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THE BAN PHUC Ni–Cu–PGE DEPOSIT RELATED TO THE PHANEROZOIC KOMATIITE–BASALT ASSOCIATION IN THE SONG DA RIFT, NORTWESTERN VIETNAM

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Abstract

The Permian–Triassic komatiite–basalt complex in the Song Da rift, northwestern Vietnam, occurs in the axial part of this structure and includes komatiites, komatiitic basalts, olivine basalts, and subvolcanic bodies of dunite and plagioclase-bearing wehrlite hosting Ni–Cu–PGE sulfide ores. Volcanic rocks contain olivine- and pyroxene-spinifex textures. The Ban Phuc deposit consists of two major orebodies. The first one is of vein type, zonal, with average Ni/Cu of 2.5 and Ni/Co of 33. In the central part, it is composed of massive chalcopyrite – pentlandite – (violarite) – pyrrhotite ores with associated sulfarsenides of Ni and Co, heazlewoodite, tsumoite, parkerite, sperrylite, and michenerite. Marginal parts of (pentlandite) – pyrrhotite – chalcopyrite, and violarite – chalcopyrite composition contain nickeline, maucherite, sperrylite, and michenerite. The second orebody is composed of disseminated ores with an average Ni content of 1.2%. The plots of mantle-normalized contents of noble metals, Ni and Cu reflect their non-fractionated distribution, typical of komatiites. Ore formation proceeded in two stages: 1) magmatic stage, including sulfide–silicate immiscibility and fractional crystallization of the sulfide melt, and 2) postmagmatic hydrothermal processes. The saturation of the komatiitic melt with respect to a sulfide at an early stage of formation of the Ban Phuc suite is suggested by a steeper trend of olivine composition on the Ni in olivine – Fo diagram compared with olivine from ore-free volcanic rocks of the komatiite–basalt series. Later on, fractional crystallization of a fluid-bearing sulfide melt was the most important factor in the formation of ore. Enrichment of Cu-bearing ores from zonal orebodies in Pd and Au corresponds to their concentration in the residual sulfide melt during fractionation of *Mss*. The unusual Pt concentrations of the Fe–Ni ores are due to the presence of sperrylite, which contains between 0.9 and 3.4 wt.% Sb at the high-temperature stage (900–1000°C) of the volatile-saturated sulfide. At the lower-temperature stage, sulfarsenides of Ni, Co, and Fe appeared, together with michenerite at 500–400°C. At 300°C and below, tsumoite and the Cu–Pb–Ag–Bi sulfosalts made their appearance.

Keywords: sulfide deposits, komatiite, ore formation, nickel, copper, platinum-group elements, sulfarsenides, Ban Phuc, Vietnam.

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SOMMAIRE

Le complexe de komatiite et basalte permo-triassique de la zone de rift de Song Da, dans le nord-ouest du Vietnam, fait partie de la zone axiale de cette structure; il inclut des komatiites, des basaltes komatiitiques, des basaltes à olivine, et des massifs subvolcaniques de dunite et de wehrlite à plagioclase renfermant un minerai sulfuré de Ni, Cu et éléments du groupe du platine. Les roches volcaniques contiennent de l'olivine et du pyroxène à texture en spinifex. Le gisement de Ban Phuc contient en fait deux accumulations de minerai. Le premier se présente en veines, et est zoné, avec un rapport Ni/Cu moyen de 2.5 et un rapport Ni/Co de 33. Sa partie centrale contient une accumulation massive de chalcopyrite – pentlandite – (violarite) – pyrrhotite, avec une association de sulfarséniures de Ni et Co, heazlewoodite, tsumoïte, parkerite, sperrylite, et michenerite. La bordure de la structure contient (pentlandite) – pyrrhotite – chalcopyrite, et violarite – chalcopyrite, avec nickeline, mauchérite, sperrylite, et michenerite. Dans la deuxième accumulation de sulfures, le minerai est plutôt disséminé, avec une teneur moyenne en Ni de 1.2%. D'après les teneurs en métaux nobles, Ni et Cu normalisées par rapport au manteau, la distribution est non fractionnée, comme c'est généralement le cas pour les komatiites. Le minerai s'est formé en deux stades: 1) stade magmatique, impliquant une immiscibilité entre sulfure et silicate et une cristallisation fractionnée du liquide sulfuré, et 2) stade hydrothermal, postmagmatique. Une saturation du magma komatiitique en sulfures à un stade précoce de l'évolution de la suite de Ban Phuc découle du tracé plus abrupte de la composition de l'olivine sur un diagramme de teneur de l'olivine en nickel en fonction de teneur en Fo, en comparaison de l'olivine provenant de roches volcaniques de la série komatiite – basalte sans minerai. Par la suite, une cristallisation fractionnée du liquide sulfuré contenant des constituents volatils est devenue le facteur le plus important dans la formation du minerai. Un enrichissement en Pd et Au dans le minerai cuprifère des accumulations zonées correspondrait à leur concentration dans le liquide sulfuré résiduel par le fractionnement de *Mss*. Les concentrations inhabituelles de platine dans le minerai Fe–Ni seraient dues à la présence de sperrylite, qui contient entre 0.9 et 3.4% d'antimoine à la température de cristallisation élevée (900–1000°C) du liquide sulfuré enrichi en composants volatils. A plus faible température, les sulfarséniures de Ni, Co et Fe ont fait leur apparition, de même que la michenerite à 500–400°C. A 300°C et moins, la tsumoïte et les sulfosels de Cu–Pb–Ag–Bi sont apparus à leur tour.

(Traduit par la Rédaction)

Mots-clés: gisements de sulfures, komatiite, formation de minerai, nickel, cuivre, éléments du groupe du platine, sulfarséniures, Ban Phuc, Vietnam.

INTRODUCTION

Deposits of Ni–Cu and Ni sulfides, commonly accompanied by mineralization in platinum-group elements (PGE), are known to be associated with komatiite–basalt complexes. The overwhelming majority of such deposits formed in the Precambrian. Examples of Phanerozoic age are quite rare. One of them is the Ban Phuc Ni–Cu sulfide deposit, northwestern Vietnam, related to a Permian–Triassic high-magnesium ultramafic–mafic volcano-plutonic complex in the Song Da zone, which corresponds in composition and geological setting to the komatiite–basalt associations (Polyakov *et al.* 1991, 1995b, 1998, Ngo Thi Phuong 1994). These and some other publications (*e.g.*, Polyakov *et al.* 1995a, Balykin *et al.* 1996, Glotov *et al.* 1991) deal mainly with the composition, geodynamic position, and evolution of the Permian–Triassic ultramafic–mafic magmatism of northwestern Vietnam. Problems of geochemistry, mineralogy, and genesis of Ni–Cu–PGE mineralization received less study, and the most comprehensive review is given in our recent work (Polyakov *et al.* 1999). Using the Ban Phuc deposit as an example, the present study is especially aimed at considering the formation of Ni–Cu–PGE ore, related to the Permian–Triassic komatiite–basalt magmatism of the Song Da zone, which is a rare and possibly unique case in Phanerozoic geological history.

THE PERMIAN–TRIASSIC KOMATIITE–BASALT COMPLEX IN THE SONG DA ZONE

The Song Da zone belongs to the rift-related Mesozoic structures of northwestern Vietnam and abounds in ultramafic–mafic volcano-plutonic complexes related to mantle magmatism. Lateral zoning is evident in the distribution of these complexes (Fig. 1). Late Permian and Permian–Triassic basalt-dominated complexes occur in lateral parts (Son La, Nam So, Ba Vi, and Kim Boi regions); they are enriched in alkalis and Ti and compositionally correspond to the olivine basalt typical of the early stages of development of continental rifts. Younger (P_2–T_1) high-Mg volcano-plutonic ultramafic–mafic associations compositionally corresponding to komatiite–basalt series occur in the central (axial) part of the Song Da rift, which includes the Na Muoi River basin and the southwestern flank of the Ta Hoa structure (Polyakov *et al.* 1991, 1995b, 1998). These were followed by a Lower Triassic trachydacite – trachyandesite – basalt association, which is comparable to contrasting (bimodal) volcanic complexes typical of the late stages of development of continental rifts.

The Late Permian basalt and basalt–picrite volcanic associations occurring on the periphery are characterized by chalcopyrite and gold mineralization (Polyakov *et al.* 1996, Balykin *et al.* 1996). The Permian–Triassic komatiite – basalt volcano-plutonic complex in the axial

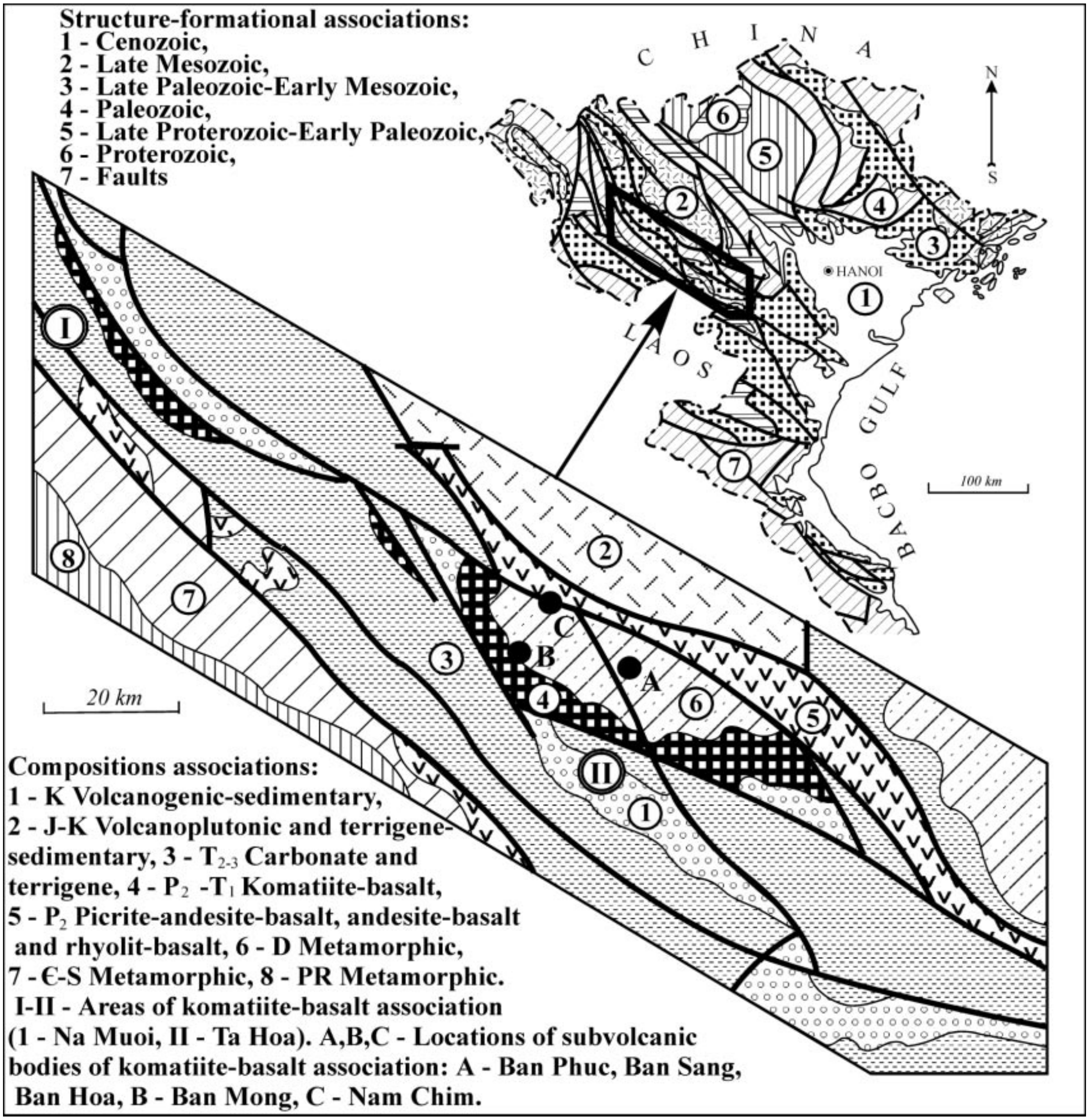

FIG. 1. Schematic geological structure of the central part of the Song Da rift in northwestern Vietnam, with occasional manifestation of the Permian–Triassic komatiite–basalt association (I Na Muoi, II Ta Hoa), the Ban Phuc Cu–Ni sulfide deposit (A), and the Ban Mong (B) and Nam Chim (C) ore occurrences. The scheme is based on geological maps at a scale of 1:200 000 and 1:500 000 and on our data. The general geological map of North Vietnam (the upper figure) shows schematic outlines of the geological structure of the central part of the Song Da rift.

part of the Song Da zone is accompanied by occurrences of Ni–Cu sulfide ore. The Ban Phuc deposit in the Ta Hoa region is related to ultrabasic rocks of this complex.

High-magnesium volcanic rocks of the komatiite – basalt composition and associated small subvolcanic intrusions of basic and ultrabasic composition are most completely and typically represented in the Na Muoi River basin, where they make up a continuous belt more than 30 km long and about 3 km wide. The sequence is dominated by high-Mg low-alkali olivine basalts and ultrabasic extrusive rocks, in combination with small subvolcanic bodies of plagioclase-bearing wehrlite. In their contents of Mg, alkalis, and Ti and in other geochemical characteristics (Table 1), the ultramafic and mafic volcanic rocks correspond to olivine basalt, komatiitic basalt, and komatiite.

TABLE 1. REPRESENTATIVE COMPOSITION OF ROCKS OF THE KOMATIITE–BASALT ASSOCIATION OF THE SONG DA STRUCTURE, NORTWESTERN VIETNAM

	B6865	G946	P31-89	G1456	G1448	12-86	P129	G1436	T1633	T1610	T1639	T1640	T1647	SL100-2P	2-98	2-101
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
SiO_2 wt.%	44.44	44.59	43.62	44.87	46.03	48.54	46.34	50.28	46,46	46 62	45,35	45,68	45,08	43 25	45.36	44.11
TiO_2	0.34	0.52	0.47	0.59	0,61	0.49	0.74	0.66	0.35	0.77	0.58	0.74	0.48	0.81	0.21	0.21
Al_2O_3	10,38	9 06	9,25	10.70	10.53	12.23	12.78	13.94	6.27	14.32	6.77	8.35	5.55	8.79	2,77	3,03
Fe_2O_3	10.95	11.46	12,12	12,33	11,41	9.44	12.10	9.34	11.22	13.90	11.14	11.69	9,95	13 48	6,06	7.62
MnO	0,16	0 2	0.18	0.18	0.16	0.18	0.18	0.16	0,18	0.24	0,25	0.19	0.22	0.21	0.11	0.11
MgO	23.70	25.81	25,28	21,10	21.63	17.67	15.60	9.18	29.73	19.54	27.82	23.26	33.81	24.47	42,60	43,01
CaO	9.26	7.97	8.32	9.23	8.64	11.17	11 04	13,71	5.27	3 59	7.05	8.49	4.42	8.50	1.84	0.77
Na_2O	0.59	0.31	0.54	0,80	0,86	0.05	0.93	2.41	0.33	0.93	0,69	1.09	0,33	0 33	0.37	0.71
K_2O	0.04	0.04	0.06	0.06	0.08	0.03	0.05	0,07	0,10	0 03	0,28	0,42	0.10	0.05	0.64	0.34
P_2O_5	0.14	0,04	0,16	0,14	0.05	0.20	0.24	0.04	0.09	0.06	0.07	0.09	0,06	0 11	0,04	0.09
Ni ppm	1200		1100	670	1100	310	1500	120	1406	546	1226	1067	1500	10.69	2437	2908
Co	87		88	86	71	42	90	37	85	73	76	85	85	106	79	79
Cu	74		80	95	90	170		110	60	13	112	47	50	243	14	14
Cr	1400		2700	1000	2300	860	5400	400	1213	1038	1500	2640	1370	1533	547	274
V	170		230	190	250	260	320	320	180	190	135	165	156	185	56	55
Rb	0.7	4				n.d		n.d.	8.9		14.4	16.2	3.7			
Sr	43	71.4				25		84	25.8	11.75	96	121.8	36,7			
Y	8.4	16.9				13,3		18	9,84	21,6	16.7	17.4	9.9			
Zr	10	30.5				13		31	26.6	33.1	59	67.9	25.6			
Ta	0,05		0,13	0.05	0.06	0.07	0 05	0,15	0.15	0.08	0,04	0,25			0.21	0.18
Nb	n.d.	0.74				n,d.		2.1	6.31	2.09	7.74	7.64	4.16			
Cs	0.97	3.98	0.38	1,7	0.7	0.4	1.0	0.4	5 2	0.2	0.5	1.1			3.3	2.1
La	0,62	0,77	2.1	1.03	0.91	1.05	0.71	3	1.96	1.28	0.9	6.3	1.8		6,8	5.9
Ce	2	2.3	5.3	3.2	2.9	2,9		7.2	4,3	3,7	2,5	13.7	4.2		12	10.9
Nd	6	2,5	6	2.9	2.8	3	6	4,9	2.6	3.5	2.1	7..7	2,8		5.5	5.1
Sm	0 64	1	1.24	1.11	1.1	0.81	0,75	1.5	0,75	1,37	0 ,79	1 94	0.82		1.03	1.03
Eu	0 26	0,42	0.46	0.43	0.47	0.31	0,5	0.49	0.24	0.42	0.32	0,56	0,25		0.18	0.14
Gd	0 98	1.5	1.6	1.52	1.7	1 11	1 37	2.7	0,9	2	1	2.1	1		0.9	0,9
Tb	0.18	0.28	0.3	0,3	0.3	0 21	0.25	0.5	0.16	0.37	0.2	0.33	0.18		0.14	0.15
Yb	0,86	1.49	1.25	1.37	1.31	1,06	1.12	2.04	0.69	1.77	0.9	1 12	0.71		0.46	0.46
Lu	0.13	0,24	0.19	0.21	0.2	0.17	0,17	0.31	0.1	0.26	0.14	0.16	0 11		0.07	0.07
Hf	0,23			0.74	0.68	0,6	0.75	0.67	0,6	0 6	0.5	1.3	0.5		1,28	0.84
Th	0.3		0.4	0.5	0.4	0,4	0.24	0.9	0.62	0.26	0.15	1.63	0.47		4.1	2.2
U									0.19	0.2	0.2	0 35	0.2		2.1	0.69

Samples 1–8: Na Muoi region; 1–5: komatiite, 6,7: komatiite basalt, 8: olivine basalt. Samples 9–16; Ta Hoa region; 9–10: komatiite (9) and komatiite basalt (10) from the effusive unit in the Deo Chen pass; 11–13: serpentinized peridotite of the Nam Chim dyke, 14: amphibolitized and serpentinized peridotites of the Ban Mong dyke, 15–16: serpentinized peridotites of the Ban Phuc massif. The compositions are recalculated on an anhydrous basis. n.d.: not detected.

Komatiite – basalt volcanic rocks are porphyritic, and commonly amygdaloidal. Their phenocrysts are represented by olivine and clinopyroxene. Olivine occurs commonly in the form of elongate needles (Fig. 2A). Olivine basalts have a pyroxene spinifex texture (Figs. 2D, E, F). Intrusive analogues of komatiites vary in structure and texture from well-crystallized varieties that correspond in composition to plagioclase-bearing wehrlite to porphyritic rocks with a cryptocrystalline pyroxene–plagioclase groundmass (matrix). All varieties contain olivine not only in the form of idiomorphic phenocrysts but also in the form of elongate needles (Figs. 2B, C).

Permian–Triassic volcanic rocks and associated ultrabasic intrusions from the Ta Hoa region are compositionally close to the rocks of the high-Mg ultramafic–mafic volcano-plutonic association in the Na Muoi River basin (Table 1). Structurally, the Ta Hoa region also belongs to the central part of the Song Da rift (Fig. 1). In addition to volcanic rocks, the Ta Hoa ultramafic–mafic complex includes dikes of komatiite–basalt composition and small lenticular and stock-like bodies of peridotite and serpentinite (Ban Phuc, Ban Hoa, Ban Sang), hosting ores of copper, nickel, and PGE of the Ban Phuc deposit. Somewhat westward, dikes of komatiite–basalt and komatiitic compositions occur at the mouth of the Nam Chim and Ban Mong rivers (Table 1). These are thin intrusive bodies with no signs of differentiation by accumulation. The Ban Mong River dike is associated with an occurrence of Ni–Cu–PGE ore similar to the Ban Phuc deposit. Thus it is quite probable that a subvolcanic vent facies of the Permian–Triassic komatiite–basalt association of the Song Da rift is denuded in the central, deeply eroded part of the Ta Hoa anticlinorium structure (in the region of the Ban Phuc deposit). Among others, it is represented by ultramafic intrusions associated with Ni–Cu–PGE deposits.

The Permian–Triassic age of the rocks of this complex is inferred from the fact that in the Na Muoi region, they are concordantly overlain by a carbonate–shale

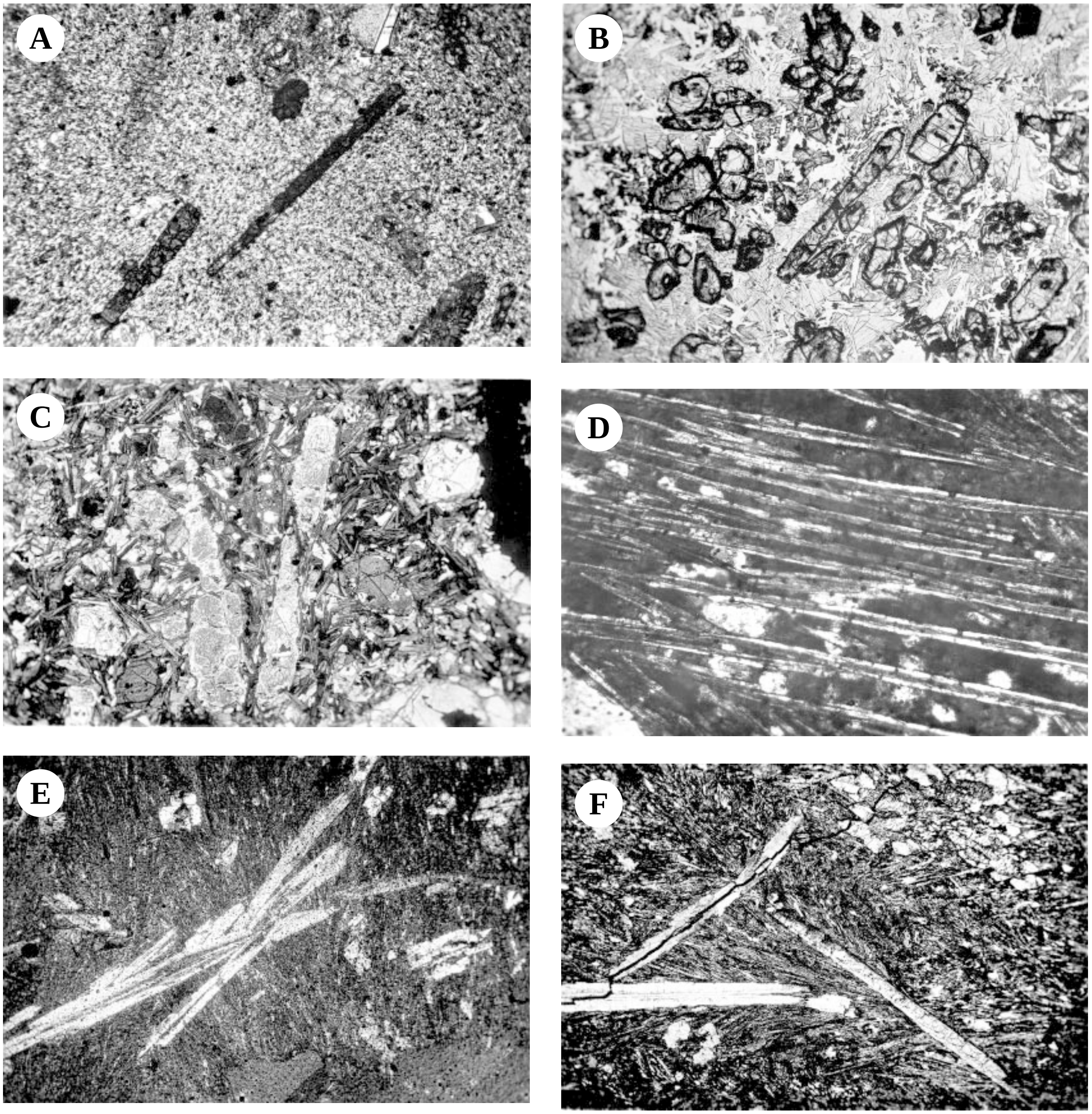

FIG. 2. Photographs of the microstructures of rocks from the komatiite–basalt complex in the Na Muoi region. A. High-magnesium komatiite basalt with acicular olivine, sp. P130/89, ×30, crossed nicols. B. Porphyritic basaltic komatiite with microdiabasic groundmass, sp. P46/89, ×30, crossed nicols. C. Porphyritic komatiite with microdiabasic groundmass, sp. B6892, ×30, crossed nicols. D, E, F. Basalts with high content of Mg and pyroxene spinifex texture, sp. P73/89, ×100, crossed nicols (D), P71/89, ×16, crossed nicols (E), and G1462, ×16, crossed nicols (F).

sequence containing Lower Triassic fauna and flora. Also, intrusive bodies break through an association of Carboniferous–Permian terrigenous sediments (in the Na Muoi region) and Devonian deposits containing Upper Devonian conodonts and foraminifers (in the Ta Hoa region). The age of the complex determined by the Rb–Sr method on komatiitic basalts of the Na Muoi region is 257 ± 24 Ma (Polyakov *et al.* 1996, 1998).

In general, the rocks of the Permian–Triassic ultramafic–mafic association of the axial part of the Song Da rift are rich in Mg, Al, Ni, Co, Cu, and Cr, and are poor in Ti, Fe, Na, K, P, Cs, Rb, Sr, Nb, Ta, Hf, Zr, Y, and the rare-earth elements, *REE* (Table 1). Contents of rare and rare-earth elements on a spider diagram (Fig. 3), normalized to the composition of primitive mantle (McDonough 1992), show a weakly differentiated trend, with element contents exceeding the primary mantle levels chiefly by a factor of 1 to 10. Exceptions are higher contents of Cs, Rb, Th, La, Ce, and Sr in olivine basalts and serpentinized peridotites, and contents of Nb, Ta, Hf, Zr, Tb, and Y close to those in the primary mantle, in komatiites and komatiitic basalts. According to contents and pattern of distribution of *REE* (Polyakov *et al.* 1996), the rocks of this association are subdivided into three groups: 1) komatiites and komatiitic basalts, with a flattened pattern of *REE* distribution and with a 3–20-time excess of their contents as compared with their contents in chondrite, 2) olivine basalts, enriched in the light rare-earth elements (*LREE*) by a factor of 20–40 relative to their contents in chondrite and characterized by a negative Eu anomaly, and 3) the Ban Phuc serpentinized peridotites, having a differentiated pattern of *REE* distribution, with contents of the *LREE* and the heavy rare-earth elements (*HREE*) exceeding those in chondrite by a factor of 5–25 and 2–3, respectively, and a negative Eu anomaly. These characteristics of composition and *REE* distribution pattern in the Ban Phuc peridotites are due, most likely, to secondary variations in the initial composition of these rocks, with their olivine and pyroxene replaced by serpentine, chlorite, and tremolite, and with biotite and magnetite appearing at that stage (Polyakov *et al.* 1996).

The rock-forming minerals in this complex are olivine ($Fo_{92–78}$) enriched in Ni (up to 0.4 wt.% NiO) and Ca (up to 0.3 wt.% CaO), plagioclase ($An_{52–85}$) with elevated contents of total iron (up to 1.5 wt.% ΣFeO) and orthoclase end-member (up to 3 mol. %), and subcalcic clinopyroxene ($Wo_{36–47}En_{42–52}Fe_{9–17}$). Accessory minerals are represented by low-Ti and high-Mg aluminous chromian spinel (34–51 wt.% Cr_2O_3, 17–31 wt.% Al_2O_3, 11–15 wt.% MgO) and by ilmenite; sulfides, sulfarsenides, arsenides, native copper, chromian magnetite, and platinum-group minerals are scarcer.

To reveal similarities and differences in the Permian–Triassic complex of high-Mg basic and ultrabasic rocks of northwestern Vietnam with komatiite–basalt, picrite–basalt, and marianite–boninite associations from other regions of the world, these associations were compared according to their bulk composition. This complex differs from picrite–basalt associations in having higher contents of Mg, Ni, Co, Cr, Yb and Lu, and lower contents of Ti, Fe, Ca, Na, K, Rb, Sr, V, Nb, Ta, Zr and *LREE* in rocks of the same type. Approximately the same differences are revealed in a comparison of the chemical composition of rocks of the ultramafic–mafic complex of the axial part of the Song Da rift with picrite–basalt associations of the periphery of this structure (Table 2). The complex under study differs from high-Mg basic and ultrabasic rocks of marianite–

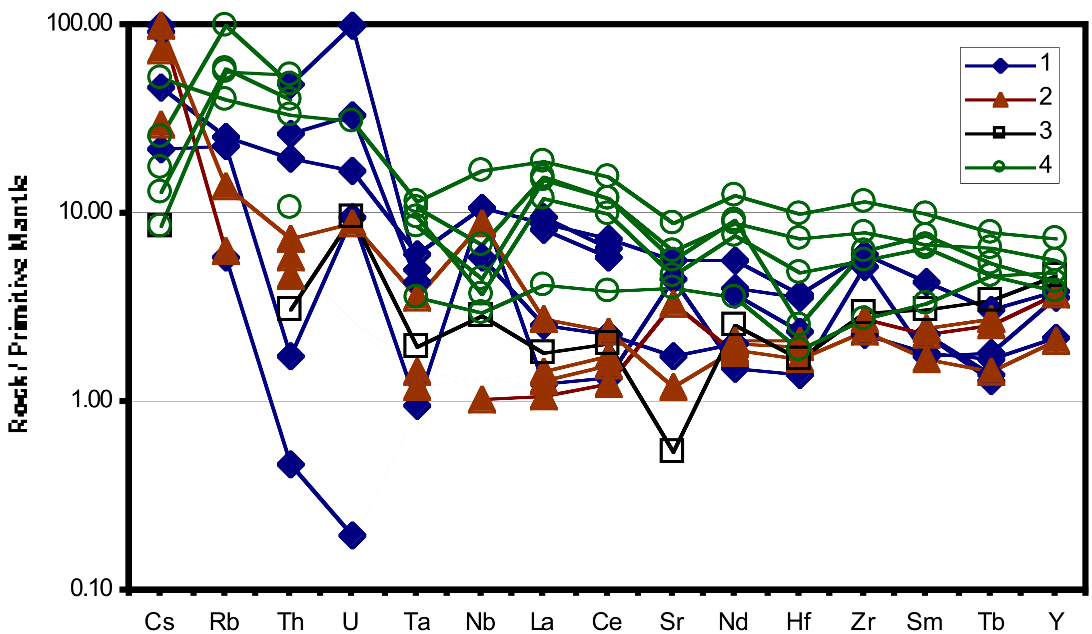

FIG. 3. Primitive-mantle-normalized concentrations of rare and rare-earth elements in the rocks of komatiite–basalt association of the Song Da structure in northwestern Vietnam 1 serpentinized peridotites of the Ban Phuc massif, 2 komatiites, 3 komatiitic basalts, 4 olivine basalts. Chondritic values after McDonough & Sun (1995).

TABLE 2. AVERAGE CHEMICAL COMPOSITION OF PETROGRAPHIC GROUPS OF THE PERMIAN–TRIASSIC PICRITE – ANDESITE – BASALT AND KOMATIITE – BASALT ASSOCIATION, SHONG DA RIFT

	1(5)		2(11)		3(52)		4(51)		5(32)		6(41)		7(47)		8(2)	9(6)		10(6)	
	X	σ	*X*	σ	*X*	σ	*X*	σ	*X*	σ	*X*	σ	*X*	σ	*X*	*X*	σ	*X*	σ
SiO_2, wt.%	44.46	0.59	48.21	2.34	49.44	2.58	44.65	0.89	47.74	1.54	50.06	2.04	44.12	2.16	44.86	48.18	3.17	48.89	2.95
TiO_2	2.09	0.50	1.80	0.40	2.31	0.81	0.45	0.08	0.67	0.14	0.78	0.20	0.19	0.10	0.44	0.69	0.10	1.02	1.31
Al_2O_3	7.62	0.82	11.83	1.33	14.08	1.16	8.84	0.61	12.32	1.07	14.01	1.04	2.47	1.11	5.91	11.34	1.60	14.36	0.82
Fe_2O_3	13.09	0.56	11.98	1.15	12.88	2.01	11.82	0.30	11.00	0.55	10.74	1.20	8.85	5.07	11.84	11.69	1.49	11.34	1.04
MnO	0.20	0.01	0.2	0.03	0.20	0.03	0.17	0.02	0.16	0.02	0.16	0.03	0.12	0.06	0.18	0.20	0.03	0.18	0.01
MgO	21.15	2.08	12.10	1.62	7.09	1.57	25.94	1.45	14.48	2.26	9.52	1.41	41.62	4.02	31.66	17.19	2.08	9.61	1.56
CaO	10.15	1.4	10.54	2.07	9.66	2.23	7.60	0.74	11.86	3.06	10.74	2.07	1.74	1.70	4.61	9.45	3.28	11.07	3.74
Na_2O	0.65	0.47	2.08	0.71	2.93	1.09	0.40	0.29	1.49	0.84	2.82	0.86	0.40	0.38	0.33	1.07	0.74	2.84	1.54
K_2O	0.33	0.2	1.06	0.51	1.10	0.74	0.05	0.02	0.15	0.19	0.49	0.53	0.43	0.45	0.10	0.10	0.06	0.52	0.48
P_2O_5	0.26	0.05	0.20	0.05	0.30	0.15	0.08	0.05	0.14	0.09	0.14	0.10	0.06	0.05	0.07	0.09	0.07	0.18	0.13

The compositions shown are compared on an anhydrous basis; the figures in parentheses refer to the number of samples analyzed in each category. Samples 1–3: Picrite – andesite – basalt association of the Nam So region; 1: picrite, 2: picrodolerite, 3: basalt and andesite. 4–6: Komatiite – basalt association of the Na Muoi region; 4: komatiite, 5: komatiite – basalt, 6: olivine basalt. 7–10: Komatiite - basalt association of the Ta Hoa region; 7: dunite and wehrlite of the Ban Phuc massif, 8–10: section of the southwest part of Ta Hoa; 8: komatiite, 9: komatiite basalt, 10: olivine basalt.

boninite associations in having much lower contents of SiO_2 for equal or higher contents of MgO. At the same time, the Permian–Triassic ultramafic–mafic complex of the axial part of the Song Da rift is most strongly similar in its main petrochemical and geochemical characteristics (Table 1) to komatiite–basalt associations, in particular, to those of Munro Township, Ontario, and Gorgona, Columbia (Echeverria 1980, Arndt & Nisbet 1982, Polyakov *et al.* 1991, 1996, Balykin *et al.* 1996).

To prove that the complex of high-Mg ultrabasic and basic rocks of the axial part of the Song Da rift form a komatiite–basalt association, we attempted to estimate a possible composition of the parental melt. For this purpose, we used the Fo–Di–Prp model system (Davis & Schairer 1965) and our own algorithm for recalculating rocks to the high-pressure mineral paragenesis. This recalculation showed that the total modal contents of apatite, ilmenite, and phlogopite in rocks of the high-Mg ultramafic–mafic complex of the axial part of the Song Da rift do not exceed 1–2 wt.%, whereas in the rocks of the picrite–basalt and picrite–dolerite associations of peripheral regions, they make up no less than 5–7 wt.%. Hence, compared to the mantle underlying the high-Mg ultramafic–mafic complex from the axial part of the Song Da rift, the mantle underlying picrite–basalt and picrite–dolerite associations are enriched in fusible volatiles. This agrees with Arndt's hypothesis (1976) that the komatiitic melts formed under advanced melting of a depleted mantle substrate after basaltic magmas enriched in incompatible elements had been removed.

Such a sequence of formation of the above associations was established in the Song Da rift. The picrite–basalt and picrite–dolerite associations at its periphery formed in an initial stage of geodynamic evolution of this structure from subalkaline and high-Ti basaltic melts that resulted from melting of the nondepleted mantle substrate corresponding, according to our calculations, to the composition of garnet peridotite (Balykin & Petrova 2000). Just at the taphrogenic stage of evolution of the Song Da rift, when a series of deep-seated faults originated in its central (axial) part, a Permian–Triassic high-Mg ultramafic–mafic volcano-plutonic complex formed from high-Mg, low-alkali, and low-Ti subultramafic melts, leaving behind an upper mantle depleted in fusible and volatile components as a result of removal of previous basaltic melts. Analysis of the position of compositions of the desired associations on the Fo–Di–Prp diagram (Davis & Schairer 1965) suggests that the composition of the initial melt for the komatiite–basalt complex corresponded to komatiitic basalt, whereas for the picrite–basalt and picrite–dolerite complexes, it corresponded to melanocratic basalts (Fig. 4). This inference is based on the fact that compared with other groups, these groups of rocks are closer to the Fo–Di cotectic line. The existing differences between melanocratic basalts (picrobasalts), on the one hand, and komatiitic basalts, on the other (in particular, greater enrichment of komatiitic basalts in Al and Ca) are expressed on these plots by a relative displacement of compositions of komatiitic basalts toward the garnet apex (Fig. 4).

Geology of the Ban Phuc Ni–Cu–PGE Deposit

The Ban Phuc Ni–Cu–PGE deposit lies in the central part of the Song Da rift in the core of the Ta Hoa anticlinorium (Fig. 1). This structure is elongate and follows the general northwestward strike of the Song Da rift for a distance of about 50 km, with a width of up to 20 km. Its central part, which experienced the most significant erosion, is filled with subvertically lying schists, quartzites, gneisses, marbles, siliceous limestones, and amphibolites of Devonian age. The less eroded northwestern, southeastern, and southwestern limbs of this structure are made up of volcanic rocks of a Permian–Triassic komatiite–basalt association. Its northeastern contact with rocks of Late Permian picrite – andesite – basalt, andesite – basalt, and rhyolite – basalt associations is tectonic in nature (Fig. 1).

The Ban Phuc peridotite massif, where the Ban Phuc Ni–Cu–PGE deposit occurs, is oval in shape and covers an area of about 1 km^2 on the surface. It is elongate northwestward and is funnel-shaped in section (Fig. 5). The intrusion is made up of serpentinized dunite and wehrlite, transformed in places into tremolitite. In general, the rocks are composed of serpentinized olivine (45–65 vol.%), clinopyroxene converted to amphibole (30–35 vol.%), tremolite, chlorite, and green biotite (10–15 vol.%). The accessory minerals are represented by sulfides, chromian spinel, magnetite, and ilmenite. The rocks are cut by numerous veins of pegmatitic texture varying in composition from pyroxenite to granitic, the latter containing abundant tourmaline, biotite, and muscovite, as well as by dikes of diabase and subophitic gabbro. The country rocks are schists, quartzites, and amphibolites of the Ta Hoa (D_{1-2}) Formation. Similar forms of occurrence and compositions are typical of neighboring smaller bodies of peridotite (*e.g.,* Ban Hoa, Ban Sang).

According to Vietnamese geologists, the deposit consists of two main orebodies (Fig. 1). The vein-like orebody 640 m long and 450 m wide is situated at the southwestern exocontact of the massif (Fig. 5). Its central part is composed of massive chalcopyrite – (violarite) – pentlandite – pyrrhotite ores, whose average thickness is 1.26 m. Disseminated chalcopyrite-enriched ores in selvages and disseminated mineralization in wall rocks are enriched in copper [Ni/(Ni + Cu) = 0.40] and have an average thickness of 7.15 m. They are characterized by a platy microstructure produced by chalcopyrite filling interstices between prisms of tremolite. Hydrothermal vein-type and lenticular pyrite mineralization, with low contents of Ni (0.006–0.02 wt.%), Cu (0.03–0.102 wt.%), and Co (0.001–0.055 wt.%) occurs at the flanks of the vein-like orebody and in the wall rocks. (2) The ore field made up chiefly of disseminated ores is situated at the bottom of the Ban Phuc massif. Its thickness varies from 2 to 40 m. The structure of ores is nested and veined. The content of Ni averages to 1.2 wt.%.

The reserves of the Ban Phuc deposits are as follows: 119,400 tonnes Ni, 40,500 tonnes Cu, 3,400 tonnes Co, 161,000 tonnes S, 14 tonnes Te, and 67 tonnes Se (Tran Van Tri 1995, Le Van De 1995). According to the average Ni/(Ni + Cu) value of 0.75 in the ores and their mineral composition, including PGE mineralization, the Ban Phuc deposit and Ni–Cu–PGE ore occurrences of this region correspond essentially to Ni and Ni–Cu types of sulfide deposits genetically related to komatiitic rocks (Polyakov *et al.* 1995a, 1996).

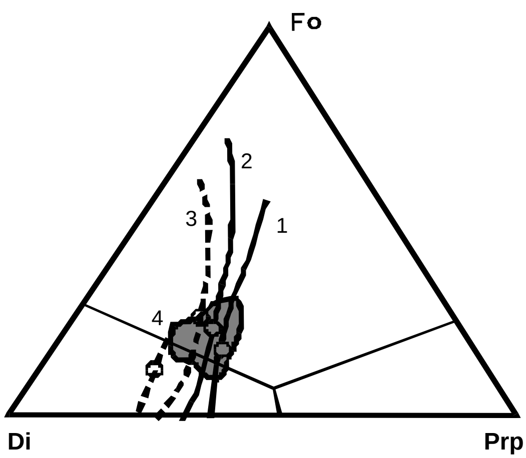

Fig. 4. Variations in compositions of komatiite–basalt and picrite–diabase associations of northwestern Vietnam in terms of the system Di–Fo–Prp at 40 kbar (Davis & Schairer 1965). Curves 1–2: P_2–T_1 Komatiite–basalt association of northwestern Vietnam (1 Na Muoi, 2 Ta Hoa). Curves 3–4: P_2 Picrite–basalt (3) and picrite–dolerite (4) associations of northwestern Vietnam (3 Nam So, 4 Don Nge). Grey circles: average composition of the komatiite–basalt. Open circles: average composition of the picritic basalt and picritic diabase. Shaded field: area of the average compositions of the komatiitic basalt of the Phanerozoic komatiite–basalt associations.

Analytical Methods

The major-element composition of rocks and the contents of Rb, Sr, Nb, Zr, and Y were determined by the X-ray fluorescence method; the concentrations of *REE* were estimated by the instrumental neutron-activation analysis. Concentrations of Ni, Cu, Co, S, and noble metals in ores were established by atomic absorption. Sulfur isotopes were determined with a D model of Finnigan mass spectrometer in the Laboratory of Radiogenic and Stable Isotopes. The mineral compositions were analyzed by Camebax electron microprobe, using the RMA–92 program for data reduction. The platinum-group minerals (PGM) were analyzed under the following conditions: acceleration voltage 20 kV, probe current 20–30 nA, and counting time 10 s for each

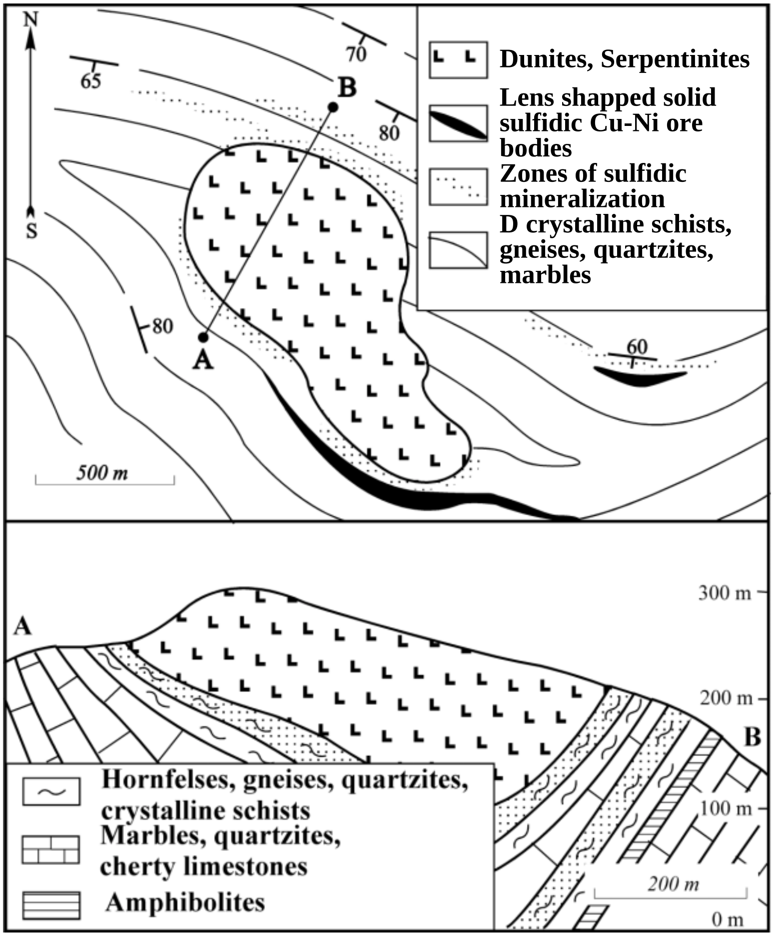

FIG. 5. Schematic geological setting of the Ban Phuc deposit, and its section through the northwestern part along the line of drill holes.

analytical line. The following standards were employed: Pt, Pd, Rh metals, $CuFeS_2$ (for Cu, Fe, S), InAs (for As), PbTe (for Pb and Te), FeNiCo (for Co), SnTe (for Sn), NiAs (for Ni), Bi_2S_3 (for Bi), and Sb_2S_3 (for Sb). Lines of interference were eliminated using a file of coefficients calculated from experimental data (Lavrent'ev & Usova 1994). All the analyses were carried out at the Analytical Center of the United Institute of Geology, Geophysics, and Mineralogy, Novosibirsk, Russia.

CHEMICAL AND MINERALOGICAL COMPOSITION OF THE ORES

The main ores of the deposit, massive chalcopyrite – (violarite) – pentlandite – pyrrhotite at the exocontact of the vein-like orebody, contain fine inclusions of Co and Ni sulfarsenides, hexatestibiopanickelite, parkerite, tsumoite, breithauptite, sperrylite, and michenerite. They contain, on average (in wt.%), 6.4% Ni, 1.6% Cu, 0.11% Co, 0.046% Se, and 0.27 ppm Au, 3 ppm Ag, and 0.12 ppm Pt. The disseminated Cu-enriched ores contain, on average: 0.49% Ni, 0.75% Cu, 0.02% Co, and 0.08–0.14 ppm Au, 3 ppm Ag, and up to 0.05 ppm Pt.

According to our data (Table 3), the maximum contents of elements in the ores of the vein-like orebody at the exocontact are 7% Ni, 5.5% Cu, 3.55 ppm Pt, and 1.33 ppm Pd; the contents of Au and Ag are low. Elevated contents of PGE are established in the Fe–Ni-enriched varieties of ores, Pt being predominant over Pd. Plots of the mantle-normalized abundances of noble metals, Ni and Cu in the ores reflect their non-fractionated distribution (Fig. 6), typical of komatiites (Barnes *et al.* 1988). The greatest similarity with the "komatiitic" distribution of metals was demonstrated for sample B–

TABLE 3. CONCENTRATIONS OF Ni, Cu, Co, S, PGE, Au, Ag AND SULFUR ISOTOPE VALUES IN ORES OF THE BAN PHUC DEPOSIT, NORTHWESTERN VIETNAM

	Sample	Ni	Cu	Co	S	Pt	Pd	Rh	Au	Ag	$\delta^{34}S$
1	B5185	7.07	0.81	0.17	34.88				0.01	2.40	
2	B5186	4.40	1.05	0.10	34.33	0.01	0.03		0.01	1.90	
3	567c/84	3.40	0.45	0.16	30.95	1.60	0.19		0.02	2.50	
4	G1429	5.60	0.16	0.20	35.07	0.91	0.35		0.03		
5	G1431	6.60	0.88	0.18	33.80	0.21	0.05		0.02	3.11	
6	M–673	3.19	0.80	0.24	23.00	0.27	0.16		0.09	2.51	
7	201E	5.15	1.89	0.08	34.20	2.45	0.22		0.02	2.94	
8	Kr6506	2.67	0.35	0.05	12.48	0.01	0.14		0.02	0.98	
9	567d/84	1.17	0.45	0.03	9.82	0.04	0.15		0.02	1.10	
10	567k/84	0.90	3.59	0.02	5.41	0.03	0.04		0.02	1.00	
11	G1422	0.26	0.18	0.06	4.40	0.03	0.03		0.05	1.42	
12	G1431/1	2.40	1.65	0.19	16.30		0.02		0.69		
13	Kr6507	3.38	3.75	0.49	20.62	3.55	0.57		0.07	3.60	
14	B5-94	0.30	2.03		30.00	0.09	0.09		0.18	1.00	
15	B1-94	0.93	1.53		7.45	0.66	1.33		0.05	1.49	
16	B2–94	0.56	1.92		7.29	0.14	0.44		0.02	2.99	
17	B3–94	0.41	4.29		8.23	0.05	0.61		0.20	6.21	
18	423	2.14	0.102	0.108	28.86		0.028	0.004			–2.0
19	PV197	4.96	0.78	0.29	34.09	0.023	0.12	0.007			–3.1
20	PV198	3.09	0.50	0.13	32.47		0.015	0.004			–2.4
21	PV200	0.11	0.48	0.11	31.16	0.004	0.046	0.005			–2.2
22	2–123	3.42	1.73	0.13	35.77	0.005	0.072	0.007			–3.1
23	2–125	1.51	3.21	0.055	24.46	0.004	0.017	0.002			2.6
24	2–133	1.07	5.50	0.054	15.33	0.012	0.011	0.002			–2.4
25	2–132	3.08	1.26	0.13	30.43	0.005	0.03	0.006			–3.1
26	B–1	4.84	1.32	0.12	30.37	0.042	0.105	0.012	0.024	3.06	

Samples G1429, G1431 and B-1 contain 71, 50, 59 ppb Ru and 237, 20, 18 ppb Ir, respectively. Sample B-1 contains 21 ppb Os. Concentrations of Ni, Cu, Co and S are quoted in wt.%, and concentrations of the PGE, Au and Ag are reported in ppm. Values of $\delta^{34}S$ are reported in ‰.

1, which has a weak Ir minimum and Pd predominant over Pt. Thus, the geochemistry of the Cu–Ni ores of the Ban Phuc deposit confirms that they belong to the komatiite–basalt association, and higher relative contents of Cu are indicative of copper enrichment in the ore–magma system.

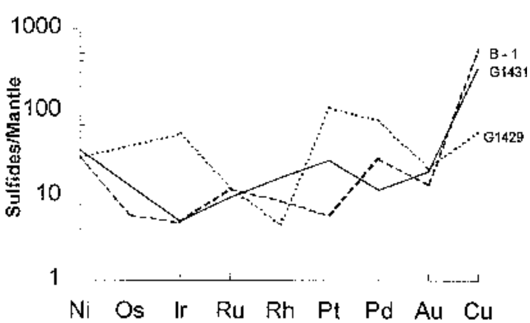

FIG. 6. Mantle-normalized metal concentrations showing the range in composition of the sulfide fraction. G1429, G1431, and B1 are specimen numbers.

SULFUR ISOTOPES

The isotopic composition of the sulfide ores is stable and varies over a narrow interval, from –2.0 to –3.1‰, averaging –2.6‰ (Table 3, Fig. 7). It does not depend on the content of sulfur in the ores nor on their composition, *i.e.*, it is nearly the same in Fe–Ni- and Cu-enriched types, which suggests the same process of ore formation for different types of Ni–Cu ores. The sulfur in pyrite in country rocks has an isotopic composition of sulfur close to the meteorite standard, and varies from –0.3 to 0.8‰, averaging –0.45‰ (Fig. 7). Differences in the isotopic composition of sulfur in the Ni–Cu ores of the Ban Phuc deposit and country rocks and the fact that the ratio of sulfur isotopes does not depend on sulfur content suggest an insignificant role of contamination by sulfur from country rocks during the formation of the Ni–Cu ores. Rather, the source of sulfur seems to have been the komatiitic magma itself.

MINERALOGY

The major ore minerals of the orebody in the exocontact part of the massif are pyrrhotite, pentlandite, chalcopyrite, and pyrite. The minerals found in subordinate amounts are violarite, heazlewoodite,

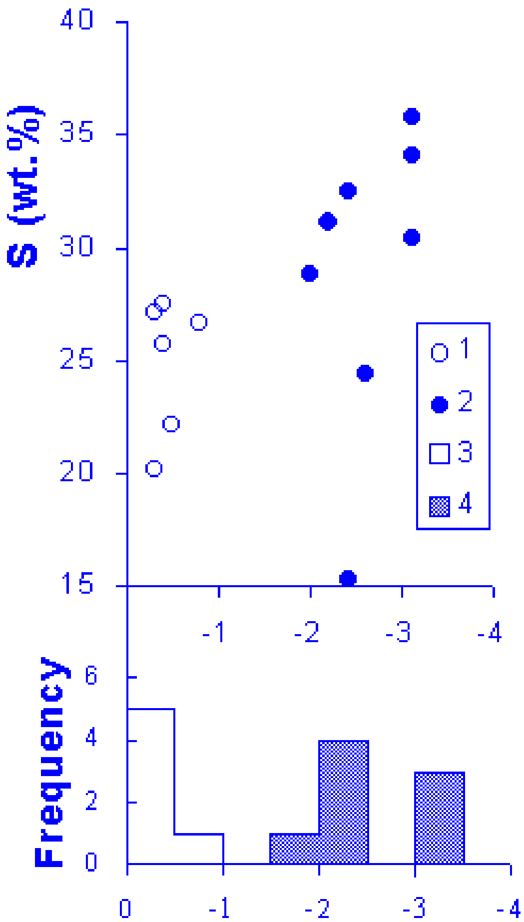

FIG. 7. Comparison of isotopic composition and S contents in ores. 1, 3: Ni–Cu–PGE ores of the Ban Phuc deposit; 2, 4: pyrite mineralization in wall rocks.

polydymite, Ni and Co sulfarsenides, Ni arsenides, Bi, Ni, and Ag tellurides, galena, sphalerite, antimonite, sperrylite, michenerite, complex Pb–Cu–Bi sulfosalts, gold, silver, and copper.

Sulfides

Pyrrhotite is the predominant mineral in the ores. In disseminated ores, it forms platy crystals and irregular aggregates both within crystals of plagioclase and pyroxene and in intergranular spaces. In some densely disseminated ores, the amount of pyrrhotite can reach 10–20 vol.%. Elongate and irregular blebs of pentlandite and chalcopyrite are observed in the majority of grains and aggregates of pyrrhotite. Their amount is variable but does not exceed 10–15 vol.%. The sulfides in massive ores usually amount to more than 90 vol.%. The portion of pentlandite in them also increases, up to 20–30 vol.%, the chalcopyrite concentration being a few percent. In places, vein-type mineralization led to an increase in the proportion of chalcopyrite in the pentlandite–pyrrhotite ores.

The composition of the pyrrhotite is characterized by a deficiency of metals with respect to sulfur; judging from the tabulated data, it belongs to either the low-Ni (0–0.08 wt.% Ni) and high-Ni (0.55–2.84 wt.% Ni) varieties (Arnold 1967). The pyrrhotite of massive ores has a higher content of Ni than the pyrrhotite from disseminated ores (Table 4). As Ni increases, so does the content of Co, to 0.18–0.35 wt.%. Pentlandite, both included in grains of pyrrhotite and present at their rim, has a moderate Ni content, with Fe/Ni close to unity, and belongs to pentlandite *s.s.* (Shishkin *et al.* 1974), as is usual in association with pyrrhotite. Violarite replaces pentlandite and forms veinlets of variable thickness. Its composition is characterized by a low content of Ni, deviating toward greigite, and Co up to 1.17 wt.%. The composition of chalcopyrite, predominant in selvages of ore veins, is nearly stoichiometric, with trace amounts of Ni (up to 0.15 wt.%) and Co (up to 0.34 wt.%: Table 4).

Sulfarsenides

Sulfarsenides of Ni, Co, and Fe in the nickel–copper ores of the Ban Phuc deposit and in other occurrences in the Ta Hoa region are represented by a series of solid solutions from cobaltite to gersdorffite, in which the arsenopyrite component does not exceed 25 mol.% (Table 5). The Co-enriched solid solutions contain inclusions of sperrylite. As the gersdorffite component increases, in addition to $PtAs_2$, the phase PdBiTe occurs among inclusions. Inclusions of Pt alloy have not been found in the Ni-enriched solid solutions, but palladium enters isomorphically into gersdorffite-dominant members of the solid solution, as is indicated by a positive correlation between Pd and Ni and a negative cor-

TABLE 4. CHEMICAL COMPOSITION OF SULFIDES, BAN PHUC DEPOSIT, NORTHWESTERN VIETNAM

	Fe	Co	Ni	Cu	Pd	S	total
1 wt.%	58.88	0.00	0.00	0.07	0.00	38.88	97.83
2	59.72	0.08	0.08	0.00	0.00	39.28	99.16
3	56.39	0.18	2.45	0.00	0.00	39.03	98.05
4	59.03	0.35	0.65	0.00	0.00	39.23	99.26
5	61.16	0.07	0.20	0.00	0.00	37.03	98.46
6	56.67	0.51	2.84	0.00	0.11	39.73	99.86
7	31.61	0.98	33.70	0.00	0.00	22.11	88.40
8	31.27	2.81	33.62	0.12	0.00	32.17	99.99
9	30.32	0.00	0.00	34.52	0.00	34.80	99.64
10	30.49	0.00	0.00	34.27	0.00	35.30	100.06
11	29.55	0.34	0.15	34.96	0.00	33.75	98.75
12	29.57	0.07	0.10	34.04	0.00	33.88	97.66

Rows: 1–6: pyrrhotite, 7–8: pentlandite, 9–12: chalcopyrite.

relation between Pd and Co. There is no incorportion of Pd in sulfides associated with sulfarsenides. The explanation is that PGE and Au have a higher affinity for an arsenide melt than for a sulfide melt once they separate (Gervilla *et al.* 1996). According to temperature curves of exsolution of sulfarsenides, the compositions that belong to the cobaltite field formed at 500°C (Klemm 1965), and the majority of compositions in the gersdorffite field lie within the interval 400–500°C. At this temperature, the platinum previously present in a sulfarsenide liquid is expected to precipitate in the form of a separate phase. The same is true for the palladium found in the highest-temperature gersdorffite (about 500°C), in the form of michenerite. As the solvus temperature decreases, the capacity of gersdorffite for Pd increases. A similar regularity has been observed in experimental work on Ni arsenides (nickeline, maucherite) (Gervilla *et al.* 1994). A genetic relationship of PGE with arsenides and sulfarsenides of Ni and Co also manifests itself in the ores of the Ta Hoa deposits. In these ores, palladium not only forms its own minerals, but also enters the structure of other minerals, its concentration reaching a few percent in the sulfarsenides.

Tellurides and antimonides

Tsumoite, BiTe, is associated with Ni and Co sulfarsenides and either forms poikilitic inclusions or epitaxically overgrows crystals to inherit their morphology. More rarely, tsumoite in the form of xenomorphic grains forms intergrowths with chalcopyrite, parkerite, Bi-dominant sulfosalts, and michenerite. It contains up to a few percent Pb (Table 6). The fact that Co and Ni sulfarsenides are epitaxically overgrown on Pb-bearing tsumoite and other low-temperature (300°C and lower) Cu–Pb–Ag–Bi sulfosalts at the Ban Phuc deposit suggests that the ore-forming process continued there at the hydrothermal stage after crystallization of the massif and sulfide melt.

Platinum-group minerals

Sperrylite is the only Pt mineral found in the ores. It is in intimate association with Ni and Co sulfarsenides and arsenides; it is included in them in the form of idiomorphic crystals. In turn, inclusions of pyrrhotite and pyroxene occur inside sperrylite crystals. A distinctive feature of the sperrylite is a high concentration of Sb, up to 3.59 wt.%. In addition, impurities of Rh, Ni, S, and, occasionally, Pd are found (Table 7). In their experiments, Furuseth *et al.* (1967) observed that the incorporation of Sb into the sperrylite structure depends directly on temperature. Similar sperrylite with 2.7 wt.% Sb was earlier found at the Driekop mine, South Africa (Tarkian & Stumpfl 1975). The contents of Rh, Sb, and Ni in sperrylite usually decreases from the core of a grain to its periphery. Of the Pd minerals, the ores contain michenerite, which forms either inclusions in the sulfarsenides or is intergrown with them and with chalcopyrite. A typical feature is the high content of Sb (Table 7), which indicates solid solution with testibiopalladite, PdSbTe, reaching 51 mol.% of the sum PdBiTe + PdSbTe. Michenerite occurs in many Ni–Cu deposits. It is significant that Sb-bearing michenerite also is found in the Kambalda sulfide ores related to Archean komatiites (Hudson *et al.* 1978). In the sulfide ores from the Ban Phuc deposit, an oxide of Pt (?) is found in association with Mn and Fe hydroxides. This mineral (in wt.%) contains 79–85% Pt, up to 2.9% Cu, up to 2.8% Mn, up to 1.6% Sb, and insignificant impurities of Fe and Ni. The proportion of oxygen was not established.

DISCUSSION

The material available shows that when the Ban Phuc Ni–Cu–PGE deposit and other ore occurrences related

TABLE 5. CHEMICAL COMPOSITION OF SULFARSENIDES OF Ni, Co, Fe AND ARSENIDES OF Ni, BAN PHUC DEPOSIT, NORTHWESTERN VIETNAM

	Fe	Co	Ni	Pd	As	Sb	S	total
1 wt.%	3.17	24.67	7.53	0.06	46.34	0.00	18.67	100.44
2	5.83	15.49	12.90	0.10	46.27	0.00	18.54	99.13
3	5.43	15.54	13.17	0.07	46.31	0.00	18.40	98.92
4	4.91	16.82	13.70	0.08	46.89	0.00	18.33	100.73
5	7.37	10.95	15.72	0.00	50.56	0.00	16.22	100.82
6	7.16	11.34	15.84	0.18	46.41	0.06	18.64	99.63
7	6.53	10.73	16.81	0.13	47.39	0.00	17.90	99.49
8	7.45	8.82	17.81	0.26	46.78	0.08	18.40	99.60
9	7.28	7.50	19.15	0.20	47.7	0.10	18.22	100.15
10	7.72	6.46	19.37	0.00	47.64	0.00	17.85	99.04
11	6.70	6.16	20.34	0.23	47.75	0.16	17.75	99.09
12	0.71	0.60	50.77	0.08	48.23	0.12	0.11	100.62
13	0.17	0.47	51.09	0.12	48.39	0.15	0.08	100.47
14	0.20	0.21	43.67	0.00	56.35	0.12	0.07	100.62
15	0.08	0.50	43.44	0.00	56.39	0.18	0.09	100.68

Rows: 1-4: cobaltite, 5-11: gersdorffite, 12-13: maucherite, 14-15: nickeline.

TABLE 6. CHEMICAL COMPOSITION OF TELLURIDES AND ANTIMONIDES, BAN PHUC DEPOSIT, NORTHWESTERN VIETNAM

	Bi	Pb	Ni	Co	Fe	Pd	Te	As	Sb	S	total
1 wt.%	1.28	0.00	22.22	0.41	0.00	0.35	49.41	0.52	23.64	0.11	97.94
2	7.19	0.00	17.54	1.74	0.09	3.03	50.56	2.93	13.82	1.21	98.11
3	7.22	0.00	18.62	0.55	0.19	2.66	52.99	0.00	14.69	0.10	97.02
4	50.24	4.51	0.22	0.00	0.00	0.00	44.13	0.00	0.00	0.00	99.10
5	50.77	4.51	0.00	0.00	0.00	0.00	43.00	0.00	0.00	0.00	98.28
6	51.51	3.02	0.00	0.00	0.00	0.00	43.98	0.00	0.00	0.00	98.51
7	59.66	0.00	26.61	0.00	0.00	0.00	0.00	0.00	2.08	9.32	97.67

Rows 1-3: hexatestibiopanickelite, (Ni,Pd)(Te,Sb); 4-6: tsumoite, BiTe; 7: parkerite, $Ni_3(Bi,Pb)_2S_2$.

TABLE 7. CHEMICAL COMPOSITION OF PLATINUM-GROUP MINERALS, BAN PHUC DEPOSIT, NORTHWESTERN VIETNAM

No.	Pt	Pd	Rh	Ni	As	Sb	Te	S	total
				Sperrylite					
1 wt.%	46,94	0,65	1.07	3.04	45.53	0.04	0.05	0.44	97.76
2	54.88	0.00	0.10	0.14	44.20	0.16	0.00	0.00	99.48
3	47.58	2.48	0.93	1.49	46.24	0.41	0,03	0.28	99.44
4	54.63	0.00	0.15	0.00	43.59	0.89	0.00	0.04	99.30
5	50,91	0.00	2.68	0.82	43.45	1.41	0.10	0.80	100.17
6	53.81	0.00	1.56	0.23	41,46	1.72	0.09	0.63	99.50
7	53.91	0,00	0.13	0.13	42.09	2.18	0,06	0,62	99.12
8	52.54	0.00	1.72	0.23	41.97	2.50	0.17	0.50	99.63
9	52,91	0,00	2.20	0.17	40.69	2,56	0,15	0.72	99.40
10	54.29	0,00	0.13	0.01	40.71	3.44	0,00	0.26	98.84
11	54,17	0,00	0.14	0.01	41.19	3.59	0.00	0.18	99.28

No.	Pt	Pd	Rh	Ni	As	Sb	Te	Bi	total
				Sb-bearing michenerite					
12	0.00	24.50	0,00	0.77	0.00	7.20	31.56	33.37	97.40
13	0.00	25.32	0.00	1.02	0.00	10,54	33.26	29.68	99.82
14	0.00	25.59	0,00	1.21	0.00	11.69	32.64	27.45	98.58
15	0.00	25.07	0,00	1.06	0.00	12.13	34.03	28.03	100.32
16	0.00	24.70	0,00	1.06	0.00	12.34	33.18	27.36	98.64
17	0.00	25.79	0.00	0.70	0.00	12.92	32.95	26.44	98.80
18	0.00	25.64	0,00	0.62	0.00	13.14	33,64	26.38	99.42
19	0.00	25.81	0.00	0.59	0.00	13.25	33.41	26.48	99.54
20	0.00	25.92	0.00	0.70	0.00	13.35	33,63	26.31	99.91
21	0.00	25,55	0.00	1.00	0.00	13.41	33.68	26.69	100.33
22	0.00	26.65	0.00	0.00	0.00	15.33	32.96	25,59	100.53

to the komatiite–basalt complex formed, the formation of Ni–Cu sulfide ore proceeded during the magmatic, the late magmatic, and the hydrothermal stages of development of the system. At the early (magmatic) stage of the process, a leading role was played by saturation of the komatiitic melt with sulfur, sulfide–silicate liquid immiscibility, and gravitational concentration of sulfide melt near the bottom of the magma chamber. At later stages of formation of the subvolcanic intrusions, the sulfide melt partly filled contraction fractures or moved along tectonic disturbances, resulting in the formation of veined mineralization in the country rocks. The low-temperature stage of ore formation involved the substitution of pentlandite with violarite and the appearance of parageneses of sulfarsenides, Bi-dominant tellurides, and platinum-group minerals.

Sulfur solubility in magnesian melts is relatively high and, according to experimental data (Al'mukhamedov & Medvedev 1982), equals 0.17–0.22% for a melt with 23.2 wt.% MgO and 40.8 wt.% SiO_2 at 1300–1400°C. With this taken into account, the source of sulfur could be the komatiitic magma itself, weakly contaminated with sulfur from country rocks. This hypothesis is also supported by a narrow range of $\delta^{34}S$, from –2.0 to –3.1‰ in ores of different compositions with high variations in sulfur content, and by the distinct isotopic composition of the Ni–Cu ores from the $\delta^{34}S$ in zones of pyrite mineralization in the country rocks (Fig. 7). Sulfur saturation of the magma leading to silicate–sulfide immiscibility seems to have occurred in subvolcanic chambers formed as closed systems, because the extrusive rocks of the komatiite–basalt complex of the Na Muoi region show no Ni–Cu sulfide mineralization. A possible cause for removal of sulfur was the decompressional degassing of the magmas effused onto the surface. This interpretation is in agreement with the observed changes in Ni contents in olivine during crystallization, which depends on the presence, amount, and degree of fractionation of the sulfide phase (Duke & Naldrett 1978, Naldrett *et al.* 1984). On the Ni_{Ol} – Fo diagram (Fig. 8), the compositions of olivine from the Ban Phuc ore-bearing massif form a steep trend reflecting a rapid depletion of the silicate part of the system in Ni, concentrated chiefly in the sulfide melt. A more gentle trend for the olivine of the komatiite–basalt association of the Na Muoi region is indicative of the absence of the sulfide phase as the main concentrator of Ni and other ore components.

Genetic Model for the Formation of the Ban Phuc Deposit

The formation of the komatiite–basalt complex of the Song Da zone led the development of the ore by sulfide–silicate liquid immiscibility in the sulfur-saturated komatiitic melt. Further evolution of the ore system and of the mineralogical and geochemical features of the ores was governed by fractional crystallization of the sulfide melt and formation of hydrothermal minerals. Thus the process of the formation of the Ban Phuc deposit was a result of the following sequence of events that occurred at the Permian–Triassic boundary.

1. At the rifting stage of evolution of the Song Da structure (about the time of the Permian–Triassic transition), a komatiite–basalt complex formed in the Na Muoi and Ta Hoa regions from high-aluminum, low-alkali, high-magnesium komatiitic to basaltic melts produced by "advanced" melting of the mantle substrate (compositionally corresponding to garnet peridotite) previously depleted by removal of subalkaline tholeiites, which were melted out at the pre-rifting stage.

2. The formation of the complex was accompanied by the appearance of intermediate chambers in the crust, where the initial melt fractionated. Cumulus peridotites formed near the bottom of the chambers as a result of olivine precipitation. The peridotites of this type make up the Ban Phuc and Ban Hoa massifs and some smaller bodies in the Ta Hoa region of the Song Da rift.

3. The Ban Phuc deposit was formed as a result of filling of the magma chamber with sulfur-saturated komatiite–basalt melt in which the presence of an independent sulfide phase led to formation of a near-bottom deposit of disseminated Cu–Ni ores (Fig. 9A). The fact that the initial melt is saturated in sulfur is supported, in particular, by the presence of sulfide segregations in

plagioclase and in the pyroxenes. The sulfide–silicate immiscibility in the magma chamber seems to have continued under decreasing temperature and during protracted crystallization, leading to an increase in SiO_2 in the residual melt, which in turn decreased the sulfur solubility (Naldrett & MacDonald 1980, Naldrett 1984).

4. The formation of the veined orebody at the exocontact of the Ban Phuc massif may have proceeded in one of two ways: 1) by transporting some part of the sulfide melt into the rocks at the exocontact along the tectonic zone during the formation of the ore deposit in the Ban Phuc massif, or 2) by the inflow of a separated sulfide liquid from an intermediate chamber (Fig. 9B). There is a considerable extent of this ore zone downward, exceeding the depth of occurrence of the lower contact of the massif (80 to 120 m from the surface) by more than 300 m. The second hypothesis is debatable, but it is viable because gravitational concentration of the sulfide liquid is possible in an intermediate chamber, by analogy with the Ban Phuc massif, to be followed by its migration upward along the fault zone owing to a difference in lithostatic pressure.

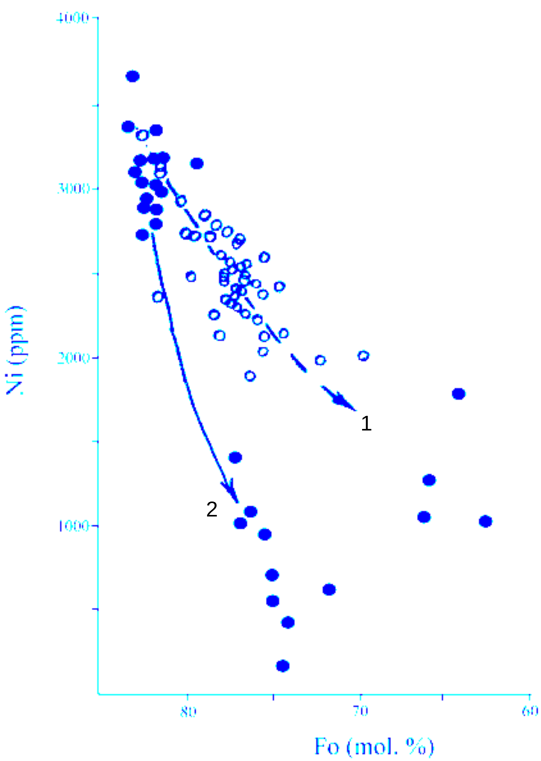

FIG. 8. Contents of Ni in olivine as a function of its composition. The olivine is from the Ban Phuc rocks (black circles) and from effusive bodies of the komatiite–basalt complex in the Na Muoi region (open circles). Arrows show variations in olivine composition during crystallization of an S-undersaturated melt (1) and during fractionation of the sulfide phase (2).

5. The formation of ores of various compositions as a result of fractional crystallization of a sulfide liquid is reflected in the structure of ore veins. The beginning of crystallization of the sulfide melt involved the formation of a Fe-rich cumulate along the coolest boundaries of the ore veins, with the concentration of the Cu-enriched residual melt in their central part (Fig. 9C). In this case, the enrichment of the residual melt in Ni, which is typical of Precambrian komatiites (Barnes *et al.* 1997), did not take place.

6. A static pressure of the country rock on the walls of the sulfide veins under crystallization led to migration of the residual sulfide melt and compatible elements toward the contacts of the veins and into the wall rock (Fig. 9D). The transport of a residual sulfide melt along the strike of the ore veins was limited, probably because of rapid freezing of the sulfide melt in thin outwedging parts.

7. The presence of an association of Co and Ni sulfarsenides with Pb-bearing tsumoite and the fact that the Cu–Pb–Ag–Bi ores contain sulfosalts, Ag tellurides, galena, and antimonite suggest that formation of the ore began with sulfide–silicate liquid immiscibility and formation of Ni–Cu ores at the magmatic stage and continued at the hydrothermal (postmagmatic) stage. Hydrothermal solutions affected the pre-existing sulfide Ni–Cu ores so that the pyrrhotite was replaced by a pyrite–marcasite aggregate, the pentlandite was replaced by heazlewoodite and violarite, and platinum-group minerals crystallized.

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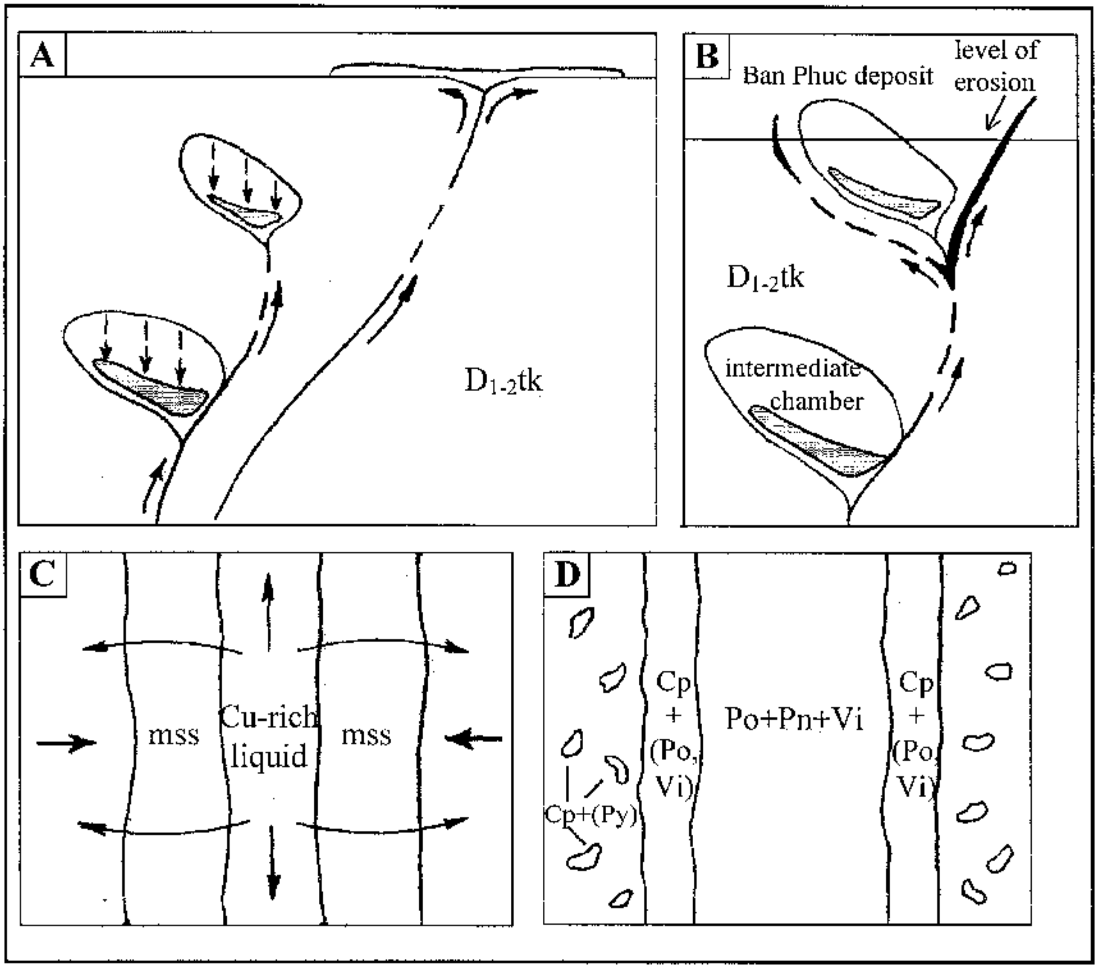

FIG. 9. A schematic diagram illustrating a succession of processes of ore formation for the Ban Phuc deposit. A. Intrusion of a komatiite–basalt melt toward the surface with the formation of subvolcanic chambers and concentration of sulfide liquid near the bottom (shaded). B. Formation of veined orebodies at the Ban Phuc deposit, with a sulfide melt supplied from an intermediate chamber. C. Fractional crystallization of the sulfide liquid with an *Mss* cumulate formed along the walls of the vein and concentration of a residual sulfide melt in its central part. Further migration of the residual melt to the near-contact parts of the veined orebody and into the wallrocks. D. Distribution of ore types in the veined orebody after solidification.

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