On the AFM chart, the pegmatoid series of the Nui Chua complex belongs to the Fe-rich tholeiite series (Fig. 4). On the chart (Fe_2O_3T + TiO_2) - (CaO + Al_2O_3) - MgO, the pegmatoid series of intrusive rocks of the Nui Chua complex are all Fe and Ti-rich, and Mg- poor (Fig. 5). These features are quite similar to the gabbroid formations that are thought to be associated with the Fe-Ti-V minerals in the Panzihua region in Sichuan province, southwest China (Fig. 3-7).

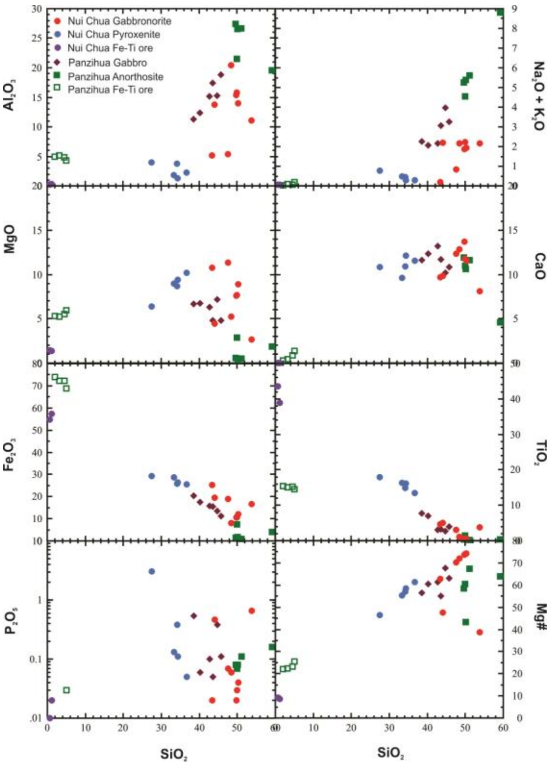

Figure 3. Harker variation diagrams for pegmatoid rocks of Nui Chua complex

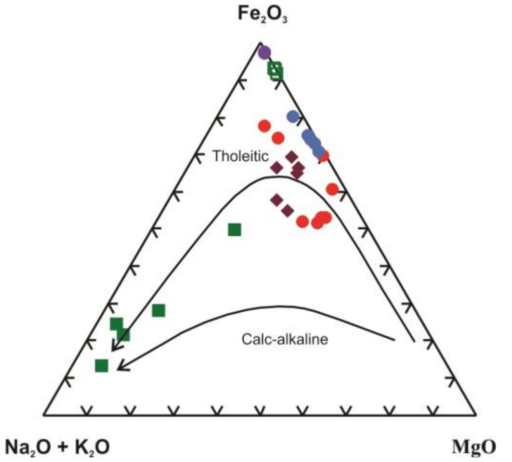

Figure 4. Line and AFM plot showing geochemical variations in the pegmatoid rocks of Nui Chua complex (lines are after Wilson, 1989). Symbols as in Fig. 3

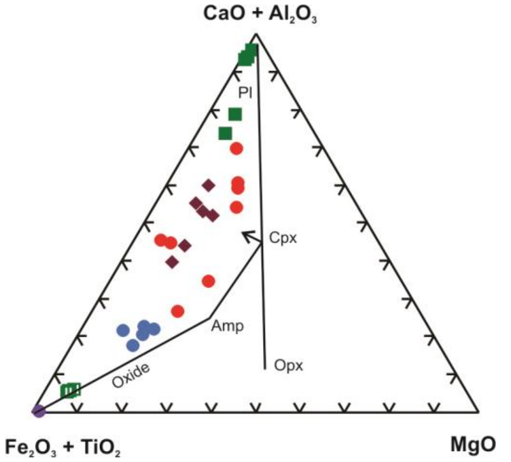

Figure 5. (CaO+Al_2O_3) - (Fe_2O_3+TiO_2) - MgO plot of pegmatoid rocks of Nui Chua complex. Symbols as in Fig. 3. Pl - Plagioclas, Cpx - Clinopyroxene, Opx - Orthopyroxene, Amp - Amphibole

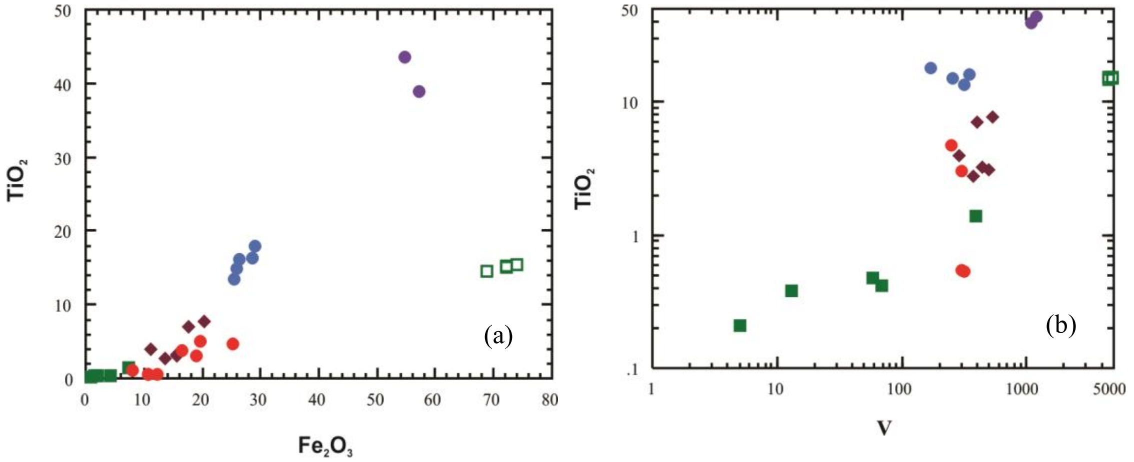

Figure 6. Plots of TiO_2 vs. Fe_2O_3 (a) and V (b) for pegmatoid rocks of Nui Chua complex

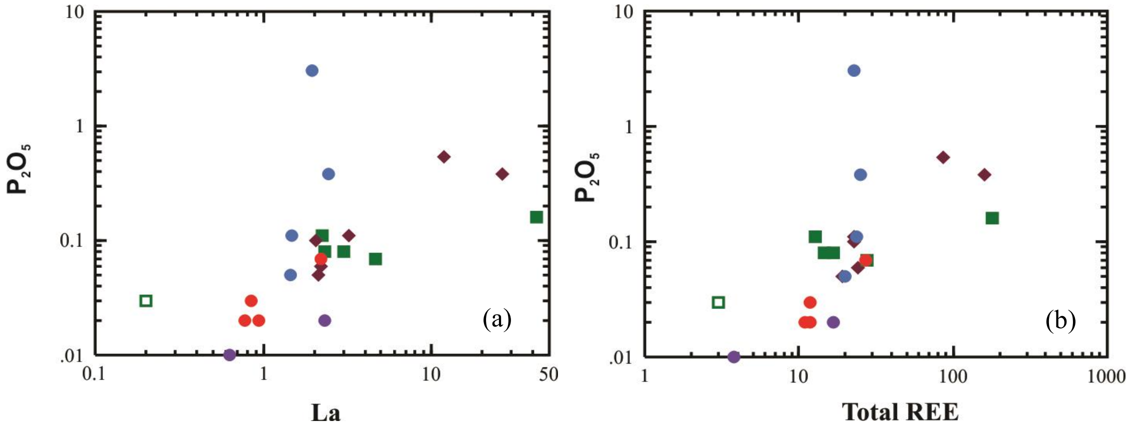

Figure 7. Plots of P_2O_5 vs. La (a) and Total REE (b) for pegmatoid rocks of Nui Chua complex

6.2. Trace elements

The Cr, Co, Ni, and Cu contents in pyroxenite are higher than that of gabbronorite rocks (Table 2). The Cu/Ni ratios in the rock samples and oxide ores range from 0.61 to 2.19 and 3.42-4.77, respectively. However, the V content is quite high and nearly equal to that in pyroxenite and gabbronorite, respectively, 171-345 ppm and 252-318 ppm. W is strongly differentiated in titanomagnetite and positively correlated with TiO_2 (Fig. 6). Sc in pyroxenite is higher than in gabbronorite, respectively, at 46-67 ppm and 34-67 ppm (Table 2). The concentration of P_2O_5 in intrusive formations is positively correlated with La and the total weight of rare earth elements (Fig. 7).

The intrusive rocks are mostly higher in the rare earth elements than chondrite with heavy rare earth (HREE) predominating light (L)REE resulted in $(La/Yb)_N$ in the range of 0.49-0.91. Eu negative anomalies are mainly expressed in gabbronorite and oxide ore samples. In general, the content of REE in the ore samples is lower than that of intrusive samples and having Eu and Ce negative anomalies (Fig. 8a). This same trend is also shown in the primitive mantle trace element normalization configuration curve (Fig. 8b), which clearly shows the negative anomalies at Nb, Ta, Th, U, Sr, and Zr; however, almost gabbronorite rocks show positive anomalies at Sr, Cs, Ti, and K (Fig. 8b).

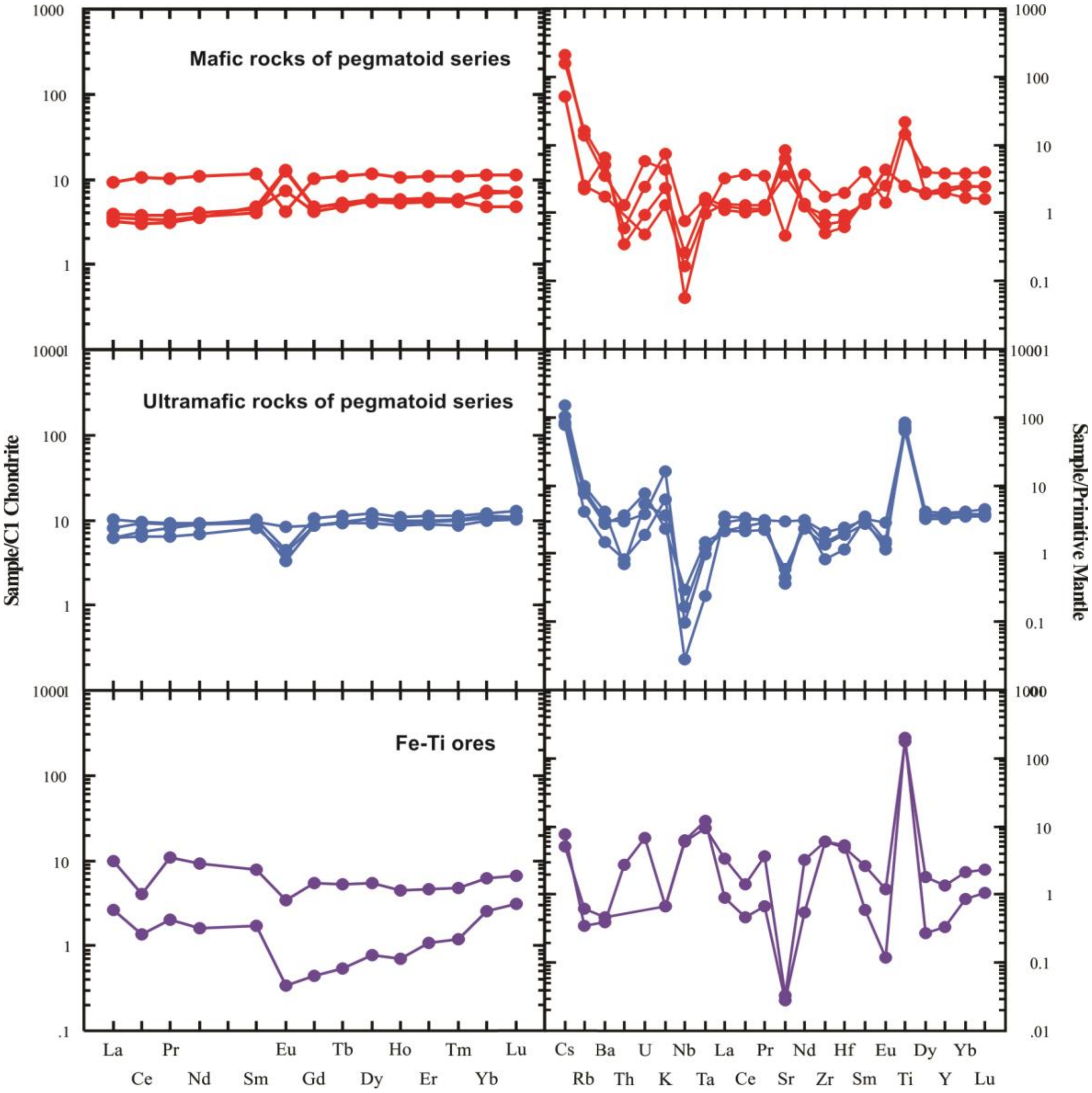

Figure 8. Chondrite-normalized REE patterns and Primitive-normalized trace element patterns for the pegmatoid rocks of Nui Chua complex. Normalization values are from Sun and McDonough (1989)

7. Discussions

7.1. Petrogenesis of the pegmatoid series

The chemical composition and distribution characteristics of trace elements and rare earth of mafic and ultramafic rocks show that they share the same magma source (Figs. 3-8).

The pegmatoid series of the Nui Chua complex, are rich in Fe, Ti, and poor Si that are not comparable with conventional tholeiitic magma (Figs. 4, 5). If combined with the disseminated ore bodies and oxidized ore bodies, these intrusions are richer in Fe, Ti, and Si poor (Tables 1-2). Moreover, according to the studies of rock-forming minerals in the Nui Chua complex in Polyakov et al. (2009), pyroxene in gabbronorite and pyroxenite of pegmatoid series is characterized by high Fe and low Al.

In addition, in some samples, the presence of ilmenite exsolution lamellae in clinopyroxene showed that pyroxene was crystallized from Ti-rich melt (Figs. 2c, d). Thus, pegmatoid series rocks of the Nui Chua complex with characteristics of Fe-, Ti-rich and the presence of Ti-rich clinopyroxene prove that the primary magma is rich in Fe and Ti.

Currently, there are several explanations for the origin of Fe and Ti-rich magma as follows: (i) Fe-rich is thought to be the nature of the original magma, or due to partial melting, but it is difficult to imagine how high- Fe magma moved from the mantle to the lower crust; (ii) Fe is enriched as a result of the assimilation of Fe-rich rocks by partial melting of the mantle source to produce conventional basaltic magma. However, there was no sign of Fe-rich rocks in the study area; (iii) Another possible mechanism is that Fe-rich liquid is formed by the process of differentiation. Fractional crystallization of minerals such as olivine, clinopyroxene, plagioclase can enrich Fe in the residual melt (Hanski, 1992). The pegmatoid magma series in intrusive formations being studied here are analogous to those of Panzihua intrusion in Sichuan Province, China (Zhou et al., 2005), which are thought to be fractional crystallization products at later stages. This is entirely consistent with the results of Tran et al. (2008) and Polyakov et al. (2009) when modeling the fractional crystallization of layered and pegmatoid series intrusion, thereby confirming that the pegmatoid series was formed as a product of fractional crystallization from Fe- and Ti-rich residual melt after crystallization of the layered intrusive rocks. The depth of formation of this pegmatoid series does not exceed the depth of the differentiated series of 2 kbar, because at the outcrops observed was the presence of hornblende-bearing rock in the inner contact zone, and the surrounding rocks are formations of very weak metamorphic facies (Polyakov et al., 2009). Therefore, this study once again confirms that the pegmatoid series is formed by the fractional crystallization process at a depth not too far from the magma chamber of the layered magma series.

Moreover, the process of differentiation had formed a stratified magma chamber with olivine deposits on the bottom and high Fe and Ti-rich melt on the top. This is evident in the presence of olivine in the differential series and completely absent in the pegmatoid series in the Nui Chua complex. The pegmatoid series has typical trace element geochemistry that is Ti positive anomaly, Nb and Th negative anomaly, and low content of Hf, Zr, and U (Table 2, Fig. 8b). These geochemical characteristics cannot be explained by a contamination process in the upper crust, because the upper crust rocks are rich in Zr, U, Th, and Hf, and poor in Ti, Nb, and Ta (Taylor and McLennan, 1985). This is also shown by Eu positive anomaly in most samples (Fig. 8a). With these characteristics, Hoang H.T. et al. (2004) suggested that the Nui Chua complex was a product of island arc features. However, the Nui Chua intrusion has a crystalline age of 264-251 Ma (Tran T.H. et al., 2008; Tran Q.H. et al., 2018). As is well known, the geological history of Vietnam during the transition period from Paleozoic to Mesozoic took an important position, including some major tectonic periods (Tran and Vu, 2011). According to current literature (e.g., Borisenko et al., 2008; Chen et al., 2014; Zaw et al., 2014; Nevolko et al., 2018), during this period there were four main tectonic phases in northern Vietnam, including (1) the formation of the active continental margin, (2) the collision between South China and Indochina, (3) and (4) a series of the collision leading to the formation of the Truong Son folded belt (Zaw et al., 2014) corresponding to the periods of 300-290 Ma, 253-251 Ma, and 245-220 Ma and 218-185 Ma. However, in the period 260-

250 Ma, there was very clear evidence of the formation of magmatic complexes related to mantle plume, reflecting one of the major events of the South China mountain building process, e.g., the emergence of Emeishanmantle plume igneous province (Tran T.H. et al., 2008; 2016). The formation of Emeishan plume magmas occurred on the ground of interaction between South China and Indochina tectonic plates. This led to the complex tectonic fluctuations of the subduction and collision context with the context of plume-related formation on the continental plate margin, all had invoked various assumptions about the tectonic evolution of Indochina (e.g., Chen et al., 2014; Faure et al., 2018; Ngo et al., 2015; Shi et al., 2015; Zaw et al., 2014). The crystalline age of the Nui Chua complex intrusions corresponds to this period and is closely similar to the Panzihua intrusive formations in Sichuan Province, China. These formations are thought to be involved in the destruction of the Yangtze continental margin under the influence of the mantle plume (Zhou et al., 2005; Tran T.H. et al., 2008; Polyakov et al., 2009).

7.2. The origin of Fe-Ti oxide ore mineralization

The differentiation process can produce Fe-rich melts, similar to the case of Bushveld mafic complexes (South Africa) (Scoon and Mitchell, 1994). The Nui Chua pegmatoid series is similar to a number of other intrusions (for example, Panzihua in Sichuan province, or some intrusive complexes in South Africa) that are distinguished from Fe-rich tholeiitic magma (Pang et al., 2008).

As known, the correlation of the major elements of Fe-Ti oxide ore with those of the pegmatoid series intrusion shows that they are quite similar, their Al_2O_3, (Na_2O + K_2O) and Mg# are positively correlated with SiO_2, in contrast, MgO, Fe_2O_3, TiO_2, and P_2O_5 are inversely correlated with SiO_2, while CaO almost unchanged (Fig. 3). Oxide ore samples have lower REE content than intrusive samples with negative anomalies at Eu and Ce. However, the geochemical tendency of rare earth elements was similar to that of pegmatoid series intrusions of the Nui Chua complex (Fig. 8a). This same trend is also shown in the primitive mantle trace element normalization configuration (Fig. 8b). On this diagram, it is clear that the anomalies at Nb, Ta, Th, U, Sr, and Zr and positive anomalies at Cs, Ti, and K (Fig. 8b). Based on these geochemical features, it can be assumed that Fe-Ti oxide ores are of magma origin.

The process of forming Fe-Ti oxide from magma sources is explained by many different mechanisms. There are currently two main ore formation mechanisms that are still under debate, such as (i) the crystallization of Fe-Ti-rich immiscible liquids separated from basaltic magma (Wang and Zhou, 2013; Zhou et al., 2013; Liu et al., 2014); (ii) the crystallization and gravity deposition of Fe-Ti oxide minerals from Fe-Ti enriched magma (Clark and Kontak, 2004; Pang et al., 2008; Bai et al., 2012; Song et al., 2013; Luan et al., 2014). The first formation mechanism is the immiscible silicate liquids proposed for the formation of Fe-Ti-V (-P) oxide deposits in the magmatic intrusions of the Bushveld Complex in South Africa (Van Tongeren and Mathez, 2012). This has been demonstrated by experiments that the liquid immiscibility developed in the later stages of the tholeiitic magma and Fe, Ti, P are divided into Fe-rich immiscible liquids during the immiscibility separation of Fe- and Si-rich silicate melts (Charlier and Grove, 2012). However, in this case, the Fe-rich immiscible liquid-rich usually contains SiO_2 from 33.4 to 52.6 wt.%, Fe_2O_3T from 5.6 to 36 wt.%, TiO_2 from 0.08 to 12.2 wt.%, and P_2O_5 from 0.07 to 10.2 wt.%. In the case of the Nui Chua complex, the Fe-Ti oxide ore bodies in Na Hoe are rich in TiO_2 (38.95-43.59 wt.%) and

Fe_2O_3T (54.73-57.24 wt.%), very poor SiO_2 (0.69-1.22 wt.%), P_2O_5 (0.01-0.02 wt.%) (Table 1). If the Fe-Ti oxide ore here is made up of Fe-rich liquid like the Fe-Ti ore production mechanism in the Bushveld block in South Africa, they will have apatite accumulations (Eales and Cawthorn, 1996). However, the actual samples in the study area are absent from these accumulations. Thus, the mechanism of forming Fe-Ti oxide ore from Fe-rich immiscible liquid for the formations here is unlikely. This is further confirmed by field observations such as Fe-Ti oxide ores are located in gabbro rocks rather than anorthosite rocks as in Bushveld in South Africa (Cawthorn and Ashwal, 2009). Therefore, the property of immiscible silicate liquid cannot explain the formation of Nui Chua Fe-Ti oxide ore. Therefore, the fractional crystallization of mafic magma towards Fe enrichment is explained by Ti enrichment in layered mafic magma (Morse, 1980, 1990; Lee, 1996). According to the major and trace element geochemistry of the intrusive pegmatoid series of this study along with the previous results of Tran T.H. et al. (2008) and Polyakov et al. (2009) suggested that primary magma underwent varying degrees of fractional crystallization and cumulate soon after the equilibrium was reached. This is also evident when olivine is only found in stratified series rocks but not in pegmatoid series (Tran T.H. et al., 2008; Polyakov et al., 2009). The crystallization sequence of the Nui Chua complex can be proposed as follows: olivine is the earliest phase, followed by plagioclase and clinopyroxene and finally Fe-Ti oxide.

8. Conclusions

Detailed studies on geological, lithological, mineralogical characteristics, geochemistry of major and trace elements of pegmatoid series of the Nui Chua complex, as well as Fe geochemical ore data, allow to make the following remarks:

The pegmatoid series of Nui Chua complex includes rock types such as plagiowebsterite, clinopyroxenite, melanogabbronorite, mesogabbro, gabbronorite, leucogabbronorite. These rocks are mostly olivine-free. Massive or infiltrated Fe-Ti oxide ores appear layered or lenticular only in the pegmatoid series rocks.

The geochemical characteristics of pegmatoid series rocks show that they are rich in Fe, Ti, and V and poor in Mg; their heavy rare earth elements (HREE) are richer than light rare earth elements (LREE), showing negative anomalies at Nb, Ta, Th, U, Sr, and Zr, and positive anomalies at Cs, Ti, and K.

Fe-Ti oxide ores having a geochemical tendency similar to the pegmatoid series suggest they are formed from magmatic origin related to intrusive pegmatoid series. The pegmatoid series of Nui Chua complex and Fe-Ti oxide ores were formed as a product of the fractional crystallization process from the Fe-Ti-rich residual melt after crystallization of the layered rocks. Accordingly, the crystallization sequence can be proposed as follows: olivine is the earliest phase, followed by plagioclase and clinopyroxene, and finally Fe-Ti oxide.

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