

Petrology and rock-forming mineral compositions of the ultramafic complex from Cao Bang province, Northern Vietnam

Ngo Xuan Thanh¹, Vu Anh Dao¹, Vu Manh Hao^b,
Bui Hoang Bac¹, Le Xuan Truong¹, Tran My Dung^b

Accepted on November 30, 2017

Abstract

The Northeast Vietnam is offered critical clues on convergent margin tectonics of South China and Indochina blocks. In this area, mafic-ultramafic rocks scattered along Cao Bang – Tien Yen fault zone. Here we present petrological, mineral composition data from the ultramafic rocks from the Cao Bang areas, Northeastern Vietnam. The data will contribute better understanding on petrogenesis, tectonic setting of the rocks in the near future further studies.

Introduction

In Vietnam, Permo-Triassic magmatic rocks appeared quite commonly from North Vietnam (north of Song Ma suture zone) to Truong Son range (south of the Song Ma suture). The Permo-Triassic granitoids that outcrop in the southern side of the Song Ma suture zone are interpreted to be products of southward subduction of the Paleo-Tethyan oceanic lithosphere beneath the Indochina terrane during the Permian to Triassic (e.g. Hutchison, 1989; Lan et al., 2000; Hoang et al., 2004; Liu et al., 2012). Permo-Triassic magmatic rocks in the Northeast Vietnam consist of ultramafic, mafic, andesitic and acidic rocks. Previous studies of the mafic and andesitic rocks in the area have proposed that they are members of a ophiolitic complex located along the Babu-Phu Ngu suture zone which is extended from Vietnam to southern China; both arc/back-arc (Thanh et al., 2014); and Emeishan plume (Thanh et al., 2004; Hoa et al., 2008, Polyakov et al., 2009) or passive margin rifting (Halpin et al., 2015). The ultramafic and acidic magmas in the area, however, have not yet been studied for their compositions as well as their tectonic nature.

In this report, we present petrology and mineral compositions of the rock-forming in the ultramafic rocks from the Cao Bang areas, Northeast Vietnam (Fig. 1a) that can serve a potential petrology to partly contribute to understand the tectonic nature of the rocks.

Geological background

Igneous rocks in the Cao Bang area are ranged from basic to acidic in compositions, and are formed during Permian to Middle-

Triassic (Luong and Bao, 1981; Khuc, 1990, 2000; Hoa et al., 2008a, Thanh et al., 2014). The mafic - ultramafic rocks are generally exposed in the northwest-southeast that associated with similar trending of Cao Bang – Tien Yen fault system (Fig. 1). The ultramafic intrusions are of plagioclase bearing lherzolite and wehrlite scattered in the area, and commonly occurred in association with gabbro, diorite, basaltic andesite and andesite (Thanh et al., 2014). The relationship of the intrusive rocks with surrounding sedimentary rocks is unclear due to later faulting and displacement. Locally, the intrusion of the gabbroic and ultramafic rocks into the Carboniferous and Permian limestone can be observed (Hoa et al., 2008; Hoang et al., 2009). These rocks have been previously proposed as Permian to Triassic ages based on their relation with sedimentary rocks (Luong and Bao, 1981; Khuc, 1990, 2000). Zircons from these mafic complexes have been dated to be 239–272 Ma by SRHIMP methods and they are consistent with the ages the associated granites (ca. 244–266 Ma) in the area by Ar-Ar methods (Hoa et al., 2008, Halpin et al., 2015). The similar ages are also reported by Thanh et al. (2014) using Rb-Sr dating for set of basalt and gabbroic diabase from Cao Bang.

Petrography

The ultramafic rocks consist mainly of olivine, clinopyroxene, mica, orthopyroxene opaque minerals and secondary amphibole, chlorite, serpentine. The ultramafic rocks present cumulate textures of the heteradcumulate type (Fig. 2a, b), which is characterized by the presence of orthocumulus olivine crystals (chadacrysts) either inside pyroxenes (oikocrysts) or in the matrix in adcumulus form.

^a Hanoi University of Mining and Geology, Dong Ngac, Tu Liem, Hanoi, Vietnam

^b General Department of Geology and Minerals of Vietnam, No.6 Pham Ngu Lao, Hanoi, Vietnam

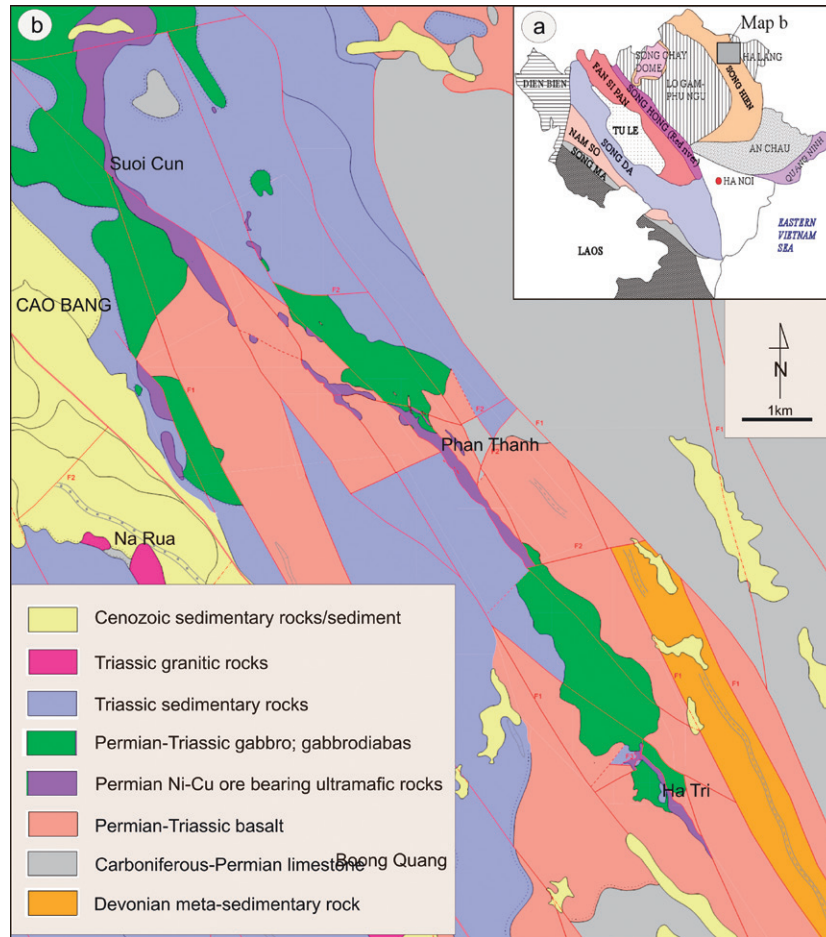


Figure 1. Simplified geological map of the Cao Bang area showing the ultramafic occurrences

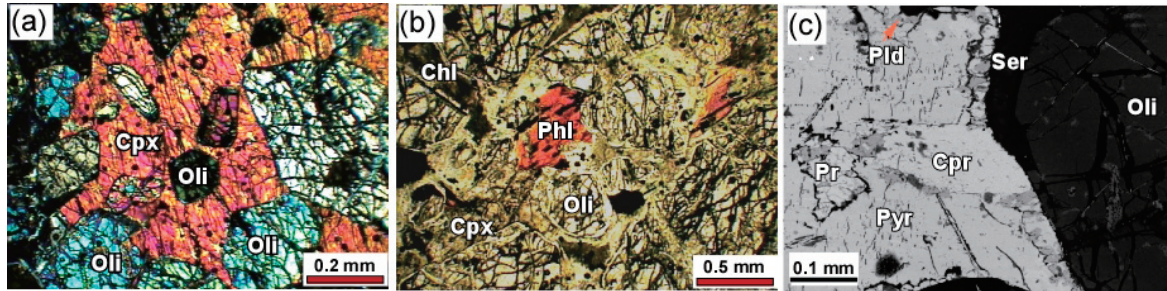


Figure 2. Photomicrographs (a, b) and BSE image showing the mineral composition and texture of the ultramafic rocks. Oli: olivine; Cpx: clinopyroxene; Phl: phlogopite; Chl: chlorite; Pyr: pyrrhotites; Pr: pyrites; Cpr: chalcopyrites; Pld: pentlandite

The clinopyroxene contain numerous olivine inclusions (Fig. 2a), they are generally rimmed by high pleochroic brownish amphibole. Greenish to reddish-brown micas are commonly occurred in most of the rocks. Pyrites, pyrrhotites, chalcopyrites, pentlandite and rare chromian spinel are the main opaque minerals in the ultramafic rocks (Fig. 2c).

Mineral chemistry of the mafic-ultramafic rocks

Electron microprobe analyses of minerals were carried out at

Okayama University of Science (Japan) using a JEOL JXA-8900R. The quantitative analyses on mineral chemistry were performed with 15 kV accelerating voltage, 12nA beam current and 3 μ m beam size. Natural and synthetic silicates and oxides were used for calibration. The ZAF method (oxide basis) was employed for matrix corrections. Estimating Fe²⁺ and Fe³⁺ contents from total FeO is based on the charge balance using stoichiometric criteria (Droop, 1987). The representative data are shown in Table 1, 2, 3, 4, 5, 6, 7, 8, 9 and Fig. 3.

Orthopyroxene

Representative orthopyroxene compositions are given in Table 1, 2. The orthopyroxene occurred mainly in the plagioclase bearing lherzolite have $En_{0.74-0.83}Wo_{0.01-0.04}Fs_{0.14-0.25}$, Mg# ($100 * Mg / (Mg + Fe^{2+}) = 74.5-85.5$) and Al_2O_3 (0.14–2.08 wt%), Cr_2O_3 (<0.56 wt%), CaO (0.45–2.10 wt%) contents. All the orthopyroxene compositions fall within the Mg-rich augite field on the En-Wo-Fs diagram (Fig. 3a). All the orthopyroxene compositions fall within the Mg-rich enstatite field on the En-Wo-Fs diagram (Fig. 3a).

Clinopyroxene

Representative analyses of clinopyroxenes are given in Table 3, 4, and are shown in a ternary plot of En-Wo-Fs (Fig. 3a). Clinopyroxene compositions are similar from both the lherzolites and wehrlite in composition with $En_{0.47-0.55}Wo_{0.34-0.4}Fs_{0.07-0.13}$. They have CaO (16.80–21.05 wt%), MgO (16.28–20.10 wt%), TiO_2 (<1.70 wt%), FeO (4.47–8.03 wt%), Cr_2O_3 (0.41–1.11 wt%), Na_2O (0.159–1.74 wt%), MnO (<0.25 wt%) contents. Their Mg# varies from 81.0 to 87.6. All the orthopyroxene compositions fall within the Mg-rich augite field on the En-Wo-Fs diagram (Fig. 3a).

Olivine

Representative olivine compositions are given in Table 5, 6, 7. Olivine from the plagioclase bearing lherzolite has forsterite numbers $[Fo = Mg / (Mg + Fe^{2+})]$ ranging from 0.82 to 0.84 (Table 5, 6), that is higher than those from wehrlite (0.79–0.80) (Table 7). All

the analyzed olivines have very low TiO_2 content.

Chromian spinel

Fine-grained chromian spinel is rarely occurred as accessory phases in cumulate lherzolites. The representative analyses are given in Table 8. They have compositional contents of Al_2O_3 (8.96–30.03 wt%), Cr_2O_3 (30.33–39.98 wt%) and low MgO (5.12–13.18 wt%). Chromian spinel has large range in TiO_2 contents (0.22–9.8 wt%) with Cr# $[Cr / (Cr + Al)]$ of 0.40–0.78 and Mg# $[Mg / (Fe^{2+} + Mg)]$ of 0.17–0.60, and moderate Fe^{3+} $[Fe^{3+} / (Fe^{3+} + Cr + Al)]$ of 0.1–0.23 (Fig. 3c).

Mica

Micas occur as an accessory phase in the ultramafic rocks, making up one of the post-cumulus phases in the wehrlite and lherzolites. Their representative compositions are presented in Table 9. The mica compositions are similar from the both rock types, having high MgO (15.59–22.68 wt%), Al_2O_3 (10.98–13.83 wt%) and K_2O (7.11–9.35 wt%) contents, and low FeO_T (6.57–9.34 wt%), CaO (<0.26 wt%) and Na_2O (0.84–1.19 wt%) contents. SiO_2 content varies from 37.29 to 39.71 wt%, and Mg# is between 0.77 and 0.84. They fall in the phlogopite compositional field on the Al^{IV} versus $Fe^{\#}$ $[Fe^{2+} / (Fe^{2+} + Mg)]$ diagram of Deer et al. (1966) (Fig. 3c).

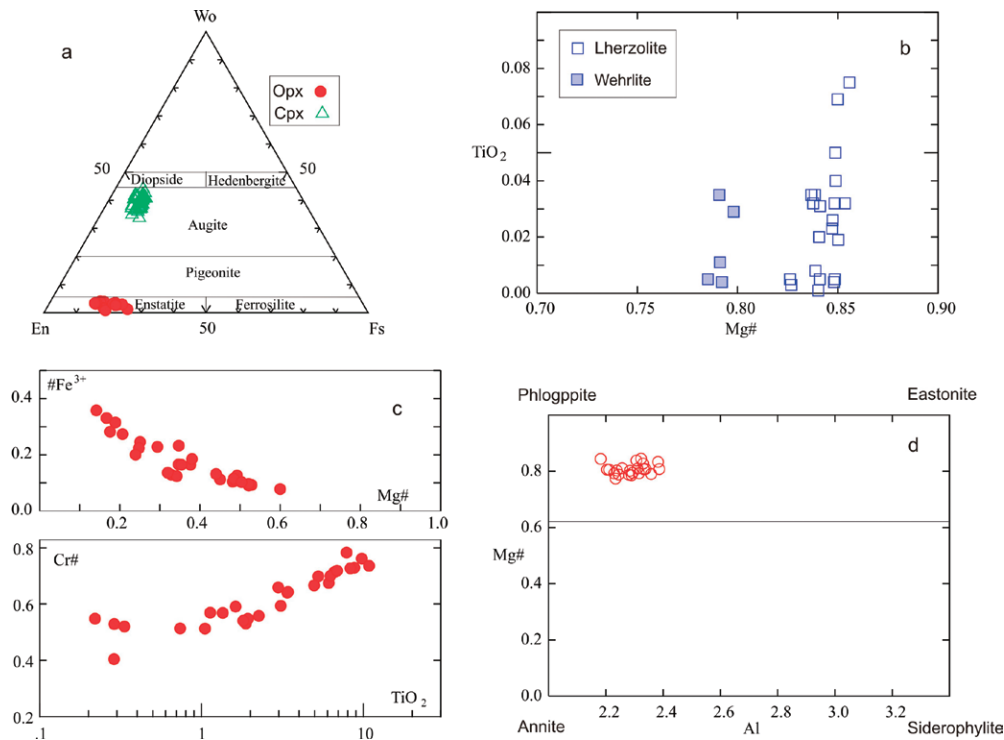


Figure 3. Diagrams of En-Wo-Fs of pyroxenes (a) (Morimoto, 1988), Mg# vs. TiO_2 of olivine (b), Mg# vs. Fe^{3+} and TiO_2 vs. Cr# of chromian-spinel (c) and Al vs. Mg# of mica (d) (Deer et al., 1966) from the ultramafic rocks in Cao Bang area, NE Vietnam.

Acknowledgements

We express our thanks to Dr. Tetsumaru Itaya (Japan Geochronology Network) for his supporting EPMA analyses. Ngo Xuan Thanh acknowledges the support from the Vietnam Ministry of Education and Training under grant number B2016-MDA-06DT.

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Table 1: Orthopyroxene compositions of the ultramafic rocks from the Cao Bang area

No.	252	253	254	255	297	298	301	309	310	311	313	314	315	316
SiO2	54.535	54.669	55.068	55.029	55.974	56.332	55.796	55.684	55.749	55.035	55.938	55.143	55.233	56.100
TiO2	0.264	0.460	0.413	0.430	0.094	0.184	0.058	0.380	0.453	0.427	0.369	0.318	0.383	0.397
Al2O3	0.993	1.596	1.564	1.633	0.211	0.334	0.135	1.413	1.376	1.600	1.469	1.221	1.639	1.435
Cr2O3	0.326	0.500	0.454	0.517	0.022	0.093	0.000	0.531	0.505	0.432	0.558	0.392	0.517	0.519
FeO	10.632	10.903	10.148	10.323	12.119	12.012	12.617	9.545	9.683	9.710	9.772	9.628	9.698	9.277
MnO	0.199	0.000	0.182	0.114	0.103	0.138	0.254	0.081	0.286	0.183	0.044	0.205	0.046	0.251
MgO	30.038	29.457	29.863	29.674	31.123	30.661	30.762	31.080	31.243	30.934	30.783	31.627	31.354	30.642
CaO	1.634	2.035	2.103	1.799	0.920	0.768	0.446	1.777	1.658	1.785	1.754	1.788	1.673	1.737
Na2O	0.054	0.022	0.074	0.027	0.013	0.015	0.002	0.013	0.051	0.000	0.028	0.028	0.036	0.028
K2O	0.019	0.034	0.021	0.000	0.000	0.000	0.000	0.007	0.011	0.000	0.001	0.016	0.000	0.000
NiO	0.076	0.083	0.058	0.065	0.112	0.055	0.050	0.061	0.052	0.106	0.069	0.101	0.060	0.103
Total	98.770	99.759	99.948	99.611	100.691	100.592	100.120	100.572	100.067	100.212	100.785	100.467	100.639	100.389
O=23														
Si	7.496	7.450	7.468	7.481	7.610	7.604	7.591	7.471	7.455	7.474	7.491	7.519	7.462	7.534
Ti	0.027	0.047	0.042	0.044	0.009	0.019	0.006	0.038	0.046	0.043	0.037	0.031	0.038	0.040
Al	0.161	0.256	0.250	0.262	0.033	0.053	0.022	0.223	0.217	0.252	0.232	0.189	0.256	0.226
Cr	0.035	0.054	0.049	0.056	0.002	0.010	0.000	0.056	0.053	0.046	0.059	0.041	0.054	0.055
Fe	1.222	1.243	1.151	1.174	1.354	1.356	1.435	1.071	1.083	1.083	1.094	1.059	1.076	1.036
Mn	0.023	0.000	0.021	0.013	0.012	0.016	0.029	0.009	0.032	0.021	0.005	0.023	0.005	0.028
Mg	6.155	5.985	6.037	6.014	6.197	6.170	6.239	6.217	6.228	6.151	6.145	6.204	6.203	6.102
Ca	0.241	0.297	0.306	0.262	0.132	0.111	0.065	0.255	0.238	0.255	0.252	0.252	0.238	0.249
Na	0.014	0.006	0.019	0.007	0.003	0.004	0.001	0.003	0.013	0.000	0.007	0.007	0.009	0.007
K	0.003	0.006	0.004	0.000	0.000	0.000	0.000	0.001	0.002	0.000	0.000	0.003	0.000	0.000
Ni	0.008	0.009	0.006	0.007	0.012	0.006	0.005	0.007	0.006	0.011	0.007	0.011	0.006	0.011
Total cation	15.387	15.353	15.352	15.320	15.365	15.348	15.393	15.353	15.372	15.335	15.330	15.339	15.349	15.289
Fs	0.160	0.165	0.154	0.158	0.176	0.178	0.185	0.142	0.143	0.145	0.146	0.141	0.143	0.140
En	0.808	0.795	0.806	0.807	0.807	0.808	0.806	0.824	0.825	0.821	0.820	0.825	0.825	0.826
Wo	0.032	0.039	0.041	0.035	0.017	0.015	0.008	0.034	0.031	0.034	0.034	0.034	0.032	0.034

Table 2: Orthopyroxene compositions of the ultramafic rocks from the Cao Bang area (continue)

No.	347	351	359	364	365	376	378
SiO ₂	53.289	55.233	55.671	55.066	55.385	54.271	55.442
TiO ₂	0.501	0.164	0.242	0.414	0.592	0.676	0.645
Al ₂ O ₃	2.079	1.083	0.939	1.184	1.169	1.252	1.197
Cr ₂ O ₃	0.394	0.371	0.271	0.494	0.204	0.312	0.339
FeO	14.056	15.520	13.367	12.944	13.413	13.380	13.381
MnO	0.165	0.296	0.223	0.225	0.253	0.299	0.329
MgO	27.685	27.102	28.204	28.246	27.441	27.782	27.310
CaO	1.459	0.628	1.795	1.654	1.516	1.471	1.353
Na ₂ O	0.056	0.019	0.032	0.055	0.080	0.030	0.018
K ₂ O	0.022	0.000	0.000	0.018	0.015	0.019	0.000
NiO	0.011	0.005	0.048	0.028	0.020	0.002	0.074
Total	99.717	100.421	100.792	100.328	100.088	99.494	100.088
O=Z3							
Si	7.371	7.551	7.572	7.460	7.525	7.491	7.509
Ti	0.052	0.017	0.025	0.042	0.060	0.070	0.066
Al	0.339	0.175	0.151	0.285	0.187	0.204	0.191
Cr	0.043	0.040	0.029	0.053	0.022	0.034	0.036
Fe	1.626	1.889	1.521	1.466	1.694	1.545	1.550
Mn	0.019	0.034	0.026	0.026	0.029	0.035	0.038
Mg	5.709	5.524	5.719	5.745	5.558	5.717	5.716
Ca	0.216	0.092	0.262	0.240	0.221	0.218	0.196
Na	0.015	0.005	0.008	0.014	0.021	0.008	0.005
K	0.004	0.000	0.000	0.003	0.003	0.003	0.000
Ni	0.001	0.001	0.005	0.003	0.002	0.000	0.008
Total cation	15.395	15.327	15.317	15.338	15.322	15.325	15.314
Fs	0.215	0.252	0.203	0.197	0.227	0.207	0.208
En	0.756	0.736	0.762	0.771	0.744	0.764	0.766
Wo	0.029	0.012	0.035	0.032	0.030	0.029	0.026

Table 3: Clinopyroxene compositions of the ultramafic rocks from the Cao Bang area

No.	1	2	6	9	15	18	19	26	27	30	33	34	35	36
SiO ₂	52.203	52.641	53.215	52.245	52.496	52.470	53.030	52.115	53.087	52.361	52.365	51.721	52.442	52.050
TiO ₂	0.000	0.000	0.000	0.038	0.013	0.017	0.000	0.478	0.543	0.536	0.506	0.443	0.460	0.521
Al ₂ O ₃	2.850	2.739	1.575	2.388	2.536	2.803	2.396	2.226	2.466	2.659	2.801	2.834	2.829	2.728
Cr ₂ O ₃	1.016	1.042	0.692	1.066	0.726	1.009	0.869	0.630	0.669	0.732	0.930	0.911	1.048	1.036
FeO	6.031	6.975	6.285	4.720	5.095	5.046	6.048	7.039	6.499	6.169	6.131	6.501	6.396	6.293
MnO	0.145	0.217	0.196	0.115	0.128	0.199	0.163	0.191	0.137	0.187	0.152	0.106	0.144	0.191
MgO	17.027	17.865	20.105	18.155	19.017	17.529	18.013	17.857	17.891	17.144	17.614	16.796	16.256	17.376
CaO	19.807	18.561	17.588	19.612	18.690	19.904	18.942	19.011	19.295	19.629	19.000	19.756	19.716	19.814
Na ₂ O	0.159	0.260	0.228	0.266	0.340	0.251	0.215	0.207	0.229	0.361	0.252	0.249	0.281	0.202
K ₂ O	0.000	0.032	0.009	0.015	0.003	0.004	0.000	0.018	0.012	0.021	0.007	0.062	0.000	0.014
Total	99.238	100.332	99.893	98.620	99.044	99.232	99.676	99.772	100.828	99.799	99.758	99.379	99.572	100.225
O=6														
Si	1.926	1.918	1.930	1.925	1.899	1.927	1.941	1.912	1.926	1.920	1.919	1.908	1.910	1.902
Ti	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.013	0.015	0.015	0.014	0.012	0.013	0.014
Al	0.124	0.118	0.067	0.104	0.110	0.121	0.103	0.096	0.105	0.115	0.121	0.123	0.121	0.118
Cr	0.030	0.030	0.020	0.031	0.021	0.029	0.025	0.018	0.019	0.021	0.027	0.027	0.030	0.030
Fe	0.186	0.213	0.191	0.145	0.157	0.155	0.185	0.216	0.197	0.189	0.188	0.201	0.195	0.192
Mn	0.005	0.007	0.006	0.004	0.004	0.006	0.005	0.006	0.004	0.006	0.005	0.003	0.004	0.006
Mg	0.936	0.970	1.087	0.997	1.045	0.959	0.982	0.976	0.967	0.937	0.962	0.924	0.937	0.947
Ca	0.783	0.725	0.683	0.774	0.739	0.783	0.743	0.747	0.750	0.771	0.746	0.781	0.770	0.776
Na	0.011	0.018	0.016	0.019	0.024	0.018	0.015	0.015	0.016	0.026	0.018	0.018	0.020	0.014
K	0.000	0.001	0.000	0.001	0.000	0.000	0.000	0.001	0.001	0.001	0.000	0.003	0.000	0.001
Total cation	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000
Al ^{IV}	0.073	0.076	0.059	0.070	0.086	0.071	0.058	0.080	0.073	0.077	0.080	0.087	0.086	0.092
Al ^{VI}	0.051	0.042	0.009	0.034	0.025	0.050	0.045	0.016	0.033	0.038	0.041	0.037	0.036	0.026
X _{Mg}	0.834	0.820	0.851	0.873	0.869	0.861	0.841	0.819	0.831	0.832	0.837	0.822	0.828	0.831
En	0.491	0.509	0.554	0.520	0.539	0.506	0.514	0.503	0.505	0.494	0.507	0.485	0.493	0.494
Wo	0.411	0.380	0.349	0.404	0.381	0.413	0.389	0.385	0.392	0.406	0.394	0.410	0.405	0.405
Fs	0.098	0.111	0.097	0.076	0.081	0.082	0.097	0.111	0.103	0.100	0.099	0.105	0.102	0.100

Table 4: Clinopyroxene compositions of the ultramafic rocks from the Cao Bang area (continue)

No.	37	38	39	40	41	42	43	44	45	46	56	58	61	62
SiO ₂	51.989	52.410	52.060	52.461	51.966	52.442	52.451	52.418	53.745	54.066	52.497	53.380	53.247	53.665
TiO ₂	0.465	0.472	0.500	0.475	0.452	0.512	0.522	0.521	0.366	0.273	0.791	0.442	0.365	0.396
Al ₂ O ₃	2.784	2.961	2.899	2.903	2.843	3.057	3.027	2.940	1.519	1.359	2.767	1.524	1.556	1.549
Cr ₂ O ₃	0.964	1.073	1.014	1.072	0.986	1.095	1.113	1.050	0.619	0.663	0.414	0.560	0.528	0.623
FeO	6.394	6.411	5.920	6.141	6.552	6.385	6.134	6.435	6.781	7.028	6.793	8.029	7.185	7.144
MnO	0.133	0.210	0.155	0.203	0.151	0.148	0.072	0.187	0.248	0.203	0.219	0.215	0.211	0.118
MgO	18.944	17.567	17.340	17.015	16.939	17.222	17.541	17.708	18.346	18.927	16.429	19.284	18.689	17.992
CaO	17.964	18.657	19.662	19.609	19.600	19.170	19.368	19.212	18.884	17.812	19.279	16.811	18.078	18.094
Na ₂ O	0.207	0.279	0.226	0.220	0.268	0.251	0.210	0.248	0.180	0.200	1.004	0.221	0.334	0.208
K ₂ O	0.010	0.010	0.012	0.053	0.020	0.022	0.003	0.021	0.005	0.000	0.103	0.019	0.063	0.023
Total	99.854	100.050	99.788	100.152	99.777	100.304	100.441	100.740	100.693	100.531	100.296	100.485	100.256	99.812
O=6														
Si	1.876	1.898	1.909	1.908	1.910	1.916	1.911	1.904	1.952	1.964	1.913	1.940	1.951	1.970
Ti	0.013	0.013	0.014	0.013	0.012	0.014	0.014	0.014	0.010	0.007	0.022	0.012	0.010	0.011
Al	0.121	0.126	0.125	0.124	0.123	0.132	0.130	0.126	0.065	0.058	0.119	0.065	0.066	0.067
Cr	0.028	0.031	0.029	0.031	0.029	0.032	0.032	0.030	0.018	0.019	0.012	0.016	0.015	0.018
Fe	0.197	0.194	0.182	0.187	0.201	0.195	0.187	0.195	0.206	0.213	0.207	0.244	0.216	0.219
Mn	0.004	0.006	0.005	0.006	0.005	0.005	0.002	0.006	0.008	0.006	0.007	0.007	0.006	0.004
Mg	1.039	0.948	0.947	0.949	0.928	0.938	0.952	0.959	0.993	1.025	0.892	1.045	1.002	0.984
Ca	0.708	0.763	0.772	0.764	0.772	0.750	0.756	0.748	0.735	0.693	0.753	0.655	0.708	0.712
Na	0.015	0.020	0.016	0.016	0.019	0.018	0.015	0.017	0.013	0.014	0.071	0.016	0.023	0.015
K	0.000	0.000	0.001	0.002	0.001	0.001	0.000	0.001	0.000	0.000	0.005	0.001	0.003	0.001
Total cation	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000
Al ^{IV}	0.110	0.095	0.089	0.089	0.086	0.085	0.089	0.092	0.047	0.037	0.075	0.055	0.045	0.035
Al ^{VI}	0.011	0.032	0.037	0.036	0.037	0.047	0.041	0.034	0.018	0.021	0.045	0.011	0.021	0.031
X _{Mg}	0.841	0.830	0.839	0.836	0.822	0.828	0.836	0.831	0.828	0.828	0.812	0.811	0.823	0.818
En	0.534	0.498	0.498	0.500	0.488	0.498	0.502	0.504	0.513	0.531	0.482	0.538	0.520	0.514
Wo	0.364	0.400	0.406	0.402	0.406	0.398	0.399	0.393	0.380	0.359	0.406	0.337	0.368	0.372
Fs	0.101	0.102	0.095	0.098	0.106	0.104	0.099	0.103	0.107	0.111	0.112	0.126	0.112	0.115

Table 7: Olivine compositions of the lherzolite rocks from the Cao Bang area

No.	245	248	249	263	280	281	283	288	289	290	291	296	303	304
SiO ₂	39.519	40.721	39.587	40.350	40.293	40.333	40.024	40.162	40.393	39.211	40.484	40.040	39.801	39.906
TiO ₂	0.000	0.003	0.005	0.035	0.000	0.001	0.035	0.031	0.032	0.020	0.005	0.000	0.008	0.000
Al ₂ O ₃	0.042	0.040	0.032	0.062	0.015	0.067	0.035	0.000	0.000	0.041	0.060	0.071	0.048	0.009
Cr ₂ O ₃	0.038	0.036	0.019	0.099	0.000	0.006	0.064	0.046	0.021	0.021	0.007	0.041	0.097	0.000
FeO	16.803	16.182	16.397	15.311	15.083	15.023	15.275	15.084	15.218	15.339	15.240	15.354	15.239	15.422
MnO	0.237	0.166	0.094	0.121	0.184	0.283	0.132	0.080	0.283	0.201	0.090	0.098	0.166	0.072
MgO	43.117	43.332	43.735	44.034	44.255	44.329	44.503	44.801	44.070	45.418	45.226	44.603	44.497	45.011
CaO	0.209	0.183	0.189	0.062	0.156	0.135	0.149	0.116	0.154	0.156	0.118	0.168	0.136	0.130
Na ₂ O	0.000	0.000	0.023	0.037	0.000	0.021	0.000	0.000	0.000	0.009	0.014	0.000	0.004	0.027
K ₂ O	0.000	0.000	0.000	0.006	0.013	0.028	0.003	0.000	0.000	0.009	0.000	0.014	0.000	0.023
NiO	0.228	0.178	0.213	0.250	0.225	0.228	0.284	0.249	0.238	0.225	0.274	0.294	0.285	0.202
Total	100.193	100.841	100.294	100.367	100.224	100.454	100.504	100.569	100.409	100.650	101.518	100.683	100.281	100.802
O=	4.000													
Si	1.008	1.017	0.998	1.010	1.009	1.008	1.001	1.003	1.011	0.983	1.002	1.000	0.999	0.996
Ti	0.000	0.000	0.000	0.001	0.000	0.000	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000
Al	0.001	0.001	0.001	0.002	0.000	0.002	0.001	0.000	0.000	0.001	0.002	0.002	0.001	0.000
Cr	0.001	0.001	0.000	0.002	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.001	0.002	0.000
Fe	0.353	0.338	0.346	0.320	0.316	0.314	0.320	0.315	0.318	0.321	0.315	0.321	0.320	0.322
Mn	0.005	0.004	0.002	0.003	0.004	0.006	0.003	0.002	0.006	0.004	0.002	0.002	0.004	0.002
Mg	1.613	1.613	1.644	1.643	1.652	1.652	1.660	1.667	1.644	1.697	1.668	1.661	1.664	1.675
Ca	0.006	0.005	0.005	0.002	0.004	0.004	0.004	0.003	0.004	0.004	0.003	0.004	0.004	0.003
Na	0.000	0.000	0.001	0.002	0.000	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.001
K	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
Ni	0.005	0.004	0.004	0.005	0.005	0.005	0.006	0.005	0.005	0.005	0.005	0.006	0.006	0.004
Total	2.991	2.982	3.002	2.989	2.991	2.992	2.997	2.996	2.989	3.017	2.998	2.998	3.000	3.005
Mg#	0.821	0.827	0.826	0.837	0.839	0.840	0.839	0.841	0.838	0.841	0.841	0.838	0.839	0.839

Table 8: Olivine compositions of the Iherzolite rocks from the Cao Bang area (continue)

No	402	403	406	407	411	419	420	421	423	424	428	433	435	436
SiO ₂	40.150	39.522	40.139	40.023	40.014	39.437	40.012	40.450	39.960	40.565	40.376	40.314	40.213	40.010
TiO ₂	0.004	0.019	0.000	0.032	0.075	0.026	0.005	0.050	0.000	0.069	0.032	0.040	0.023	0.000
Al ₂ O ₃	0.020	0.032	0.000	0.043	0.052	0.011	0.050	0.021	0.017	0.041	0.026	0.025	0.040	0.044
Cr ₂ O ₃	0.000	0.000	0.011	0.018	0.000	0.000	0.003	0.000	0.000	0.000	0.030	0.004	0.064	0.093
FeO	14.540	14.322	14.121	13.997	13.737	14.560	14.435	14.058	14.721	14.052	14.347	14.367	14.479	14.131
MnO	0.126	0.043	0.053	0.029	0.191	0.176	0.315	0.130	0.111	0.159	0.190	0.060	0.158	0.248
MgO	45.551	45.607	45.637	45.754	45.748	45.369	45.346	44.253	45.004	44.644	45.052	45.294	45.026	45.083
CaO	0.081	0.082	0.108	0.090	0.105	0.082	0.071	0.066	0.115	0.102	0.112	0.109	0.146	0.191
Na ₂ O	0.021	0.014	0.005	0.000	0.011	0.002	0.009	0.000	0.000	0.011	0.002	0.000	0.021	0.002
K ₂ O	0.000	0.000	0.009	0.000	0.000	0.000	0.019	0.003	0.000	0.012	0.031	0.000	0.000	0.000
NiO	0.229	0.170	0.197	0.232	0.248	0.163	0.164	0.139	0.270	0.236	0.293	0.215	0.267	0.232
Total	100.722	99.811	100.280	100.218	100.181	99.826	100.429	99.170	100.198	99.891	100.491	100.428	100.437	100.034
O=														
Si	0.999	0.992	1.001	0.998	0.998	0.991	0.998	1.017	1.000	1.014	1.006	1.004	1.003	1.001
Ti	0.000	0.000	0.000	0.001	0.001	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.000
Al	0.001	0.001	0.000	0.001	0.002	0.000	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Cr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.002
Fe	0.302	0.301	0.294	0.292	0.286	0.306	0.301	0.296	0.308	0.294	0.299	0.299	0.302	0.296
Mn	0.003	0.001	0.001	0.001	0.004	0.004	0.007	0.003	0.002	0.003	0.004	0.001	0.003	0.005
Mg	1.689	1.706	1.696	1.701	1.701	1.700	1.687	1.659	1.680	1.663	1.673	1.682	1.674	1.682
Ca	0.002	0.002	0.003	0.002	0.003	0.002	0.002	0.002	0.003	0.003	0.003	0.003	0.004	0.005
Na	0.001	0.001	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.001	0.000
K	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.001	0.000	0.000	0.000
Ni	0.005	0.003	0.004	0.005	0.005	0.003	0.003	0.003	0.005	0.005	0.006	0.004	0.005	0.005
Total	3.001	3.008	3.000	3.001	3.000	3.008	3.001	2.981	2.999	2.985	2.994	2.995	2.996	2.997
Mg#	0.848	0.850	0.852	0.854	0.856	0.847	0.848	0.849	0.845	0.850	0.848	0.849	0.847	0.850

Table 7: Compositions of olivine inclusions in pyroxene of the wehrlite rocks from the Cao Bang area

No	357	358	361	362	370	377	379	380
SiO ₂	39.026	39.678	39.999	40.238	39.401	39.919	39.224	39.624
TiO ₂	0.035	0.004	0.000	0.029	0.005	0.000	0.000	0.011
Al ₂ O ₃	0.044	0.064	0.044	0.045	0.016	0.013	0.000	0.004
Cr ₂ O ₃	0.022	0.077	0.021	0.010	0.000	0.000	0.030	0.000
FeO	19.419	19.210	18.587	18.550	20.031	19.212	19.725	19.303
MnO	0.171	0.249	0.150	0.128	0.127	0.174	0.223	0.146
MgO	41.190	41.076	41.237	41.110	41.082	41.022	41.006	41.052
CaO	0.161	0.182	0.146	0.195	0.160	0.121	0.148	0.164
Na ₂ O	0.000	0.000	0.012	0.000	0.005	0.019	0.015	0.029
K ₂ O	0.007	0.000	0.000	0.006	0.010	0.000	0.003	0.013
NiO	0.155	0.187	0.156	0.167	0.131	0.190	0.118	0.132
Total	100.230	100.727	100.352	100.478	100.968	100.670	100.492	100.478
O=								
Si	0.999	1.008	1.016	1.020	1.002	1.014	1.002	1.009
Ti	0.001	0.000	0.000	0.001	0.000	0.000	0.000	0.000
Al	0.001	0.002	0.001	0.001	0.000	0.000	0.000	0.000
Cr	0.000	0.002	0.000	0.000	0.000	0.000	0.001	0.000
Fe	0.416	0.408	0.395	0.393	0.426	0.408	0.421	0.411
Mn	0.004	0.005	0.003	0.003	0.003	0.004	0.005	0.003
Mg	1.571	1.556	1.561	1.553	1.558	1.553	1.562	1.559
Ca	0.004	0.005	0.004	0.005	0.004	0.003	0.004	0.004
Na	0.000	0.000	0.001	0.000	0.000	0.001	0.001	0.001
K	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ni	0.003	0.004	0.003	0.003	0.003	0.004	0.002	0.003
Total	3.000	2.990	2.984	2.979	2.998	2.987	2.998	2.991
Mg#	0.791	0.792	0.798	0.798	0.785	0.792	0.787	0.791

Table 11: Chromian-spinel compositions of the ultramafic rocks from the Cao Bang area

No	68	67	88	89	93	94	97	104	106	107	108
SiO ₂	0.062	0.084	1.200	0.031	0.042	0.060	0.009	0.065	0.027	0.058	0.015
TiO ₂	2.260	2.981	3.389	1.624	0.220	3.423	6.589	1.133	1.811	6.256	6.873
Al ₂ O ₃	19.649	13.391	13.683	18.561	21.820	13.143	8.312	19.257	19.872	8.924	8.957
Cr ₂ O ₃	36.991	38.579	36.287	39.947	39.419	35.266	30.758	37.930	34.857	31.091	34.077
FeO	20.078	24.411	23.903	19.914	18.833	28.959	32.786	24.737	25.922	31.321	26.710
Fe ₂ O ₃	10.065	12.111	13.525	9.221	8.614	14.441	17.818	9.907	10.676	17.573	15.082
MnO	0.273	0.519	0.294	0.358	0.213	0.427	0.316	0.300	0.321	0.482	0.430
MgO	10.935	7.498	8.232	10.488	10.747	5.120	3.928	7.220	6.835	4.587	7.978
NiO	0.088	0.191	0.108	0.069	0.084	0.072	0.163	0.091	0.119	0.165	0.211
Total	99.437	98.577	99.343	99.309	99.142	99.512	98.909	99.679	99.391	98.741	98.873
O=4											
Cr	0.923	1.019	0.955	1.005	0.978	0.939	0.847	0.970	0.893	0.851	0.910
Ti	0.054	0.075	0.085	0.039	0.005	0.087	0.173	0.028	0.044	0.163	0.175
Al	0.731	0.527	0.537	0.696	0.808	0.522	0.341	0.734	0.759	0.364	0.357
Fe ³⁺	0.239	0.304	0.339	0.221	0.204	0.366	0.467	0.241	0.260	0.458	0.384
Fe ²⁺	0.530	0.682	0.665	0.530	0.495	0.816	0.955	0.669	0.702	0.907	0.755
Mn	0.007	0.015	0.008	0.010	0.006	0.012	0.009	0.008	0.009	0.014	0.012
Mg	0.514	0.373	0.408	0.497	0.503	0.257	0.204	0.348	0.330	0.237	0.402
Ni	0.002	0.005	0.003	0.002	0.002	0.002	0.005	0.002	0.003	0.005	0.006
Mg#	0.493	0.354	0.380	0.484	0.504	0.240	0.176	0.342	0.320	0.207	0.347
Cr#	0.558	0.659	0.640	0.591	0.548	0.643	0.713	0.569	0.540	0.700	0.718

$$\text{Mg\#} = \text{Mg} / (\text{Mg} + \text{Fe}^{2+}), \text{Cr\#} = \text{Cr} / (\text{Cr} + \text{Al})$$

Table 12: Phlogopite compositions of the ultramafic rocks from the Cao Bang area

No	160	161	162	164	165	174	175	176	177	178	179	180	181
SiO ₂	39.595	39.223	38.608	38.713	37.287	38.202	37.956	38.052	38.477	38.112	38.077	38.084	38.374
TiO ₂	6.234	6.071	5.132	5.229	6.647	8.665	8.476	7.978	8.300	8.095	7.811	7.963	7.485
Al ₂ O ₃	13.055	12.021	13.829	10.982	12.776	13.333	12.794	12.693	12.872	12.751	13.176	13.218	13.557
FeO	7.756	8.650	7.839	8.012	9.343	7.490	7.616	7.442	7.387	7.467	8.041	8.062	7.344
MnO	0.026	0.047	0.039	0.107	0.097	0.000	0.000	0.000	0.056	0.030	0.075	0.000	0.054
MgO	18.284	20.624	18.448	22.191	17.947	16.979	16.309	17.323	17.166	15.593	16.718	16.589	17.231
CaO	0.001	0.042	0.050	0.005	0.260	0.004	0.006	0.006	0.017	0.000	0.027	0.012	0.007
Na ₂ O	1.006	1.191	1.096	0.939	0.994	0.993	1.038	1.027	1.051	1.062	1.034	0.844	1.000
K ₂ O	9.150	7.565	8.870	7.111	8.234	9.137	9.176	8.976	9.233	9.102	9.218	9.209	9.227
Total	95.809	96.242	95.102	94.123	94.417	95.969	94.465	94.605	95.673	93.342	95.306	95.256	95.549
O=22													
Si	5.670	5.523	5.653	5.677	5.532	5.552	5.611	5.607	5.608	5.693	5.592	5.597	5.602
Ti	0.671	0.643	0.565	0.577	0.742	0.947	0.942	0.884	0.910	0.909	0.863	0.880	0.822
Al	2.339	2.311	2.387	1.898	2.234	2.284	2.229	2.204	2.212	2.245	2.281	2.290	2.333
Mg	3.902	4.328	4.026	4.850	3.968	3.678	3.593	3.804	3.729	3.471	3.659	3.634	3.749
Ca	0.000	0.006	0.008	0.001	0.041	0.001	0.001	0.001	0.003	0.000	0.004	0.002	0.001
Mn	0.003	0.006	0.005	0.013	0.012	0.000	0.000	0.000	0.007	0.004	0.009	0.000	0.007
Fe ²⁺	0.929	1.019	0.960	0.983	1.159	0.910	0.942	0.917	0.901	0.933	0.988	0.991	0.897
Na	0.279	0.325	0.311	0.267	0.286	0.280	0.298	0.293	0.297	0.308	0.294	0.241	0.283
K	1.672	1.359	1.657	1.330	1.559	1.694	1.731	1.687	1.717	1.735	1.727	1.727	1.719
total	15.465	15.520	15.572	15.596	15.532	15.346	15.346	15.398	15.383	15.297	15.416	15.361	15.411
Mg#	0.808	0.809	0.807	0.832	0.774	0.802	0.792	0.806	0.805	0.788	0.787	0.786	0.807