

Garnet-pyroxene amphibolites near Bistrica, Souther part of Zlatibor ultramafic Massif (Yugoslavia)

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ABSTRACT. — Geopetrographic data are presented for the Bistrica amphibolites belonging to the so-called Diabase-Chert Formation. Garnet-clinopyroxene-hornblende is the main mineral assemblage. Probe data concerning the main mineral phases are given: garnet is a pyrope-almandine term in which significant amount of grossularite occur; plagioclase is extremely rich in anorthite; amphibole and clinopyroxene both display a weak but significant alkaline character. Bulk composition data suggest that the protolith is magmatic in nature. Geothermometric estimations give T values mostly in the range 800-850°C.

Key words: orthoamphibolites, geothermometry, Diabase-Chert Formation.

Introduction

Small isolated masses of metamorphic rocks belonging to the so-called Diabase-Chert Formation, occur between Bistrica and Priboj, on the southern edge of the Zlatibor Massif (Fig. 1). The composition of these rocks indicates that they are different varieties of amphibolites.

The first detailed data on the petrography of this area were presented by MARIC (1933). The amphibolites of Bistrica were also studied by MARKOVIC (1968), POPEVIC (1970) and MARKOVIC & TAKAC (1985), while occurrences of rare minerals (xenotlite and pectolite) were described by MAJER & BARIC (1971).

The most important data on the metamorphism of these rocks were presented by MAJER (1972) who described garnet-

hornblendites, POPEVIC & PAMIC (1973) who discussed corundum-amphibole schists, and POPEVIC (1974) who studied occurrences of eclogites in peridotites.

Among the various types of amphibolites, garnet-pyroxene amphibolites also occur in this area, but they have not yet been petrologically studied. Their main features and the definition of the conditions of their metamorphism are the main purpose of this paper.

Geopetrographic features

In the area of Bistrica, peridotites, gabbros, diabbases, spilites, clastites, cherts and metamorphic rocks are reported, all belonging to the Diabase-Chert Formation. Sandstones, silstones and shales make up the matrix, in which the other rocks of the Diabase-Chert Formation are embedded. However, they are rare in the considered area and display folding and foliation, particularly evident in the shales.

The so-called peridotites are mostly lherzolites, which occasionally contain small bodies of dunites and are partly sperpentinized. The pyroxenes and olivines are deformed. Banding with a NNW-SSE strike and a dip towards SE is common (POPEVIC & PAMIC, 1973).

Gabbros are not abundant. They consist of

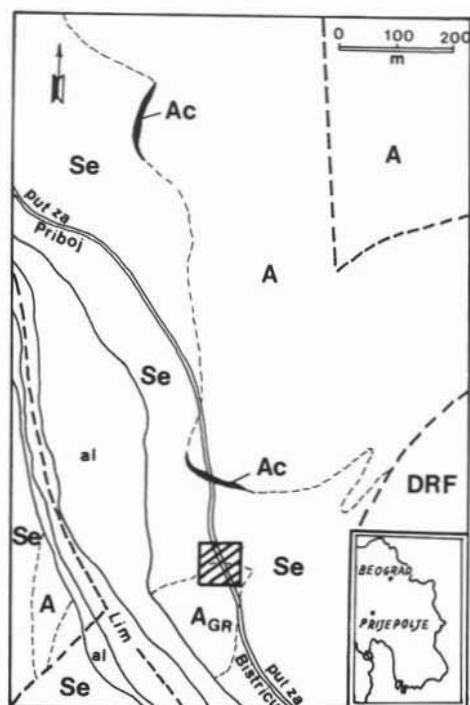


Fig. 1. — Geological sketch of Bistrica area after POPEVIC & PAMIC (1973) (simplified). Legend: Se = serpentinized ultramafics; DRF = Diabase-Chert Formation; A = amphibolites; Ac = corundum-bearing schistose amphibolites; Agr = garnet-pyroxene amphibolites; al = alluvium.

basic plagioclase, rare clinopyroxene and hornblende.

Diabases and spilites occasionally occur as independent bodies in the valley of the river Lim, or as small bodies in the sediments of the Diabase-Chert Formation.

In addition to the garnet - pyroxene amphibolites considered in the present paper, the metamorphic rocks of the Bistrica area are amphibolites, pyroxene amphibolites, garnet amphibolites (sometimes corundum-bearing), pargasite amphibolites and eclogites.

The metamorphic rocks are tectonically bounded towards all the surrounding rocks; however, the foliation in the garnet-pyroxene amphibolites is parallel to the banding in the peridotites.

The rock samples for the present study were taken just above the tunnel along the Bistrica-Priboj road. The rocks here form a body up to 100 metres thick, the contact of which

towards the peridotites is tectonic. They are dark green to black in colour: texture is banded, and parts poor in feldspars are massive. Garnet grains up to 5 mm (usually 1-2 mm) and rare concentrations of plagioclase, several mm thick, are clearly visible.

Disregarding some exceptions due to large tectonic deformations, the general strike of foliation in the garnet-pyroxene amphibolites is NNW-SSE with a dip towards ESE, i.e., parallel to the banding in the peridotites (POPEVIC & PAMIC, 1973).

The textures of these rocks is nematoblastic with granoblastic and porphyroblastic elements. Plagioclase, pyroxene and garnet are the main mineral components. Post-crystalline deformations are often visible. Accessory minerals are sphene, ilmenite and magnetite; secondary components are quartz, chlorite, calcite, zeolite, limonite and fine-grained ore minerals.

Plagioclases are in the form of grains about 0.2 mm in size, mainly making up bands, augen or irregular concentrations in which fine-grained quartz is also present. Fresh grains with fine twinned lamellae are uncommon. Deformed grains also occur. The grains are often altered (prehnitized, calcitized and zeolitized), particularly within the strongly deformed parts. Plagioclase forms up to 15% of the rock.

Hornblende is sometimes up to 3 mm in size, but is most commonly smaller than 2 mm. It is pale green to colourless. Monomineral concentrations, in which the crystals are smaller (up to 1 mm), also occur. Hornblende forms up to 40% of the rock.

Pyroxene occurs as grains up to 2 mm in size, usually 0.3-1.0 mm. They are colourless in thin section, although some have a weak pale green pleochroism. Pyroxene occasionally makes up monomineral concentrations. Some grains are partly altered into hornblende, or are weakly chloritized, mainly along the rims. Deformed grain may also be observed. Pyroxene forms up to 30% of the rock.

Garnet occurs mostly as isometric, sometimes typically idiomorphic grains up to 5 mm in size. Inclusions of pyroxene, amphibole and plagioclase are often observed

TABLE 1

Chemical analyses of three garnet-pyroxene amphibolites (new data an. S. Saponja), and four related metabasites (taken from the literature)

	1	2	3	4	5	6	7
SiO ₂	46,20	45,50	51,50	44,89	45,28	44,39	51,21
TiO ₂	1,67	1,83	1,67	0,53	0,00	0,27	0,28
Al ₂ O ₃	13,26	13,22	16,55	17,81	18,98	16,93	16,27
Fe ₂ O ₃	1,62	1,16	1,88	1,12	1,45	2,84	1,29
FeO	10,59	13,37	10,66	5,25	3,70	5,60	6,10
MnO	0,20	0,10	0,20	0,19	0,02	0,12	0,08
MgO	9,58	9,20	4,40	14,87	11,97	12,70	8,18
CaO	13,75	13,00	10,50	11,91	13,15	10,92	13,10
Na ₂ O	0,82	1,18	1,40	0,96	1,80	1,35	2,21
K ₂ O	0,02	0,05	0,05	0,04	0,80	0,10	0,10
P ₂ O ₅	0,04	0,02	0,03	0,03	0,00	0,00	0,00
H ₂ O ⁺	1,87	1,23	1,16	1,90	2,36	4,35	1,35
H ₂ O ⁻	0,29	0,29	0,53	0,31	0,65	0,20	0,08
	99,91	100,15	100,53	99,81	100,16	99,77	100,25
CIPW norms							
Q	0,00	0,00	9,94	0,00	0,00	0,00	0,36
or	0,20	0,29	0,29	0,24	0,00	0,59	0,59
le	0,00	0,00	0,00	0,00	3,49	0,00	0,00
ab	6,93	9,98	11,84	8,12	0,00	11,42	17,93
an	32,44	30,63	38,73	44,17	41,35	39,84	34,58
di	28,99	27,81	11,03	11,70	18,92	11,40	24,58
hi	18,96	10,28	21,03	8,30	14,21	10,89	18,28
ol	4,64	14,41	0,00	22,34	8,73	16,45	0,00
ap	0,09	0,05	0,71	0,07	0,00	0,00	0,00
il	3,17	3,48	3,17	1,01	0,00	0,51	0,53
mt	2,25	1,68	2,73	1,62	2,10	4,12	1,87

1-3 garnet-pyroxene amphibolite, Bistrica

4. garnet amphibolite, Bistrica (V. Majer 1979)

5. corundum amphibolite schist, Bistrica (A. Popević, J. Pamić, 1973)

6. amphibolite, Bistrica (OGK Prijepolje)

7. gabbroamphibolite, Prijepolje (OGK prijepolje)

in it. Retrograde rims of chlorite and amphibole often surround the garnet crystals.

Quartz only occurs locally as small grains 0.1-0.2 mm in size, sometimes associated with

plagioclase. Rare concentrations of quartz are also present.

Ilmenite, sphene and magnetite occur as small scattered grain 0.1-0.3 mm in size.

TABLE 2
Microprobe analyses of garnet

sample	B1/1	B1/2	B1/3	B2/1	B2/2	B2/3	B3/1	B3/2	B3/3
SiO ₂	39,98	40,00	39,21	40,53	38,36	40,26	39,64	40,03	40,10
Al ₂ O ₃	21,07	21,02	21,44	21,28	20,66	21,47	21,64	22,34	21,93
Cr ₂ O ₃	0,06	0,00	0,00	0,10	0,11	0,00	0,00	0,00	0,00
FeOtot	21,48	20,50	20,54	21,59	21,79	22,49	21,64	21,23	20,44
MnO	0,56	0,62	0,67	0,61	0,65	0,59	0,64	0,54	0,48
MgO	10,61	9,18	9,37	9,81	10,24	9,98	9,43	9,09	10,05
CaO	6,10	8,82	8,37	6,87	7,48	5,80	7,02	6,95	7,01
	99,86	100,20	99,67	100,79	99,29	100,59	100,01	100,18	100,01

Number of cations on the basis of 24 O

SiO ₂	6,05	6,06	5,96	6,10	5,85	6,08	6,02	6,07	6,06
Al ^{IV}	0,00	0,00	0,04	0,00	0,15	0,00	0,00	0,00	0,00
Al ^{VI}	3,76	3,76	3,80	3,78	3,53	3,82	3,87	3,99	3,90
Cr	0,01	0,00	0,00	0,01	0,01	0,00	0,00	0,00	0,00
Fe ³⁺	0,12	0,12	0,26	0,00	0,56	0,02	0,09	0,00	0,00
Fe ²⁺	2,60	2,47	2,35	2,71	2,22	2,82	2,66	2,69	2,58
Mn	0,07	0,08	0,09	0,08	0,08	0,07	0,08	0,07	0,06
Mg	2,39	2,07	2,12	2,20	2,33	2,25	2,13	2,05	2,26
Ca	0,99	1,43	1,37	1,11	1,22	0,94	1,14	1,13	1,13
Pyrope	38,77	33,53	34,31	36,05	36,30	36,82	34,95	34,56	37,46
Alman.	44,04	42,02	42,21	44,52	43,34	49,56	45,00	45,28	42,75
Spess.	1,16	1,29	1,39	1,27	1,31	1,24	1,35	1,17	1,02
Gross.	16,03	23,16	22,09	18,15	19,06	15,38	18,70	18,99	18,78

Calcite and sometimes zeolite are sometimes found in parts strongly affected by cataclastic processes.

Three representative rock samples were analysed for major and minor chemical components. Particularly fresh, unaltered and undeformed rock samples were carefully selected for these analyses. Chemical data are presented in Table 1, analyses 1-3.

Garnet-pyroxene amphibolites display a relatively small compositional range, of which rock sample no. 3 represents an extreme term. When the chemical analyses of the garnet-

pyroxene amphibolites are compared with those of other related metabasites (Table 1, analyses 4-7, taken from the literature), the difference in contents of some oxides may be observed: for example, TiO₂ and FeO contents are higher and Al₂O₃ and MgO contents are slightly lower.

The available chemical data may be used as an indication that metamorphism was isochemical. All chemical parameters indicate that we are dealing here with orthoamphibolites (e.g., Fig. 2), probably derived from olivine-tholeiitic basalts.

TABLE 3
Microprobe analyses of pyroxenes

sample	B1/1	B1/2	B1/3	B2/1	B2/2	B2/3	B3/1	B3/2	B3/3
SiO ₂	50,63	50,09	50,82	49,40	51,20	50,67	50,66	50,45	49,28
TiO ₂	0,00	1,00	0,00	1,09	0,11	0,00	0,00	0,00	0,99
Al ₂ O ₃	4,34	4,14	3,12	4,57	4,30	4,36	3,69	4,23	5,32
FeO _{tot}	8,92	8,85	11,43	9,00	8,48	9,20	8,97	9,56	9,62
MnO	0,08	0,13	0,12	0,15	0,15	0,11	0,12	0,13	0,14
MgO	12,77	13,07	15,09	12,45	12,99	12,70	13,50	13,15	12,52
CaO	21,55	21,73	19,19	21,72	20,51	22,19	20,91	20,81	20,10
Na ₂ O	1,40	0,82	1,08	1,22	1,36	1,35	1,26	1,38	1,33
	99,69	99,39	100,85	99,60	99,10	100,58	99,17	99,71	99,39

Number of cations on the basis of 6 O

Si	1,87	1,87	1,86	1,84	1,90	1,86	1,88	1,87	1,84
Al ^{IV}	0,13	0,13	0,14	0,16	0,10	0,14	0,12	0,13	0,16
Al ^{VI}	0,06	0,05	0,00	0,04	0,09	0,05	0,04	0,05	0,07
Ti	0,00	0,03	0,00	0,03	0,00	0,00	0,00	0,00	0,03
Fe ³⁺	0,16	0,08	0,22	0,15	0,10	0,19	0,16	0,18	0,13
Fe ²⁺	0,11	0,20	0,13	0,13	0,17	0,10	0,12	0,11	0,17
Mn	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Mg	0,70	0,73	0,82	0,69	0,72	0,69	0,75	0,72	0,70
Ca	0,85	0,85	0,75	0,87	0,82	0,87	0,83	0,82	0,80
Na	0,1	0,06	0,08	0,09	0,10	0,10	0,09	0,10	0,10

Fe³⁺ calculated according to the method of Papike et al. (1974).

Mineral chemistry

Some minerals of the garnet-pyroxene amphibolites (garnet, pyroxene, amphibole and plagioclase) were analysed using the ARL SEMQ microprobe at the Institute of Mineralogy and Petrography of Bern (under the supervision of Dr. R. Oberhansli, to whom the author is grateful).

Chemical data concerning garnets fall into a relatively small compositional field (Table 2); only Ca displays some scattering, which produces a large variation in the grossularite content, from 15.4 to 23%. The contents of almandine range from 42 to 49.5%, pyrope

from 33.5 to 38.7%, and spessartite from 1.01 to 1.39%.

Chemical data on pyroxenes are also uniform (Table 3), except for the TiO₂ content which ranges up to 4.3%. It must be emphasized that the pyroxenes are alkaline in character (Na₂O content varies from 0.82 to 1.40%) and that the iron and magnesium contents, as well as their mutual ratios, are practically the same in all the analysed pyroxene grains.

Amphiboles are also of uniform composition (Table 4). Like pyroxenes, they show a weak alkaline character.

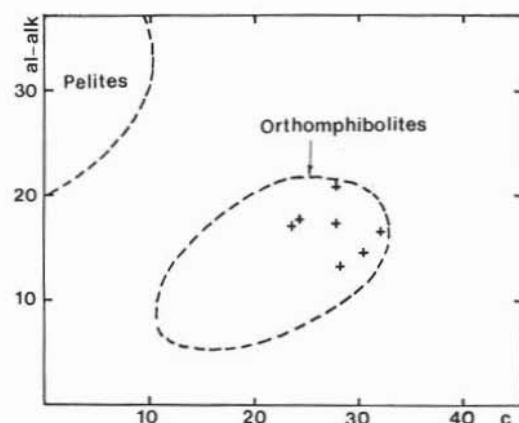


Fig. 2. — $(al-alk)/c$ diagram after WEBER-DIEFENBACH (1976), showing representative data points of the considered metabasites falling in field of orthomphibolites.

Only two plagioclase grains were analysed. Result are shown in Table 5, and indicate extreme anorthitic composition.

Metamorphism

As already mentioned, the garnet-pyroxene amphibolites consist of pyrope-almandine garnets, clinopyroxene (alkaline in character), hornblende (also alkali- and Ti-rich) and anorthite. Textural and compositional features indicate that these minerals are to be referred to a metamorphic crystallization, as products of complete alteration of the original magmatic mineral assemblage. Considering that no relics of the magmatic crystals survived, only obvious (and therefore useless) mineral reactions may be proposed in order to explain the observed metamorphic mineral assemblages.

On the contrary, the compositional features of the mineral phases may be used for better definition of the temperature values under which this metamorphism took place, values which are expected to be significantly high on the basis of the observed mineral assemblages.

Three geothermometers were used: the garnet-clinopyroxene geothermometer calibrated by POWELL (1985), the hornblende-clinopyroxene geothermometer calibrated by PERCHUK (1967, 1969, 1970), and the

TABLE 4
Microprobe analyses of amphiboles

Sample	B1/2	B2/2	B3/1	B3/2
SiO ₂	41,63	41,34	41,71	41,12
TiO ₂	2,18	2,24	2,45	2,26
Al ₂ O ₃	11,47	11,43	11,60	10,77
Cr ₂ O ₃	0,07	0,00	0,00	0,00
FeOtot	14,22	13,72	13,98	15,21
MnO	0,88	0,00	0,10	0,32
MgO	13,43	13,28	12,98	13,02
CaO	11,01	10,94	11,39	12,49
Na ₂ O	3,09	3,69	3,12	1,24
K ₂ O	0,13	0,09	0,17	0,08
	97,31	97,50	96,73	96,51

Number of cations on the basis of 23 O

Si	6,12	6,13	6,12	6,08
Al ^{IV}	1,88	1,87	1,88	1,92
Al ^{VI}	0,12	0,14	0,12	0,00
Ti	0,25	0,27	0,25	0,25
Cr	0,00	0,00	0,00	0,00
Fe ³⁺	0,71	0,65	0,71	1,13
Fe ²⁺	0,99	1,06	0,99	0,75
Mn	0,00	0,01	0,00	0,04
Mg	2,93	2,84	2,93	2,87
Ca	1,74	1,80	1,74	1,98
Na	1,06	0,89	1,06	0,35
K	8,02	0,03	0,02	0,02

Fe³⁺ calculated according to the method of Robinson et al. (1982).

hornblende-garnet geothermometer following the calibrations of both GRAHAM & POWELL (1984) and PERCHUK (1969, 1970).

POWELL's (1985) garnet-clinopyroxene geothermometer, which is a development of ELLIS & GREEN's (1979), was applied both to a Cpx-Grt pair in the core of a garnet crystal (i.e., using a clinopyroxene inclusion) and to other Cpx-Grt pairs at the rim of garnet crystals. Results are summarized in Table 6, in which the last line refers to the core of a

TABLE 5
Microprobe analyses of plagioclases

Sample	B1/1	B1/2
SiO ₂	45,76	45,32
Al ₂ O ₃	25,69	25,75
FeO	0,00	0,00
MnO	0,00	0,00
MgO	0,15	0,00
CaO	27,95	28,63
Na ₂ O	0,25	0,00
K ₂ O	0,00	0,00

Number cations on the basis of 32 O

Si	8,75	8,69
Al	5,79	5,82
Fe	0,00	0,00
Mn	0,00	0,00
Mg	0,04	0,00
Ca	5,73	5,88
Na	0,09	0,00
K	0,00	0,00

garnet and the other data to the outer parts of garnet crystals. The temperature value in the core turns out to be 1013°C, while the others are in the range 899-965°C.

Significantly lower (by about 100°C) temperature values were obtained from the hornblende-clinopyroxene pair (about 800-850°C; Fig. 3) following PERCHUK's (1967, 1969, 1970) calibration, and from the hornblende-garnet pair, using both GRAHAM & POWELL's (1984) calibration (828-879°C; Table 7) and that of PERCHUK (1969, 1970) (about 800-840°C; Fig. 4).

The above-presented different temperature values (1013°C; 965-899°C; 850-800°C) are probably due to the different methodologies and calibrations used. However, it cannot be excluded that they are partly related to the

TABLE 6
Temperature estimations on the basis of the garnet-clinopyroxene pair (POWELL, 1985)

Sample	lnKD	XCa(gr)	T(°C)	P(KB)
B1/1	1,06274	0,162	941	10
B1/2	1,19434	0,235	965	10
B1/3	1,06559	0,224	1009	10
B2/1	1,11305	0,184	944	10
B2/2	1,18125	0,193	925	10
B2/3	1,13329	0,156	905	10
B3/1	1,23785	0,190	899	10
B3/2	1,16501	0,192	931	10
B3/3	0,97473	0,190	1013	10

TABLE 7
Temperature estimations on the basis of the garnet-hornblende pair (GRAHAM and POWELL, 1984)

Sample	lnKD	XCa(gr)	T(°C)
B1/2	0,74431	0,235	879
B2/2	0,72256	0,193	843
B3/1	0,75564	0,190	828
B3/2	0,69178	0,192	853

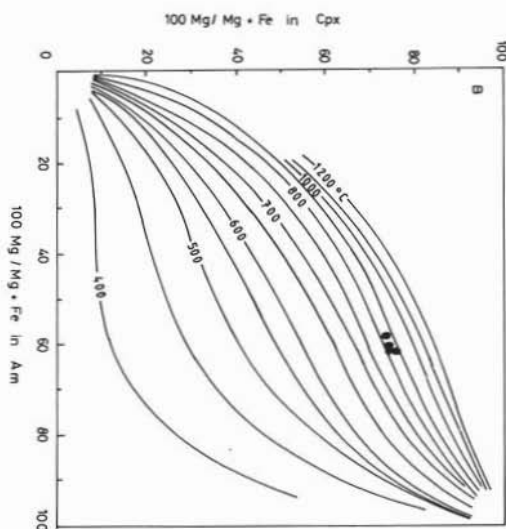


Fig. 3. — Amphibole-clinopyroxene geothermometer (after PERCHUK, 1969, 1970).

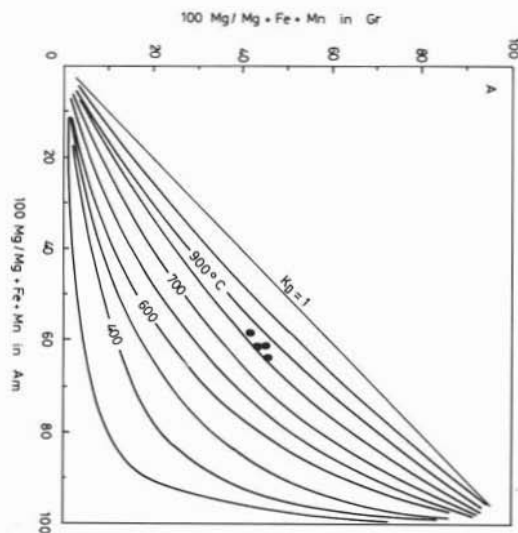


Fig. 4. — Amphibole-garnet geothermometer (after PERCHUK, 1967, 1969, 1970).

different crystallization temperatures of the pertinent mineral pairs (respectively, Cpx-Grt in the garnet core, Cpx-Grt at the garnet rim, Hbl-bearing pairs), representing in such a case a cooling path.

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