American Mineralogist, Volume 62, pages 874–886, 1977

Variation in geothermometry and geobarometry of peridotite intrusions in the Dinaride Central Ophiolite Zone, Yugoslavia

JAKOB J. PAMIĆ

Institut za geologiju, Geoinženjering
71210 Ilidža kod Sarajeva Yugoslavia

Abstract

The Jurassic ophiolite complex of the Dinarides consists predominantly of graywackes, shales, and cherts, in which are included large massifs of lherzolite with subordinate gabbro, diabase, spilite, and amphibolite. Contacts between peridotite massifs and adjacent rocks are for the most part tectonic. However, metamorphosed country rocks with primary intrusive relations are preserved in many places around larger ultramafic massifs. Two main groups of metamorphosed rocks can be distinguished:

(1) High-grade amphibolite and eclogite occur in relict zoned aureoles around the larger ultramafic bodies, and suggest metamorphism in the upper mantle. The zonation is best shown by variation of both plagioclase and amphibole composition; amphibole is mostly pargasite with variation in Mg and Fe, and the plagioclase composition varies from anorthite to oligoclase.

(2) Low-grade amphibolite with greenschist occurs in narrow zones along the borders of diabase masses adjacent to large ultramafic massifs. The changes from diabase to low-grade amphibolite are in some places gradational. The mineral assemblages include albite–oligoclase, tremolite–actinolite or green hornblende, chlorite, epidote, and relict clinopyroxene.

P,T-stabilities of the all mineral parageneses are discussed in detail and correlated with the data of experimental petrology. The genesis and the evolution of the Dinaridic peridotites are interpreted in terms of plate tectonics.

Introduction

The Central Ophiolite Zone of the Dinarides is made up of a Jurassic magmatic-sedimentary complex consisting predominantly of graywacke, shale, and chert, in which are included ultramafics, gabbro, diabase, spilite, and amphibolite. Ultramafics are common, and they vary in surface area from a few square meters to nearly one thousand square kilometers. The ultramafic massifs occur as elongated but comparatively thin plates from few hundred meters to 1–2 km thick (Roksandić, 1971/72). Ultramafic rocks consist mainly of lherzolite and have characteristic features of alpine-type peridotites (Thayer, 1960). The lherzolite and associated amphibolite have been interpreted as products of a Jurassic geologic event approximately 170 m.y. ago (Lanphere *et al.*, 1975).

Jurassic sediments, igneous rocks, and amphibolites are characteristically penetrated after the main metamorphic event with networks of veins and veinlets consisting of prehnite, calcite, epidote, quartz, albite, chlorite, and clinozoisite. The vein assemblage produced under *P,T* conditions of prehnite–pumpellyite and/or greenschist facies could be an indicator of the youngest metamorphic grade of the Jurassic magmatic-sedimentary complex (Pamić, 1972).

The Dinaridic ophiolite complex has not yet been studied in detail in terms of olistostrome or tectonic melanges. Dimitrijević and Dimitrijević (1973) made a first attempt, and they have generally concluded that the entire ophiolite complex of the Dinarides represents an olistostrome melange. It is quite certain that a part of the Dinaride ophiolite complex does not involve melanges, because undisturbed relations can be traced in large surface areas, and only in some places can the distinct elements of olistostrome melange be noticed. Only in the northeastern and eastern parts of the Dinarides, close to the ancient subduction zone (Fig. 1), has the ophiolite complex distinct characteristics of a tectonic melange.

Contacts between the Dinaridic peridotite massifs and adjacent Jurassic rocks are for the most part tectonic as in other ophiolite melanges, but primary intrusive relations between ultramafics and various country rocks are preserved in many localities. They are shown, either as complete zoned metamorphosed sequences, or in their tectonically disrupted parts. The purpose of this paper is to describe various contact-metamorphosed aureoles or their parts around some of the Dinaridic ultramafic massifs (Fig. 1). Field evidence together with results of laboratory examination will be correlated with data of experimental petrology in order to illustrate the complex thermal and pressure history during the formation and emplacement of ultramafic bodies.

General geology of the Dinaride ultramafics

The ophiolites are enclosed in country rocks composed predominantly of graywackes and shales derived from a continental source and deposited in an oceanic trench marginal to an island arc (Tišljar, 1973). Spilite with subordinate keratophyre is in places interlayered with graywackes and shales and accompanied by conformably interbedded pyroclastics. Hypabyssal diabase, occuring commonly as sills, is intrusive into graywackes and shales.

The structural relationships of the ultramafic intrusions with the country rocks are complex and varied. During subduction, solid peridotites were discordantly emplaced within the magmatic-sedimentary complex, intruded as diapirs, or intruded in association with high-grade amphibolites and eclogites. Primary relations between the members of the Dinaride ophiolites are presented in detail in a separate paper (Pamić, 1971a).

Contacts between ultramafics and adjacent rocks are mostly tectonic. However, metamorphosed coun-

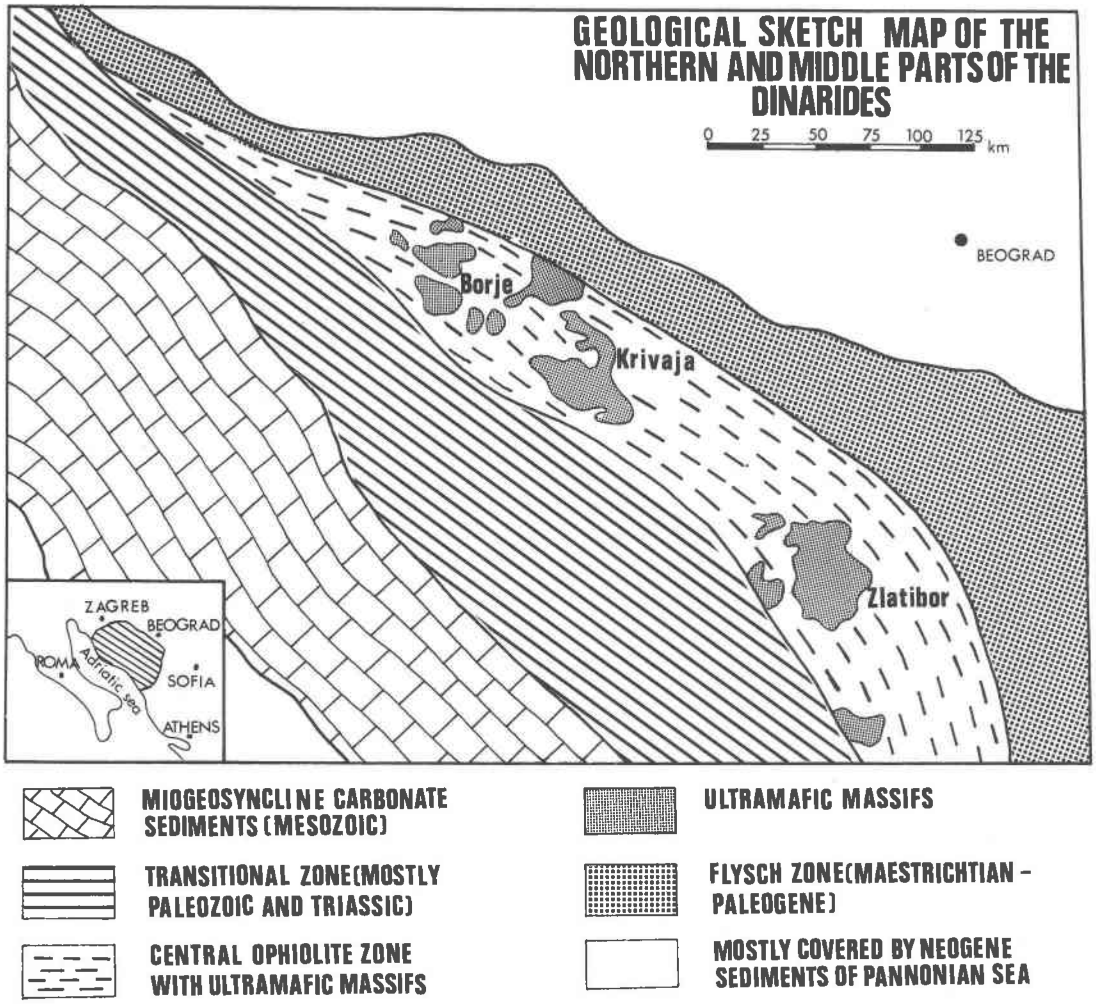

Fig. 1. Geological sketch map of the northern and middle parts of the Dinarides.

try rocks with primary intrusive relations are preserved in many places around larger ultramafic massifs. Two main groups of metamorphosed rocks can be distinguished: (1) high-grade amphibolite with eclogite and (2) low-grade amphibolite with greenschist. The two groups have not been documented to the same extent; nevertheless, available data make it possible to suggest a coherent picture of the temperature and pressure history of the Dinaride peridotite intrusions.

High-grade amphibolites with eclogites

Amphibolites with eclogites form interrupted narrow zones, usually about 100 to 1000 meters wide, around the larger ultramafic massifs. Although the length and the width of the amphibolite zones vary greatly, some can be traced along strike for more than 10–15 km. Smaller amphibolite–eclogite zones can be also found within some larger ultramafic bodies. Some comparatively large amphibolite bodies (20 km^2) associated with smaller ultramafic masses and even small amphibolite masses without peridotites are also found, and may represent transported thrust slices broken from bordering regions of dismembered ultramafic diapirs.

Contacts between high-grade amphibolites and adjacent Jurassic sediments are usually buried, and only in rare cases can the tectonic character of the contact be distinctly observed. Contacts against adjacent ultramafic rocks, where not tectonized, are frequently gradational and marked by fine alternating bands of amphibole and pyroxene schists, and peridotite. Such amphibolite masses bordering large ultramafic massifs are frequently interstratified with ultramafic lenses of various sizes.

The mineral assemblage of the amphibolites consists of amphibole and plagioclase, diopside, hypersthene, garnet, and corundum. The amphibolites have a variety of crystalloblastic textures, and they are commonly layered and foliated. Mineral assemblages of the high-grade amphibolites associated with alpine-type ultramafics in the Dinaride Central Ophiolite Zone are presented in a separate paper (Pamić *et al.*, 1973).

The Krivaja amphibolites

The Krivaja amphibolite mass exemplifies a high-grade amphibolite with eclogite, and was the first one that was studied in detail as a progressive sequence *in situ* (Pamić, 1971b; Pamić *et al.*, 1975). Amphibolites occur in the southern border of the Krivaja ultramafic massif, which covers an area of about 500 km^2. The amphibolite complex can be followed for about 15 km along the strike, its maximum width is 5–7 km, although its structural thickness is probably as much as 500–1000 meters. The Krivaja massif is monotonous in composition, and it consists mostly of moderately serpentinized lherzolite, with subordinate enstatite dunite only in the border parts adjacent to the amphibolites. The lherzolite is a typical tectonite with "gneissoid" structure, shown by centimeter-size lenses of pyroxenite embedded in a mesostasis of homogeneous serpentinized olivine. The massif represents a large concave plate about 1–2 km thick (Roksandić, 1971–72), intersected by faults dividing the massif in several blocks.

The amphibolite complex is folded, and it is characterized by tight and steep-to-vertical isoclinal folds. The amphibolites are commonly foliated and frequently layered; the layering is expressed by variation in mineral composition. The strike both of foliation and banding of the amphibolites is concordant to the foliation of the adjacent lherzolite.

The Krivaja ultramafic plate with underlying eclogite–amphibolite border is in tectonic contact with the basement consisting of Jurassic sediments, spilite, diabase, and gabbro. In few places the border part of the plate is tectonically cut by the basement rocks. It is thus evident that the border bears no genetic relation to the present tectonic base.

The relations within the Krivaja amphibolites are presented on the diagramatic sections (Fig. 2). Seven main groups of mineral assemblages can be distinguished, and they point quite clearly to a complete zonation going from the border of the ultramafic body to the tectonic base:

(1) Feldspar-free pargasite–edenite schists alternating with peridotite. The boundaries are commonly sharp, but gradational banding was also observed. This transitional zone between ultramafic massif and the amphibolite mass is commonly a few decimeters to 1–2 meters thick.

(2) Mg-pargasite + anorthite ± corundum make up interrupted zones a few tens up to 100–200 m thick along the contact with ultramafics.

(3) Kaersutite (titanian pargasite) + bytownite is rarely found as narrow zones below the pargasite schist or in the higher parts of the underlying zone.

(4) Omphacitic diopside + garnet ± plagioclase ± hornblende is a paragenesis that is most frequently lateral to the mineral assemblages described above.

(5) Pargasitic hornblende + bytownite–labradorite ± diopside is the most frequent and abundant mineral association, and it makes up the

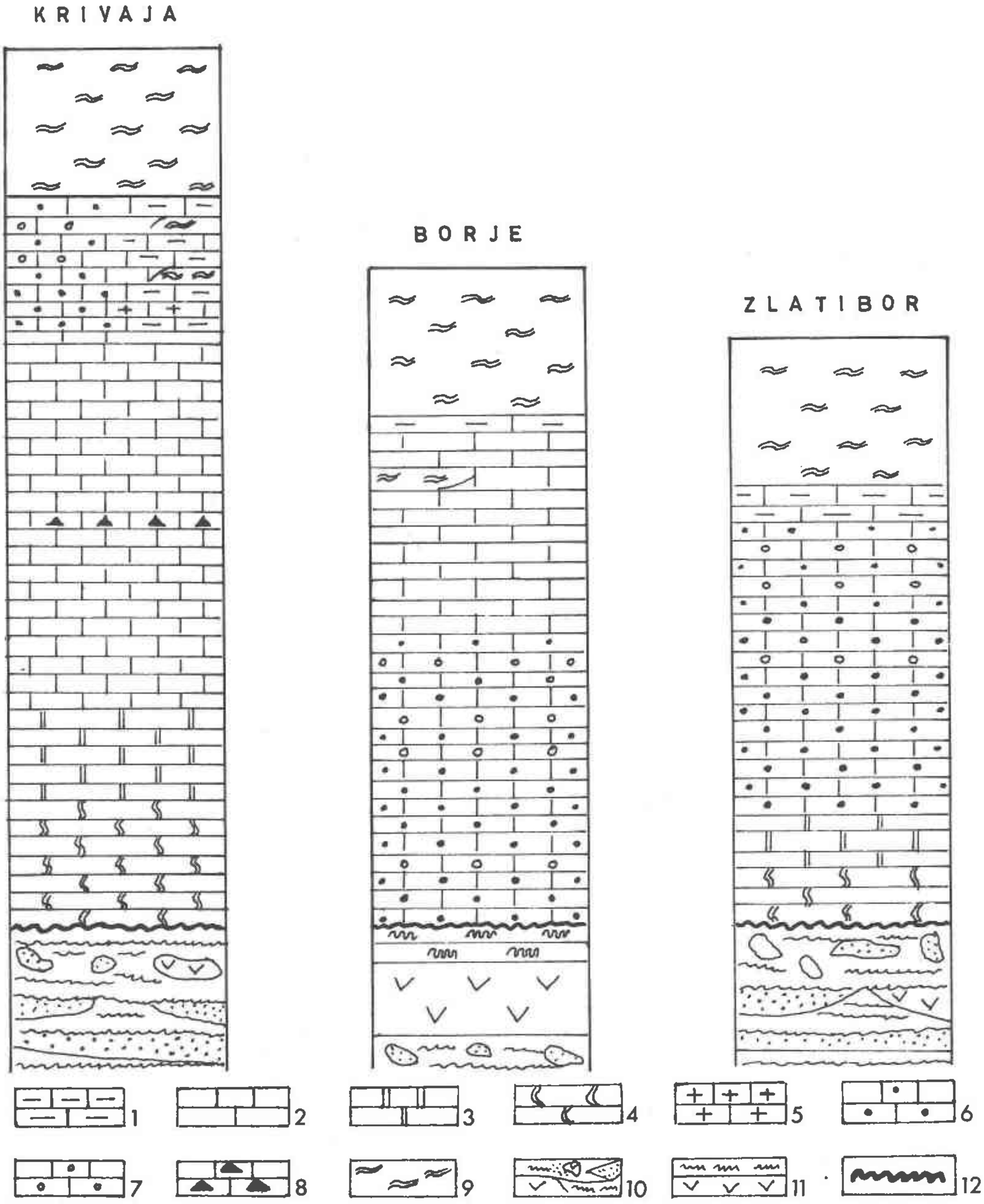

Fig. 2. Columnar sections showing the relations within the aureoles of high-grade amphibolites with eclogites. (1) Mg-pargasite–anorthite–corundum; (2) pargasitic hornblende and labradorite–bytownite–diopside; (3) amphibolite *sensu strictu;* (4) epidote amphibolite; (5) kaersutite schist; (6) garnet–diopside amphibolite; (7) eclogite; (8) hypersthene–garnet–diopside amphibolite; (9) ultramafics; (10) ophiolite magmatic-sedimentary complex (melange); (11) spilite and chert; (12) tectonic contact line.

largest part of the amphibolite complex. Middle parts of the zone are interlayered with hypersthene–garnet–diopside amphibolite.

(6) Transitional varieties of hornblende between pargasite and green hornblende + andesine ± diopside make up the outer parts of the amphibolite complex.

(7) Green hornblende (rarely brown hornblende) + oligoclase–andesine ± diopside ± epidote constitute a continuous zone on the very border of the amphibolite complex adjacent to the Jurassic sediments.

Chemical compositions of monomineralic fractions as well as of the rocks from the separated zones are presented in Tables 1 and 2.

Zonation and progressive changes within the am-

Table 1. Chemical compositions of minerals from high-grade amphibolite and eclogite

	1	2	3	4	5	6	7	8	9	10
SiO_2	37.78	41.09	39.54	38.94	41.92	38.52	46.73	44.80	41.64	45.75
TiO_2	tr.	0.20	0.36	--	--	5.35	0.40	0.77	2.28	n.d.
Al_2O_3	21.43	25.94	23.26	18.61	15.47	13.55	15.21	8.48	16.42	18.51
Fe_2O_3	3.90	0.82	3.63	1.89	3.69	5.69	0.45	3.35	3.75	2.64
FeO	10.43	8.21	10.42	16.96	3.71	7.48	2.72	10.40	6.95	
MnO	0.32	0.20	0.15	0.60	0.08	0.24	0.20	0.26	0.10	n.d.
MgO	15.30	13.55	14.60	13.75	17.05	10.87	15.21	18.17	11.88	12.22
CaO	8.98	9.59	6.68	8.90	14.00	12.70	14.93	9.48	11.99	19.65
Na_2O	n.d.	n.d.	0.28	n.d.	2.96	2.51	1.60	1.81	2.70	1.30
K_2O	n.d.	n.d.	0.16	n.d.	0.43	0.71	0.04	--	0.50	0.05
P_2O_5	n.d.	n.d.	0.13	0.09	0.10	--	n.d.	--	0.13	n.d.
H_2O+	1.84	0.56	0.10	--	0.92	1.98	2.18	1.71	1.21	n.d.
H_2O-	n.d.	0.07	0.39	--	0.15	0.21	0.12	0.53	0.14	--
	99.98	99.92	99.70	99.74	100.48	99.81	100.03	99.76	99.69	100.12
Py	56.5	51.5	54.5	45.8	Pa_{100}	Pa_{84}	Ho_{33}	Ed_{41}	Pa_{50}	
Alm	19.0	17.9	18.8	31.7			Ts_{30}	Pa_{38}	Ts_{34}	
Sp	1.0	0.4	0.3	1.1			Ed_{19}	Ts_{10}	Gp_{16}	
Gr	14.0	26.6	14.8	16.3			Pa_{18}	Ho_{11}		
And	9.5	2.6	9.7	4.8						

1. garnet from vein eclogite, Zlatibor (Popević, 1974); 2. garnet from garnet hornblendite, Zlatibor (Majer, 1973); 3. garnet from garnet-diopside amphibolite, Borje (Pamić and Majer, 1974); 4. garnet from hypersthene-garnet diopside amphibolite, Krivaja (Pamić et al., 1973); 5. Mg-pargasite, Krivaja (Pamić et al., 1973); 6. kaersutite, Krivaja (Pamić et al., 1973); 7. Mg-pargasite from garnet hornblendite, Zlatibor (Majer, 1973); 8. edenite-pargasite hornblende, the outer envelope of Krivaja (Pamić et al., 1973); 9. pargasite, the inner zone of the Borje amphibolites; 10. omphacitic diopside from the vein eclogite, Zlatibor.

phibolite complex can be followed in several ways. The plagioclase varies from anorthite to oligoclase from the contact with the ultramafic massif towards the border of the amphibolite zone. The amphibole composition changes from high edenite and particularly pargasite content to higher tschermakite and "common" hornblende content. Pamić *et al.* (1973) pointed out that the optical properties of the amphiboles from the Dinaride amphibolites, particularly their pleochroism and 2*V* values, are controlled by the concentration of edenite and pargasite respectively, and this can be easily determined by routine microscopy and U-stage method. Figure 3 shows the correlation between amphibole and plagioclase compositions within the Krivaja zoned amphibolite complex.

Zoning within the amphibolite aureole is also shown in bulk rock composition. This is most pronounced in the MgO:FeO ratio, which changes from 2.5 in amphibolites with Mg-pargasite to about 1 in the amphibolites from the outermost zones.

The Zlatibor amphibolites

The Zlatibor ultramafic massif is the largest in the Dinaride Central Ophiolite Zone, and it consists both of lherzolite and harzburgite. According to geophysical data, the massif is a thin eroded plate only a few hundred meters thick (Milovanvić and Mladenović, 1968). Amphibolites with eclogite also occur on the southern border of the massif, and they are folded together with peridotites. The high-grade amphibolites with eclogite have been described by many authors (Marić, 1933; Pavlović, 1937; Marković and Takač, 1958; Majer, 1972; Popević and Pamić, 1973; Popević, 1974).

The relations within the amphibolites are presented in columnar section in Figure 2. The amphibolite mass is here more narrow, but includes nearly all main zones as in the Krivaja amphibolites. Eclogite veins of centimeter thickness were found within the endocontact zone in the massif itself (Popević, 1974), and they contain pyrope-rich garnet (56.5% Py; Table

1, anal. 1), omphacitic diopside (Table 1, anal. 10), and enstatite.

The amphibolite aureole comprises four main mineral assemblages showing a complete zonation. The amphibolite schists containing Mg-pargasite, anorthite, and corundum are of the highest grade, and they are normally underlain by garnet–clinopyroxene amphibolites interstratified by eclogite and garnet hornblendite. Pyrope garnet contains only slightly decreased amounts of pyrope compared with the garnet from the vein eclogite within the peridotite, whereas amphibole is pargasitic hornblende (Table 1, anal. 2 and 7). The two outer zones contain green hornblende and andesine–oligoclase, with epidote in the outermost parts.

The Borje amphibolites

The Borje ultramafic massif, situated in the northwest parts of the Dinaride Central Ophiolite Zone, covers an area of about 150 km², and it consists of lherzolite. High-grade amphibolites with eclogite occur on the southern border of the massif in the form of narrow interrupted zones. One of them, situated in the area of Crni potok, has been studied in detail (Pamić and Majer, 1973), and the relations within these amphibolites are presented in the columnar section in Figure 2. The Borje massif, together with its amphibolite aureole, is also a comparatively thin plate in tectonic contact with underlying Jurassic sediments and spilite.

The amphibolite aureole is narrow and reduced by tectonics, and only two zones can be distinguished within it. The inner zone of the aureole consists of pargasitic amphibolite schists interlayered with lenses of serpentinized ultramafics. The mineral assemblage is Mg-pargasite (Table 1, anal. 9), bytownite, and diopside. Pargasite from the higher parts of the zone has an MgO:FeO ratio of about 2, whereas pargasite

Table 2. Chemical analyses of high-grade amphibolites and eclogites

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	40.96	39.75	40.10	54.05	42.74	47.30	43.42	43.31	44.89	45.28	45.78	46.60	42.68	46.14
TiO_2	0.18	0.45	--	0.49	1.39	1.53	0.07	0.05	0.53	n.d.	0.44	0.30	2.24	1.53
Al_2O_3	16.67	14.61	21.17	10.16	13.12	16.78	14.30	17.55	17.81	18.98	13.77	18.77	14.32	14.08
Fe_2O_3	1.92	2.32	8.98	2.46	4.76	2.24	2.79	1.15	1.12	1.45	1.71	2.54	6.30	5.67
FeO	5.93	4.09	1.37	5.19	8.99	6.95	2.38	3.51	5.25	3.70	5.00	3.16	10.17	7.11
MnO	0.13	0.06	0.32	0.10	0.11	0.11	0.20	0.22	0.19	0.02	0.10	0.05	0.10	0.05
MgO	13.68	14.73	10.25	11.02	12.30	7.87	15.03	12.33	14.97	11.97	12.89	7.95	6.35	8.66
CaO	15.85	18.04	14.47	14.15	11.94	12.78	13.67	19.02	1.91	13.15	13.39	18.31	12.16	10.88
Na_2O	1.74	2.15	1.63	1.88	2.33	2.27	1.02	0.84	0.96	1.80	3.07	1.24	2.70	3.37
K_2O	0.24	0.77	0.30	--	0.13	0.26	0.05	0.12	0.04	0.08	0.55	0.31	0.66	0.47
P_2O_5	0.10	0.04	0.06	--	0.19	0.18	tr.	tr.	0.03	n.d.	0.13	0.29	0.14	0.15
H_2O^+	2.58	3.48	1.41	0.76	2.26	2.13	1.46	1.61	1.90	2.36	1.83	0.25	2.02	1.43
H_2O^-	0.20	0.02	0.03	0.10	0.03	0.05	--	0.23	0.31	0.65	0.74	0.08	0.44	0.42
	100.18	100.51	100.09	100.36	100.28	100.45	100.39	100.04	100.09	100.16	99.40	99.85	100.28	99.96
or	--	--	0.6	4.2	0.6	1.6	0.6	--	--	--	--	--	--	1.7
lc	0.9	3.6	--	--	--	--	--	0.3	--	5.0	1.3	0.8	2.0	--
ab	--	--	9.8	16.2	9.4	19.4	3.1	--	8.4	5.9	--	--	--	27.0
ne	7.2	9.9	5.4	--	5.4	--	3.2	4.0	--	5.1	14.8	5.7	12.5	1.5
an	38.1	28.9	25.6	19.2	25.1	35.6	34.5	44.5	45.3	43.2	22.3	48.8	25.5	22.2
di	25.6	35.8	28.0	40.7	26.0	22.3	27.1	30.1	13.1	19.5	34.5	34.6	28.9	25.5
wo	--	--	--	--	--	--	--	12.5	--	--	13.0	2.7	11.2	--
cs	5.0	4.0	--	--	--	--	--	7.5	--	--	10.5	2.2	10.5	--
hy	--	--	--	14.9	--	5.5	--	--	8.4	--	--	--	--	--
ol	19.7	13.5	19.7	--	24.1	9.0	26.8	--	22.0	18.9	--	--	--	11.1
mt	2.8	3.5	7.0	3.6	6.5	3.2	3.9	1.5	--	2.1	2.6	3.7	5.3	8.3
il	0.3	0.8	--	1.0	2.7	3.0	--	--	--	--	0.6	0.5	4.4	2.9
ap	0.3	--	0.3	--	0.6	0.6	--	--	--	--	0.3	0.9	0.3	0.3

Krivaja: 1. vein eclogite from the endocontact peridotite; 2. uralitized eclogite, the highest parts of the aureole; 3. corundum pargasite (group 2) schist; 4. hypersthene-garnet amphibolite interlayered into amphibolites of group 3; 5. diopside amphibolite (lower parts of group 3 amphibolites); 6. amphibolite schist (group 4 amphibolites)

Zlatibor: 7. vein eclogite from the endocontact peridotite (Popević, 1974); 8. eclogite from the highest part of the aureole (Marić, 1933): 9. garnet amphibolite (Majer, 1973); 10. corundum amphibolite (Popević and Pamić, 1973)

Borje: 11. pargasite schist from the inner zone; 12. garnet amphibolites from the higher parts of the outer zone; 13. plagioclase eclogite from the outer zone; 14. diopside amphibolite from the outer zone (Pamić and Majer, 1973)

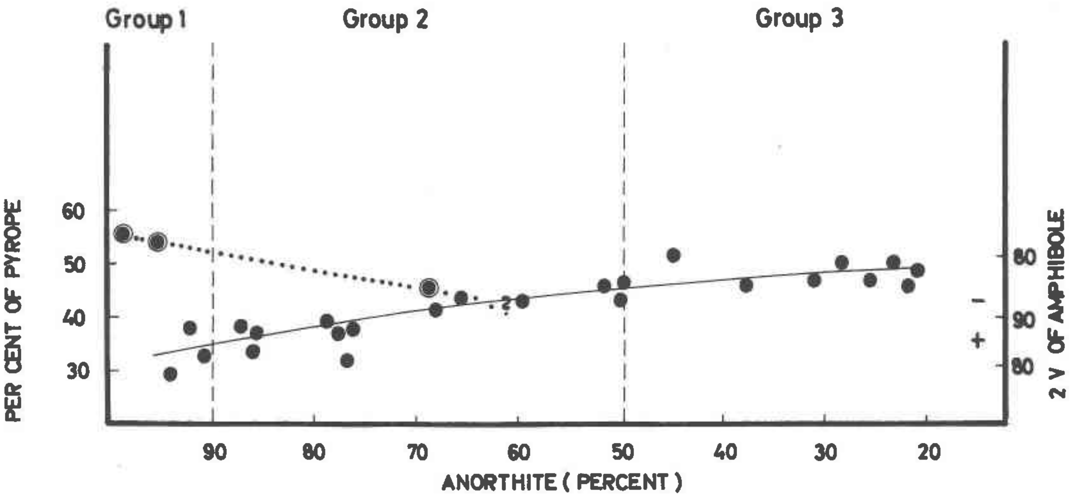

Fig. 3. Relationships between plagioclase composition and edenite-pargasite content shown by variation of axial angle of amphibole, together with partial variation of pyrope content in garnet.

○ = amphibole ⦿ = garnet

from the lower parts has a ratio of about 1. This is accompanied by changes in plagioclase composition from An_{81} to An_{74} going downwards. The outer zone of the aureole consists of garnet-omphacitic diopside amphibolites with eclogite interlayers. Garnet is rich in pyrope (Table 1, anal. 3). Change in plagioclase composition in the outer zone is not as gradational as in the amphibolites of the Krivaja massif, but the plagioclases become more sodic towards the outer parts of the zone. The border of the amphibolite aureole is strongly faulted, and the equivalents of the Krivaja and Zlatibor outer amphibolite zones are not preserved.

Summary

Large ultramafic massifs from the Dinaride Central Ophiolite Zone are frequently bordered by amphibolite aureoles. A distinct zoning can be recognized, which is more pronounced where the ultramafic massifs are less tectonically disturbed. The zoning is best shown in the variation of plagioclase and amphibole compositon. As the plagioclase becomes more sodic, pargasite and edenite components in the amphibole decrease with concurrent decrease of the MgO:FeO ratio.

The data suggest the following sequence:

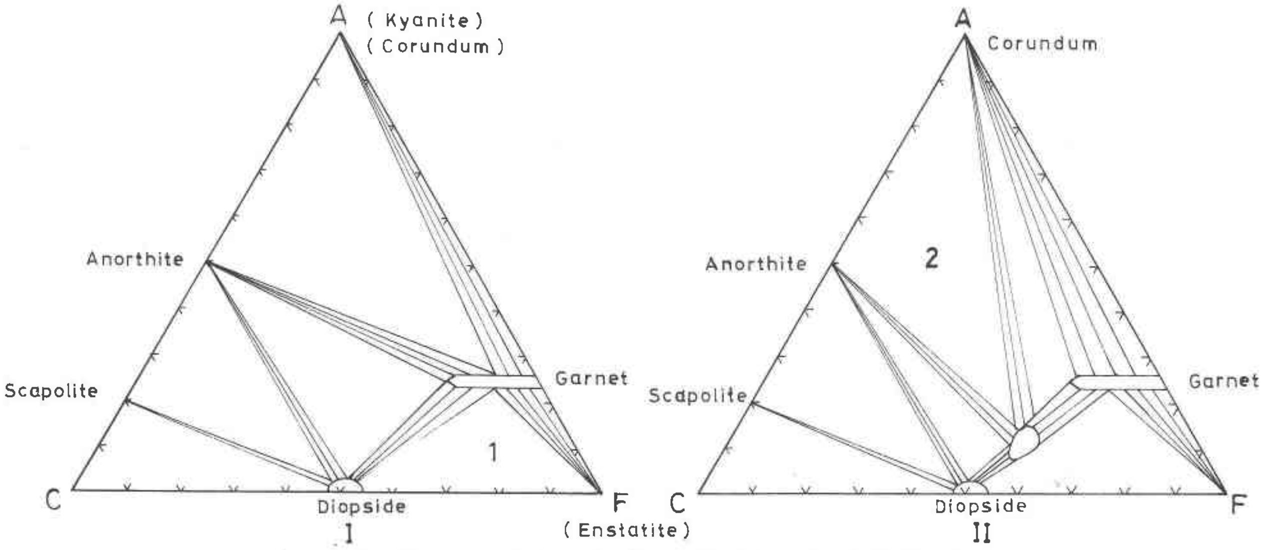

Fig. 4. ACF diagrams for the Dinaride amphibolites of the highest grade.

(1) *Mg-pargasite + anorthite (± diopside ± corundum) rocks* make up the innermost zone from tens to 100–200 meters thick close to the massif. They also occur as very narrow zones within larger amphibolite masses along the very border with the interstratified smaller ultramafic lenses. In both cases they can be interlayered with kaersutite schists.

(2) *Pargasitic hornblende + bytownite–labradorite (±diopside) rocks* are the commonest rocks within the aureoles. The changes in composition both of plagioclase and amphibole are gradational. The middle part of the zone is in some places interlayered with granulite-facies hypersthene–garnet–diopside amphibolites. It is very important to stress that pargasitic amphibolites of this group are the most characteristic rocks of the aureoles associated with the Dinaride ultramafic massifs.

(3) *Green and brown hornblende + andesine–oligoclase (± epidote ± diopside) rocks* constitute the narrow outer envelope of the amphibolite aureoles. The changes both in plagioclase and amphibole compositions continue to be gradational.

Garnet amphibolites and eclogites commonly occur together with the amphibolites of the groups 1 and 2, either as their later equivalents (the Krivaja massif) or as underlying members (the Borje massif). In some places, as for example on the southern border of the Zlatibor massif, the amphibolite aureole consists mostly of garnet amphibolites and eclogites. Pyrope content of garnets going from the vein eclogites into peridotites of the endocontact zone slowly decreases from 57 percent through 53–54 percent in the highest parts of the amphibolite aureoles to 46 percent in hypersthene–garnet–diopside amphibolites interlayered in the middle parts of the group 2 amphibolites.

Interpretation

The mineral assemblages of the amphibolite aureoles and their variation trends can be correlated with recent experimental data. Yoder and Tilley (1962) and Green and Ringwood (1967) indicated that amphiboles are stable up to 1000°C and 10 kbar in basaltic systems. They are not stable at pressures greater than 20 kbar at 1000–1200°C (Ringwood, 1969), and according to Lambert and Wyllie (1968) hornblende breaks down at 17 kbar and yields pyroxene and garnet. Gilbert (1969) indicated that pargasite and edenite are stable at 800–950°C and 20–21 kbar, whereas tschermakite-rich hornblende is stable at 800–900°C and 10–20 kbar. Kushiro (1970) produced pargasite amphibole at 1015°C and 15 kbar, whereas Yoder (1971) obtained clinoamphibole enriched in tschermakite at 10 kbar and 845–910°C. Green (1973) pointed out that amphibole is a hypersolidus mineral in pyrolite with 6 percent H_2O from just below 30 kbar to just below 10 kbar. Mysen and Boettcher (1975) found a large hypersolidus temperature interval of pargasitic hornblende in all compositions; its stability depends on bulk rock composition, and it is commonly marked by the appearance of garnet. However, they found that both pargasite and garnet are in equilibrium with spinel lherzolite at about 900–1000°C and 10–20 kbar.

All available experimental data on the stability of amphibole at high temperature and pressure appears to be in general accord, regardless of differences in starting materials and experimental conditions. The amphiboles with the highest thermal stability are pargasite and edenite, whereas the amphibole rich in tschermakite is stable at lower *P,T* conditions, and this is consistent with the results obtained on the Dinaridic amphiboles.

Experimental data for pyrope–almandine garnets (Yoder, 1955; Boyd and England, 1959; Yoder and Chinner, 1960) are in good agreement with those for amphiboles. It may be estimated that a garnet containing about 50 percent pyrope and 50 percent almandine is stable at 10 kbar and 920°C. It is of particular interest that pyrope-rich garnet was obtained together with pargasite in experiments of Gilbert, Kushiro, and Mysen and Boettcher.

It can be concluded that the mineral assemblages of the Dinaride amphibolites and eclogites associated with alpine-type ultramafics are stable at upper-mantle *P,T* conditions. Structure and texture as well as chemical trends suggest a metamorphic origin. As was mentioned above, the middle parts of the predominant pargasitic amphibolites of group 2 are interlayered with hypersthene–garnet–diopside amphibolites of the granulite facies. This mineral assemblage can be classified as Winkler's fourth group (Winkler, 1970), which is his highest grade. The interlayered pargasitic amphibolites must be of the same grade. It is evident, however, that the overlying parts of the group 2 amphibolites and the amphibolites of group 1 cannot be properly classified in terms of isograds proposed by Winkler. Finally, the comparatively small zone widths in ecologite–amphibolite aureoles make improbable an orthodox regional metamorphic origin.

On the other hand, it is clear that the Dinaridic eclogite–amphibolites cannot represent typical contact-metamorphism aureoles of orthodox intrusive contacts, because of the marked absence of chilled margins in ultramafic rocks, lack of inclusions (xenoliths) of any kind in the peridotites, and dikes of peridotites in the adjacent amphibolites. On the contrary, the peridotites adjacent to amphibolite aureoles are cut by veins of eclogites of the same composition as the eclogite interlayers in the amphibolites.

Low-grade amphibolites and greenschists

Fine-grained diabase and coarse-grained ophitic gabbro form separate bodies intruded into Jurassic graywackes and shales. They are in places entirely unrelated to ultramafic massifs, as for example on the Kozara mountain, but they commonly occur along contacts between ultramafics and Jurassic sediments. The largest bodies are sills about 10 km long and 1–4 km wide. Where not tectonized, the sills are concordant with the adjacent sediments and are rarely rythmically layered parallel to the contacts. The constitutent minerals are commonly plagioclase (labradorite), augite, and amphibole (uralite or green hornblende). Stratigraphically deeper masses are usually ophitic gabbro.

Some of the diabase–gabbro masses along the border of large ultramafic massifs are metamorphosed into amphibolites and greenschists. These amphibolites differ megascopically from the high-grade amphibolites related to peridotites. They have parallel structure, but this is shown only in foliation and lineation and never in banding. These amphibolites have nematoblastic, granoblastic, or fibrous textures, and they do not show folding. The mineralogy and chemistry have not been studied in detail, but the principal minerals are feldspar, amphibole, epidote, chlorite, and relict clinopyroxene. Relics of partly metamorphosed diabase and gabbro are frequently found within the amphibolites. The feldspar composition ranges from andesine to albite, but oligoclase is most frequent. Much of the feldspar has been replaced by clinozoisite, prehnite, and calcite. Relics of primary labradorite can be found in partly metamorphosed diabases with relict ophitic texture. Amphibole is the most abundant mineral. It is more frequently represented by colorless to greenish tremolite–actinolite, in some places with relics of primary augite. Green hornblende with distinct pleochroism in yellow and green is subordinate. Clinozoisite or epidote occurs only in some of the low-grade amphibolites containing green hornblende.

Variation in texture and proportions of minerals produce a wide variety of rocks which range in metamorphic grade from the low-amphibolite through the epidote–amphibolite to the greenschist facies. The rocks of low-amphibolite and epidote–amphibolite facies seem to be preponderant over the rocks of greenschist facies.

Chemical compositions of some low-grade amphibolites are presented in Table 3. These rocks do not show a great variation in chemical composition, and at first glance they appear to be similar in chemistry to the high-grade amphibolites and eclogites. The low-grade amphibolites, however, characteristically have MgO:FeO ratio ≤ 1, whereas in high-grade amphibolites this ratio is ≥ 1. But the fundamental difference in their chemistry is that the low-grade amphibolites are olivine basalts and tholeiites, whereas the high-grade amphibolites are alkalic basalts. Thus the low-grade amphibolites are equivalent to the diabases in their chemistry. In spite of their variety of occurrences, the low-grade amphibolites have never been found as parts of the aureoles con-

Table 3. Chemical composition of some low-grade amphibolites

	1	2	3	4
SiO_2	47.86	46.02	44.53	45.45
TiO_2	1.18	0.65	1.89	1.10
Al_2O_3	16.02	19.58	14.03	15.95
Fe_2O_3	3.41	1.68	3.37	0.97
FeO	6.17	5.43	10.14	7.93
MnO	0.04	0.10	0.17	0.09
MgO	9.19	8.30	8.95	7.36
CaO	11.58	12.56	11.20	11.73
Na_2O	2.29	2.29	3.38	2.60
K_2O	0.29	0.30	0.60	0.24
P_2O_5	0.15	0.03	0.29	0.24
H_2O^+	0.90	3.64	1.44	3.81
CO_2	--	--	--	2.19
H_2O^-	1.01	0.44	0.12	0.25
	100.09	100.58	99.98	99.91
cc	--	--	--	5.0
ap	0.3	--	0.6	0.6
il	2.3	1.4	3.9	2.3
mt	5.1	10.1	4.9	1.4
or	1.7	1.6	3.3	1.7
ab	19.4	19.9	18.3	23.1
an	33.4	43.9	6.2	32.2
di	19.3	16.2	24.2	10.4
hy	14.9	2.6	--	14.1
ol	4.1	4.9	15.8	8.7

1: low-grade amphibolites, Ozren; 2: low-grade amphibolites, Borje; 3: epidote amphibolite schist, Borje; 4: diabase, Krivaja (Karamata and Pamić, 1960).

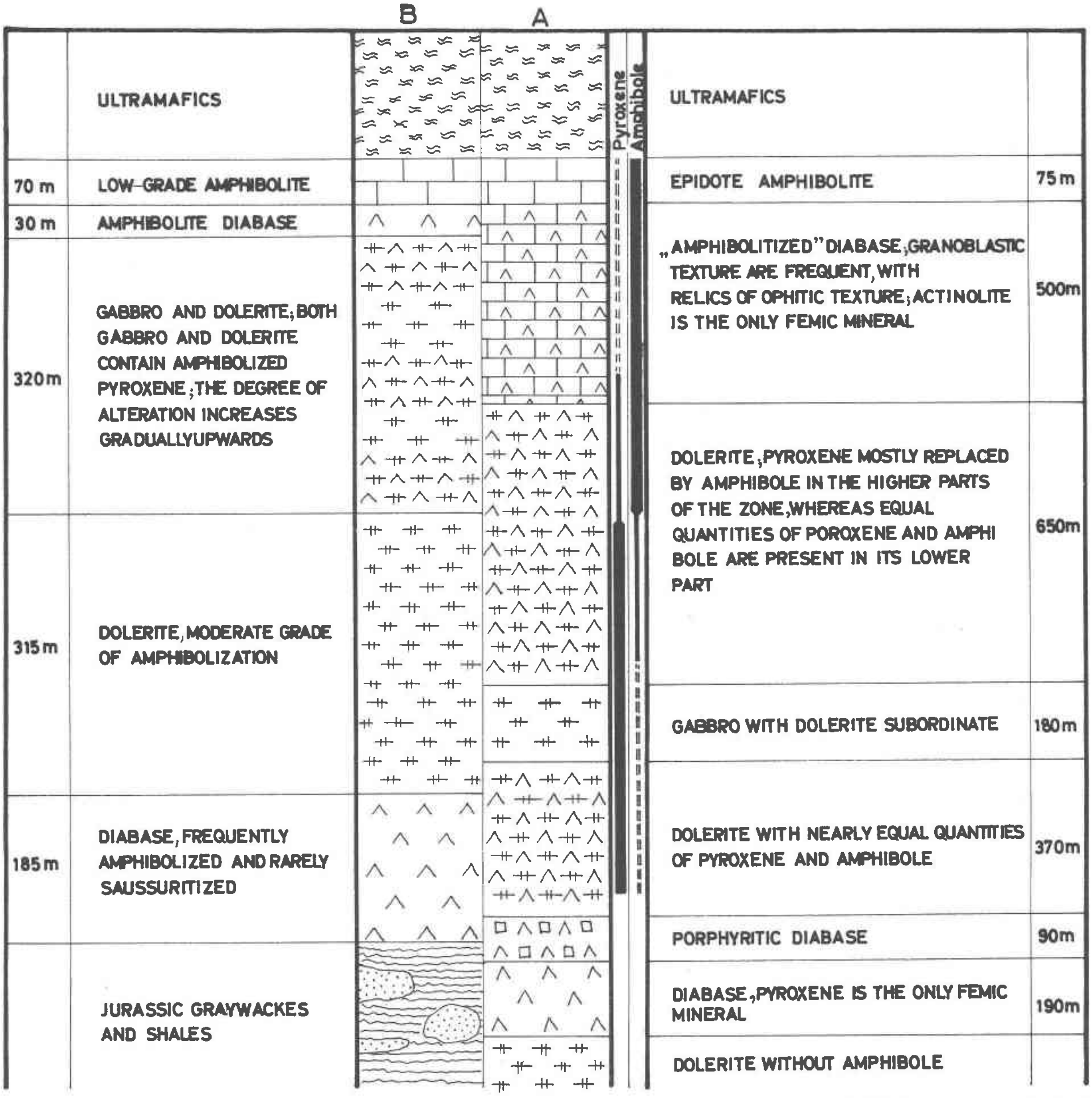

Fig. 5. Columnar sections of dolerite masses grading into low-grade amphibolites. A = higher parts of dolerite mass of Ribnica in the northern border of the Krivaja ultramafic massif; B = the Rakovac dolerite mass near the southern border of the Ozren massif.

sisting of progressively zoned high-grade amphibolites.

The relations between the diabase masses and low-grade amphibolites have not been studied in detail. The gabbro–diabase mass on the southern border of the Ozren ultramafic massif (Fig. 5B) shows increased degree of amphibolitization of clinopyroxene going upwards into the zone of overlying amphibolites capped by the Ozren ultramafic body. The relations within the higher parts of the Ribnica diabase mass from the northern border of the large Krivaja massif are presented in Figure 5A. The degree of amphibolitization is plotted in separate columns, from which it is seen that there is a gradational increase of amphibole relative to clinopyroxene. The "amphibolitized" diabase of the top is overlain by epidote–amphibolite facies rocks in tectonic contact with the adjacent peridotites.

This lower-grade amphibolite sequence is distinctly different from the high-grade amphibolites described above. The former is always genetically related to diabase, whereas the latter are only in tectonic contact with adjacent sediments and spilite and diabase.

Interpretation

The data point to a complex evolution of the Dinaride ultramafic massifs. They are enclosed by various metamorphosed country rocks and some of the amphibolite aureoles around the peridotite massifs show a distinct zonation. As discussed above, the metamorphosed aureoles around the peridotite massifs can be satisfactorily explained neither in terms of orthodox regional metamorphism nor in terms of orthodox intrusive contact metamorphism. The genesis and the evolution of the Dinaridic peridotites can be interpreted by the ideas of plate tectonics (Karamata and Pamić, 1970).

There is no evidence that the Dinaridic peridotites originated along divergent plate margins of the modern mid-ocean ridge type. However, they might have been emplaced somewhere in an area of island arc–marginal basin–continental slope, because they are included within graywackes and shales previously interlayered with spilite and intruded by diabase. Two alternatives are possible. First, it could be presumed that the ophiolite melange was formed and emplaced during subduction. Second, it could be presumed that the subduction was preceded by peridotite accretion along small-scale spreading centers within a marginal basin (Karig, 1971).

Ultramafic diapirs moving upwards along thrust zones beneath island arcs, or continental margins lying on oceanic crust may be of extremely variable heat content. The peridotites might have been intruded as a crystal mush into the uppermost parts of the mantle and into the deepest parts of the oceanic crust, where amphibolite and eclogite were formed. Subducted oceanic crust could be mixed with peridotites by rheomorphic flowage. Afterwards, the newly formed amphibolites and the peridotites might have moved to higher levels, and this can be accompanied by metamorphism at lower P,T conditions, by retrogradation of the earlier-formed high-grade amphibolites and partial serpentinization of peridotites.

The temperature of overthrusting ultramafic masses decreased as they moved upwards along very deep abyssal faults, and the igneous emplacement mechanism may have changed. The final dismembering may have ended emplacement of solid blocks. In this way metamorphic effects in country rocks of such masses could range from strong thermal with strong dynamic influence to strong dynamic with little or no thermal effects (Karamata and Pamić, 1970).

Separate phases during long and complex evolution of ultramafics can be determined, because the aureole rocks can be explored in the context of a plate tectonics model (Williams and Smith, 1973). The first phases of the Dinaride peridotite evolution occurred in the upper mantle, where they must have contained at this temperature a small quantity of fluid phases, *i.e.*, they might have represented a crystal mush. Karamata (1968) presented some evidence for the emplacement of peridotites in the form of a crystal mush. But the compositional differences within the amphibolite aureoles suggest that the connection of ultramafics with the amphibolites occurred under variable P,T conditions within the upper mantle itself.

The high-grade amphibolites and eclogites may have formed in the upper mantle by the direct crystallization of a basalt liquid enriched in water (Yoder and Tilley, 1962; Green and Ringwood, 1967). This presumption is more plausible, because Dinaridic amphibolites have the chemical composition of alkalic basalt, and they cannot be correlated either with the adjacent gabbro or with diabase. However, the alkalic character of the high-grade amphibolites might have also resulted from metasomatic processes. The high-grade amphibolites, despite their origin, might have been transported towards the surface along with ultramafic diapirs. Fairly narrow zones of low-amphibolite and epidote–amphibolite facies rocks within the aureoles might have resulted from changeable velocities of the upward-moving diapirs or even their temporary arrest in higher levels.

The Dinaridic high-grade amphibolites associated with alpine-type peridotites, despite their origin, are characteristically pargasitic in composition. Alternating bands of high-grade amphibolites and alpine peridotites are evidence (Fig. 6) that their mineral assemblages were equilibrated under the same P,T conditions, and that they together underwent deep-seated metamorphism. Although sufficient attention has not been paid to the high-grade amphibolites and their mineralogy, they have been reported from some ophiolite belts, as for example from the Alps (Vogt, 1962), from the Urals (Morkovkina, 1967), and from Tinaquille, Venezuela (MacKenzie, 1960). Pargasite is characteristically present as a byproduct in all experiments carried out under high pressures with the natural lherzolite (Kushiro, 1970; Mysen and Boettcher, 1975). On the other hand, amphibolite-facies rocks are common on the ocean floors (Miyashiro, 1972), and the presence of pargasitic amphibolites on the ocean floor has been reported (Kašincev, 1973).

It can also be concluded that the high-grade parga-

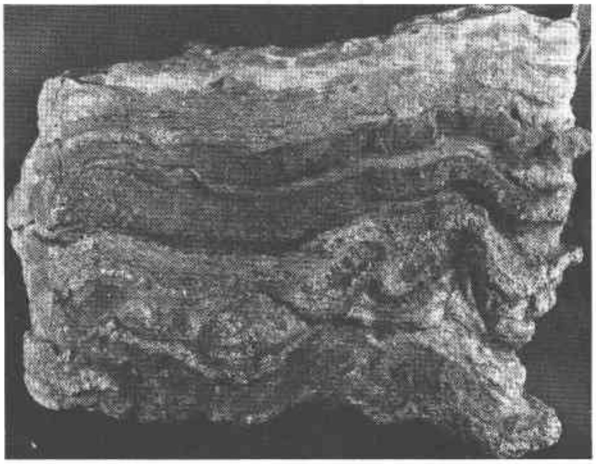

Fig. 6. Layered and interfolded high-grade amphibolites and peridotites; darker bands are amphibolites, and lighter bands are various ultramafic rocks.

sitic amphibolites with eclogites represent typical products of metamorphic processes in the upper mantle. Taking into account the experimental data, P,T conditions for pargasite can be estimated at about 1000°C and more than 10–20 kbar. Using Raheim and Green (1975) K_D diagrams as a function of pressure and temperature for coexisting garnet and clinopyroxene, the stability of pyrope garnet from the vein eclogite of the endocontact zone of the Zlatibor ultramafic massif is about 17–18 kbar and 920°C.

As to the low-grade amphibolites, it can be presumed that during the formation of melange some parts of sediments with spilite and diabase were subducted along large reverse faults and were metamorphosed by ultramafic diapirs under stress conditions. Depending on the depth of subduction, difference in composition, thermal capacity of ultramafic diapirs, and velocities of their movements, various metamorphic products can be expected.

Subducted diabases were metamorphosed into epidote amphibolites and greenschists at 400–500°C and at 5 kbar less (Miyashiro, 1972). It can be presumed that metamorphism was caused by ultramafic diapirs with lower thermal capacity, especially in places where only greenschists occur without epidote amphibolites.

This medium to low pressure metamorphism must have operated under strong dynamic influence, indicated by comparatively narrow zones of very different mineral composition. This is quite conceivable, because at higher levels ultramafic diapirs represented solid and heated blocks without fluid phases. Depths of subduction must have been comparatively small and thermal gradients high, as indicated by the characteristic absence of glaucophane schists.

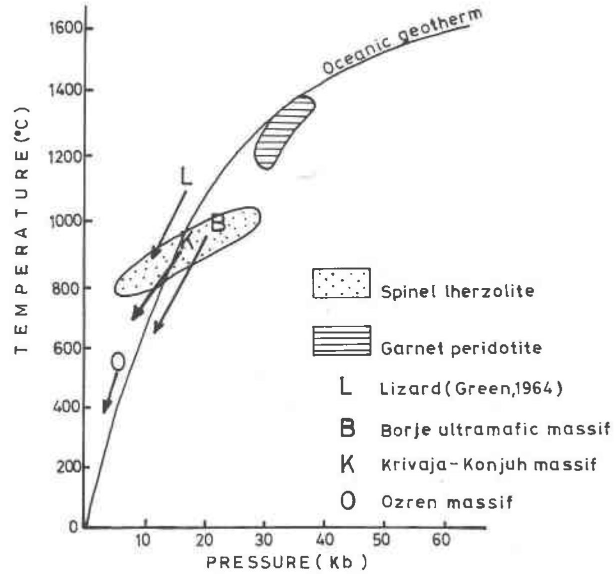

Fig. 7. Interpreted conditions of formation of various contact-metamorphosed sequences around some of the Dinaride ultramafic massifs according to MacGregor (1974).

Final stages of subduction processes and subsequent tectonic movements increased the degree of dismembering and resulted in the common occurrence of metamorphic blocks formed at extremely variable P,T conditions within the chaos of melange.

Acknowledgments

The author is indebted to Dr. I. D. MacGregor and Dr. W. G. Ernst of the University of California, to Dr. T. P. Thayer of the U. S. Geological Survey, and to Dr. F. R. Boyd of the Geophysical Laboratory for critical reading of a draft of the manuscript.

References

Boyd, F. R. and J. England (1959) Pyrope. *Carnegie Inst. Wash. Year Book, 58,* 83–87.

Dimitrijević, M. D. and M. N. Dimitrijević (1973) Olistostrome mélange in the Yugoslavian Dinarides and late Mesozoic plate tectonics. *J. Geol., 81,* 328–340.

Gilbert, M. C. (1969) Reconnaissance study of the stability of amphiboles at high pressure. *Carnegie Inst. Wash. Year Book, 68,* 167–171.

Green, D. H. (1973) Contrasting melting relations in a pyrolite upper mantle under mid-oceanic ridge, stable crust and island arc environment. *Tectonophysics, 17,* 285–297.

——— and A. E. Ringwood (1967) The genesis of basaltic magmas. *Contrib. Mineral. Petrol., 15,* 103–190.

Karamata, S. (1968) Zonality in contact metamorphic rocks around the ultramafic mass of Brezovica (Serbia, Yugoslavia). *Congr. Geol. Int., 23rd Sess., Prague, 1,* 197–208.

——— and J. Pamić (1970) Some considerations about the genesis of alpine ultramafites of the Dinarides. *7th Congr. Geol. SFRY, Zagreb, 2,* 139–156.

Karig, D. A. (1971) Origin and development of marginal basins in the western Pacific. *J. Geophys. Res., 76,* 2542–2561.

Kašincev, G. L. (1973) Novie dannie ob izveržennih i metamorfic českih porodah severo-vostočnoj časti Indijskogo okeana. *Okeanologija, 13,* 848–851.

Kushiro, I. (1970) Stability of amphibole and phlogopite in the upper mantle. *Carnegie Inst. Wash. Year Book, 68,* 245–247.

Lambert, I. B. and P. J. Wyllie (1968) Stability of hornblende and a model for the low velocity zone. *Nature, 219,* 1240–1241.

Lanphere, M. A., R. G. Coleman, S. Karamata and J. Pamić (1975) Age of amphibolites associated with alpine peridotites in the Dinaride Ophiolite Zone, Yugoslavia. *Earth and Planet. Sci. Lett., 26,* 271–276.

MacGregor, I. D. (1974) The system MgO–Al_2O_3–SiO_2: solubility of Al_2O_3 in enstatite for spinel and garnet peridotite composition. *Am. Mineral., 59,* 110–119.

MacKenzie, D. B. (1960) High-temperature alpine-type peridotite from Venezuela. *Geol. Soc. Am. Bull., 71,* 303–317.

Majer, V. (1972) Granatski hornblendit kod Bistrice na Limu (Srbija, Jugoslavija). *Geol. glas., 16,* 133–136.

Marić, L. (1933) Geološka proučavanja Stare Raške-Prilog petrografiji Stare Raške. *Glas. Srp. Kralj. Akad. Nauka, 158,* 147–187.

Marković, B., i L. Takač (1958) Postanak amfibolita na obodu zlatiborskog masiva i njihov snačaj za tektoniku ove oblasti. *Zbor. rad. Geol. inst. Jovan Žujović, SANU, 10,* 105–118.

Milovanović, B. and M. Mladenović (1968) On some results of geophysical and geological research in the ophiolite zone of the inner Dinarides. *Bull. Geol. Geophys. Res., 24–25,* 7–23.

Miyashiro, A. (1972) Pressure and temperature conditions and tectonic significance of regional and ocean-floor metamorphism. *Tectonophysics, 14,* 141–159.

Mysen, B. and A. L. Boettcher (1975) Melting of a hydrous mantle: I. Phase relations of natural peridotite at high pressures and temperatures with controlled activity of water, carbon dioxide and hydrogen. *J. Petrol., 16,* 520–548.

Morkovkina, V. F. (1967) *Gabbro–peridotitovaja formacija Urala.* Izdatelstvo Nauka, Moskva.

Pamić, J. J. (1972) Metamorphic grade of the Jurassic magmatic-sedimentary (Diabas-Hornstein) formation of the Dinaride Ophiolite Zone. *Bull. Sci. Yugosl. Acad. Sci. Arts, 17,* 151–152.

——— (1971a) Some petrological features of Bosnian gabbro–peridotite complex in the Dinaride zone of Yugoslavia. *Tschermaks Mineral. Petrogr. Mitt., 15,* 14–42.

——— (1971b) Amphibolites associated with the large Krivaja-Konjuh ultramafic massif (Yugoslavia). *Bull. Sci., 16,* 3–4.

——— and V. Majer (1973) Eklogiti i amfiboliti Crnog potoka na južnom obodu borjanskog ultramafitskog masiva. *Geol. glas., 17,* 152–165.

———, S. Šćavničar and S. Medjimurec (1973) Mineral assemblages of amphibolites associated with alpine-type ultramafics in the Dinaride Ophiolite Zone. *J. Petrol., 14,* 133–157.

———, O. Sunarić-Pamić, J. Olujić and R. Antić (1975) Petrografija i petrologija krivajsko-konjuškog ofiolitskog kompleksa. *Acta geol. Yugosl. Acad. Sci.,* in press.

Pavlović, S. (1937) Les roches de Zlatibor (Yugoslavie) et leur relations avec les formations cristallophylliennes et sedimentaires environnantes. *Bull. Soc. fr. Mineral., 60,* 5–137.

Popević, Al. (1974) Žilni eklogit Bistrice. 8th Congr. geol. Soc. Fed. Repub. Yugosl., Bled, in press.

——— and J. Pamič (1973) Korund amifbolitski škriljci u amifbolitima Bistrice na južnom obodu zlatiborskog ultramafitskog masiva. *Glas. Prir. muz. srp. zem., A, 28,* 31–39.

Raheim, A. and D. H. Green (1975) *P,T* paths of natural eclogites during metamorphism—a record of subduction. *Lithos, 8,* 317–328.

Roksandić, M. M. (1971/72) Geotektonski položaj i oblik velikih peridotitskih masiva Dinarida u svetlosti geofizickih podataka. *Zav. geol. geofiz. istr.,* 139–147.

Ringwood, A. E. (1969) Composition and evolution of the upper mantle. *Am. Geophys. Union Monogr., 13,* 1–17.

Thayer, T. P. (1960) Some critical differences between alpine-type and stratiform peridotite–gabbro complexes. *21st Int. Geol. Congr., 13,* 247–259.

Tišljar, J. (1973) Kvantitativni petrološki studij sedimenata "flišne serije" i jurske vulkanogeno-sedimentne formacije Borovičkog potoka u sjevernom krilu vareškog antiklinorijuma. *Geol. glas., 17,* 250–301.

Vogt, P. (1962) Geologisch–petrographische Untersuchungen in Peridotitstock von Finero. *Schweiz. Mineral. Petrogr. Mitt., 42,* 59–126.

Williams, H. and W. R. Smith (1973) Metamorphic aureoles beneath ophiolite suites and alpine peridotites: tectonic implications and west Newfoundland examples. *Am. J. Sci., 273,* 594–621.

Winkler, H. G. (1970) Abolition of metamorphic facies, introduction of the four divisions of metamorphic stage, and of a classification based on isograds in common rocks. *Neues Jahrb. Mineral., 5,* 189–248.

Yoder, H. S. (1955) Role of water in metamorphism. *Geol. Soc. Am. Spec. Pap., 62,* 505–524.

——— (1971) The join diopside–pyrope–H_2O at 10 kbar: its bearing on the melting of peridotite, the ACF metamorphic facies, and the gedrite–hornblende miscibility. *Carnegie Inst. Wash. Year Book, 69,* 176–181.

——— and G. A. Chinner (1960) Almandite–pyrope–water system at 10,000 bars. *Carnegie Inst. Wash. Year Book, 59,* 81–84.

——— and C. E. Tilley (1962) Origin of basalt magmas: an experimental study of natural and synthetic rock systems. *J. Petrol., 3,* 342–532.

Manuscript received, June 4, 1976; accepted for publication, February 8, 1977.