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The Sudetic ophiolite: current view on its geodynamic model*

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Newly acquired geochemical data on the geochemistry of rodingites and amphibolites from ultrabasic massifs adjacent to Góry Sowie block combined with other available data in the literature, show that Sudetic ophiolite can be interpreted as "surviving" fragment of obducted rock series previously formed in MOR regime and overthrusted onto Góry Sowie block.

INTRODUCTION

The objective of this paper is to present new interpretation of geodynamic position of the Sudetic ophiolite. To attain this objective the relationship between mineralogy, petrography, untrace element geochemistry, and structural setting of different rocks: ultramafic rocks and serpentinites, gabbros and metabasites as well as rodingites (metasomatic by-products of serpentinization) and amphibolite dykes from serpentinite massifs adjacent to the Góry Sowie block was used for unravelling the geodynamic environment of the ophiolite.

GEOLOGY

The Sudetes are situated at the northeastern border of the Bohemian Massif, being the eastern part of the Variscan orogen in Europe (Fig. 1).

There are two general geotectonic models of the Sudetes, both arised from extreme contrasts of petrology and ages of individual bodies: (1) a model based on the conviction that the Sudetes stemmed as eastern continuation of Saxothuringian and Moldanubian units due to strike-slip displacement and Early Carboniferous uplift, hence the Sudetes and their foreland represent a part of Variscan orogen (W. Franke *et al.*, 1993); (2) the terrane concept, with boundaries reflecting Caledonian plate boundaries followed by subsequent (Variscan or Silurian) plate interaction (G. J. H. Oliver *et al.*, 1993; Z. Cymerman, M. A. J. Piasecki, 1994); according to this opinion the Góry Sowie unit together with neighbouring oceanic remnants are regarded as the Central Sudetian Terrane (Z. Cymerman, M. A. J. Piasecki, *op. cit.*).

The Góry Sowie block is one of the most extensive geological units of the Sudetes. It is composed of gneisses and migmatite gneisses, with minor granulites, serpentinites, ultrabasic rocks, amphibolites, and calc-silicate rocks. The Góry Sowie block is considered as Proterozoic or Late Riphean according to H. Dziedzic (1985), Cadomian? (Z. Cymerman, 1990). Z. Cymerman (*op. cit.*) suggested that the Góry Sowie block was a fragment detached from the Bohemian Massif, during obduction and wedging of the ophiolite sequence on the periphery of the Bohemian Massif. Major

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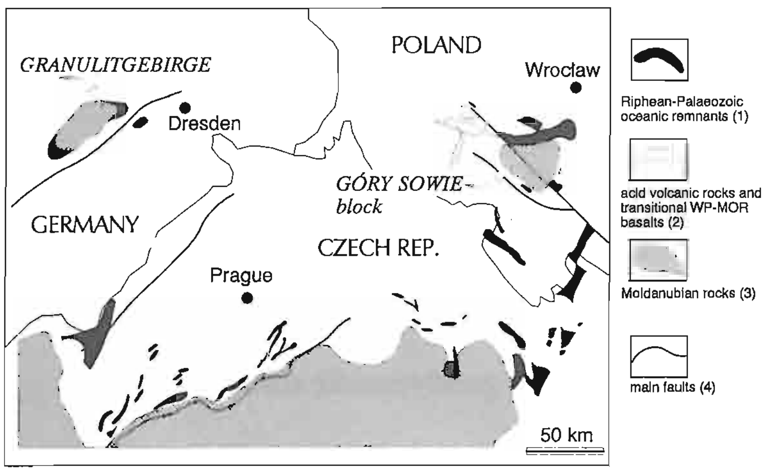

Fig. 1. Schematic geological sketch of mafic-ultramafic rock sequences in Saxothuringian zone (compiled after Z. Mísař, 1985; W. Narębski, A. Majerowicz, 1985; W. Franke *et al.*, 1993)

Schematyczny szkic geologiczny występowania skał maficznych i ultramaficznych w strefie saksońsko-turyngskiej (zestawiony na podstawie Z. Mísařa, 1985; W. Narębskiego, A. Majerowicza, 1985; W. Frankego i in., 1993)

1 — paleozoiczne i ryfejskie pozostałości struktur oceanicznuch, 2 — kwaśne skały wulkaniczne i bazalty o charakterze przejściowym WP-MOR (bazalty wewnątrzpłytowe-bazalty grzbietów środkowooceanicznych, 3 — skały Moldanubiku, 4 — główne uskoki

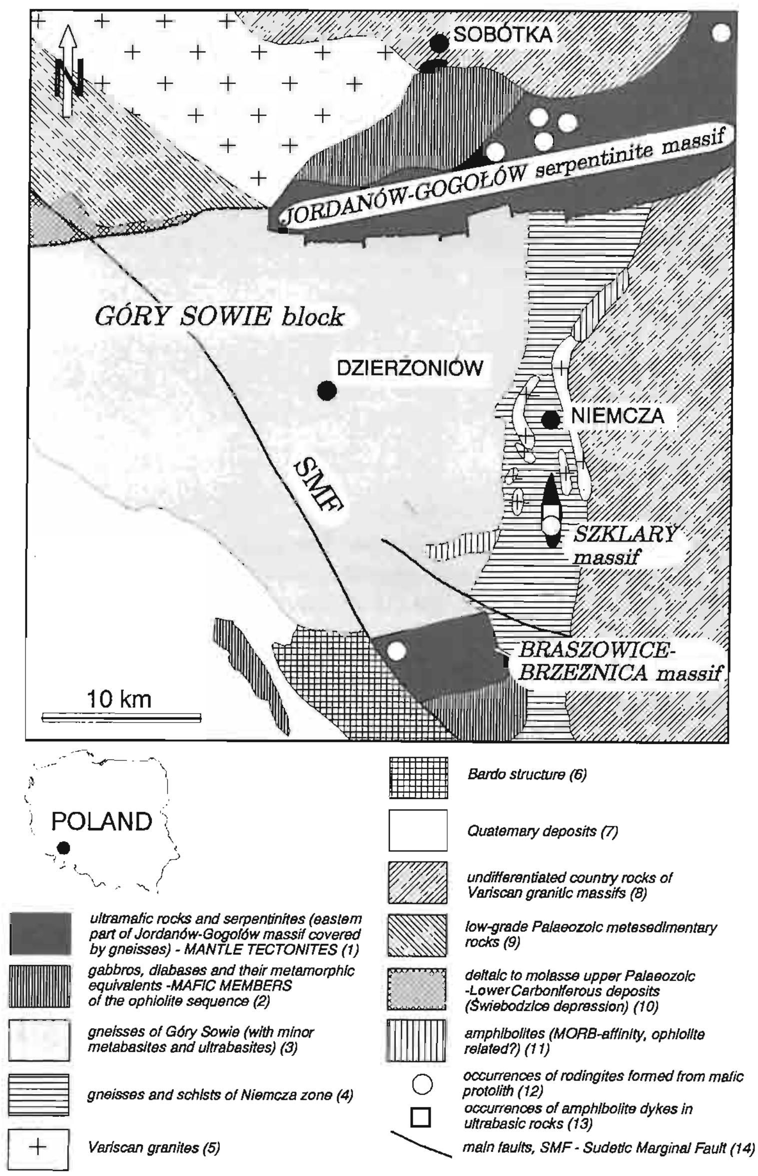

Fig. 2. Simplified geological sketch map of the ultrabasic and basic massifs around Góry Sowie block (after C. Pin *et al.*, 1988, modified)

Uproszczona mapa geologiczna rozmieszczenia masywów ultrazasadowych i zasadowych wokół bloku Gór Sowich (według C. Pina i in., 1988, zmieniona)

1 — skały ultramaficzne i serpentynity (wschodnia część masywu Jordanowa-Gogołowa przykryta gnejsami) — poziom tektonitów płaszczowych, 2 — gabra, diabazy i ich odpowiedniki metamorficzne — człony maficzne sekwencji ofiolitowej, 3 — gnejsy Gór Sowich (z podrzędnymi wystąpieniami zmetamorfizowanych skał zasadowych i ultrazasadowych), 4 — gnejsy i łupki strefy Niemczy, 5 — granity waryscyjskie, 6 — struktura Barda, 7 — osady czwartorzędowe, 8 — różne skały otaczające masywy granitów waryscyjskich, 9 — paleozoiczne skały osadowe słabo zmetamorfizowane, 10 — osady deltowe i molasowe górnego paleozoiku — dolnego karbonu (depresja Świebodzic), 11 — amfibolity o pokrewieństwie MORB (bazalty grzbietów środkowooceanicznych), być może związane genetycznie z ofiolitem, 12 — wystąpienia rodingitów powstałych z protolitu maficznego, 13 — wystąpienia dajek amfibolitowych w skałach ultrazasadowych, 14 — główne uskoki, SMF — sudecki uskok brzeżny

deformation and low-pressure metamorphic events recorded in the Góry Sowie block took place during Late Devonian (A. Żelaźniewicz, 1987) and are attributed to the emplacement of Variscan magmas (H. Dziedzic, 1985).

Small bodies of ultramafic rocks (spinel lherzolites and pyrope lherzolites) and serpentinites commonly occur within gneisses of the Góry Sowie block. Timing of garnet growth in Góry Sowie peridotites was evaluated at about 400 Ma and it is considered as age of emplacement of the peridotites into granulites (H. K. Brueckner *et al.*, 1996). The ultrabasic bodies within Góry Sowie gneisses frequently contain metamorphic assemblage: brucite, talc, tremolite, anthophyllite, cummingtonite and phlogopite (P. Gunia, 1994; P. Gunia, J. Szczepański, 1994; E. Dubińska, A. Żelaźniewicz, unpubl. data). The age of metamorphic events that affected the ultrabasic rocks and their relation to Góry Sowie gneisses metamorphism is still unknown.

Góry Sowie unit also comprises numereous mafic inclusions, frequently amphibolites. Part of amphibolites derived from tholeiites and showed N-MORB (normal mid-ocean ridge basalts) — to E-MORB (enriched mid-ocean ridge basalts) — affinity (H. Dziedzic, 1995). According to J. A. Winchester *et al.* (in press) metabasites from Góry Sowie block can be considered as formed from either oceanic (N-MORB affinity) and continental protolith; some of them represent Ti- and REE-poor variety. Their contacts with Góry Sowie gneisses are generally obscured (A. Żelaźniewicz, pers. inf.).

The peridotites and serpentinites adjacent to the Góry Sowie (Fig. 2) are considered as the lower part (mantle tectonites) of the dismembered ophiolitic suite (A. Majerowicz, 1979; W. Narębski *et al.*, 1982; P. Gunia, 1992; W. Narębski, A. Majerowicz, 1985), and as of Palaeozoic age (about 350 Ma according to C. Pin *et al.*, 1988, about 420 Ma after G. J. H. Oliver *et al.*, 1993). Taking into account the results of H. K. Brueckner *et al.* (1991) the age of ca. 350 Ma can be tentatively regarded as related to a metamorphic episode.

The Sudetic ophiolite sequence comprises mafic section of variable geochemical characteristics: gabbros and metagabbros, with minor sheeted dykes, have N-MORB geochemical affinity (C. Pin *et al.*, 1988; A. Majerowicz, M. Mierzejewski, 1995). Origin of other metaigneous rocks, located west of Góry Sowie block (western part of Polish Sudetes) is disputable. According to W. Narębski *et al.* (1986) they show affinity to both ocean floor tholeiites and island arc tholeiites and are believed to be displaced fragments of the same ophiolite sequence. H. Furnes *et al.* (1989, 1994) considered this rock series as tholeiite-alkaline transitional sequence ranging from rhyodacitic lavas formed by crustal melting to E- and N-MORB metabasalts. J. A. Winchester *et al.* (1995) interpreted Palaeozoic metaigneous rocks located west of Góry Sowie block (western part of Polish Sudetes, about 500 Ma according to G. J. H. Oliver *et al.*, 1993), as formed in intracratonic rift floored by oceanic crust.

The Variscan granites situated east of Góry Sowie block, within Niemcza zone, are dated as 340 Ma (G. J. H. Oliver *et al.*, 1993) and they unquestionably record a continental episode of the geological evolution.

Extensive Hercynian deformation tectonically dismembered the ophiolite. Thus, detailed structural studies are difficult; as a result there are only rough evaluation of its original structure, e.g., the Góry Sowie block was regarded as a nappe emplaced in Carboniferous time (C. Pin *et al.*, 1988), displaced to the north over upthrusting slices of oceanic crust into a continental environment (Z. Cymerman, 1990). However, ultramafic rocks and their metamorphic equivalents from circum-Góry Sowie ultrabasic massifs show only negligible penetrative deformation textures (E. Dubińska, 1995; A. Żelaźniewicz, 1995), which should be expected beneath the overlying Góry Sowie block.

ULTRABASIC ROCKS

Three ultrabasic massifs are located close to the Góry Sowie block (Fig. 2):

— Jordanów–Gogołów serpentinite massif (the largest, adjacent to the northern border of the Góry Sowie block),

Table 1

Ultramafic rocks, serpentinites, and products of their metamorphism and alteration (ultrabasic massifs surrounding Góry Sowie block)

Ultramafic rocks	Serpentinites	Products of serpentinite metamorphism and alteration
Jordanów–Gogołów serpentinite massif		
Harzburgite, minor lherzolite, dunite and wehrlite	pseudomorphic lizardite-chrysotile serpentinites grading into antigoritic serpentinite; chrysotile veins and asbestos; mylonitic serpentinite; rosette lizardite serpentinite; scarce foliated serpentinites, wild distribution within Jordanów–Gogołów massif	chlorite-talc-phlogopite (often altered to different interstratified minerals) ± amphibole (tremolite to pargasite) zones adjacent to apophyses of Variscan granitoids; carbonate (up to listwaenites) and silica veins and impregnations; scarce weathered pockets containing smectite
Braszowice–Brzeźnica massif		
Harzburgite, lherzolite	antigoritic serpentinites; pseudomorphic serpentinites; rosette serpentinites; serpentinite breccias and mylonites	serpentinites locally overprinted by talc and tremolite; carbonate (up to listwaenites) and silica veins and impregnations
Szklary massif		
Harzburgite, wehrlite, clinopyroxenite	antigorit serpentinites; minor pseudomorphic serpentinites; chrysotile asbestos	serpentinites usually overprinted by chlorite and tremolite ± talc ± anthophyllite; chlorite-tremolite-talc schists in shear zones; chlorite-talc-phlogopite (completely altered to intermediate chlorite-vermiculite) ± tremolite ± anthophyllite zones adjacent to apophyses of Variscan granitoids; carbonate and silica veins and impregnations (up to birbirites); rocks highly, although irregularly, weathered

After: E. Dubińska (1982*a*, 1995); E. Dubińska, A. Wiewióra (1988); E. Dubińska *et al.* (1995); P. Gunia (1987,1992); J. Jelitto *et al.* (1993); M. Juskowiak (1957); I. Kossowska, S. Maciejewski (1994); A. Majerowicz, C. Pin (1994); J. Niśkiewicz (1967); A. Szymkowiak (1981) and unpubl. data

Table 2

Representative whole-rock compositions of ultrabasic rocks from massifs adjacent to Góry Sowie block

Component weight %	Jordanów-Gogołów massif			Szklary massif			Braszowice-Brzeźnica massif		
	7N[1]	3W[1]	Gol*[2]	30/227*[3]	28/133*[3]	6/315a*[3]	29/1N[3]	3/37ING[3]	8/40N[3]
SiO_2	40.18	39.62	45.42	39.79	37.48	37.79	39.70	38.17	39.70
TiO_2	0.08	0.12	-	0.05	0.10	0.10	0.02	0.12	0.01
Al_2O_3	0.76	1.69	0.95	2.28	1.66	1.98	1.33	0.61	1.09
Fe_2O_3	5.71	4.30	8.12	7.00	8.26	7.86	6.25	8.28	3.86
Cr_2O_3	0.42	0.48	0.37	0.37	0.42	0.37	0.27	0.26	0.26
FeO	1.41	2.50					2.03	1.64	4.87
MnO	0.07	0.15	0.13	0.07	0.11	0.13	0.07	0.09	0.14
MgO	38.52	41.10	43.65	33.83	38.12	37.03	39.10	36.23	43.70
NiO	0.37	0.38	0.29	0.29	0.33	0.34	0.24	0.22	0.27
CaO	0.46	0.53	0.83	0.85	1.31	0.94	0.30	1.46	0.30
Na_2O	0.10	0.06	0.10	0.70	0.22	1.06	0.30	0.04	0.30
K_2O	0.04	0.03	0.08	0.15	0.16	0.22	0.01	0.04	0.01
Ign. loss	12.22	9.28			9.70	12.17	10.63	10.v68	5.37
Total	100.56	100.50	99.94	100.21	97.87	99.99	100.25	98.79	100.18
Ign. loss			8.88	12.96					

*Total iron as Fe_2O_3; [1]after E. L. Metwally (1995); [2]after E. Dubińska *et al.* (1995); [3]after P. Gunia (unpubl. data); 7N, 3W, Gol, 30/227, 28/133, 6/315a, 29/1N, 3/37ING, 8/40N — sample numbers

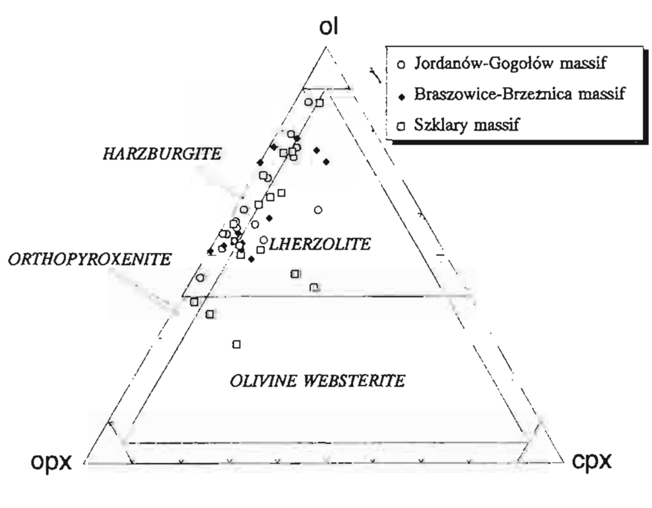

Fig. 3. CIPW normative compositions of ultrabasic rocks from massifs adjacent to Góry Sowie block; the sources of the data are following: P. Gunia (1992 and unpubl. data); A. Majerowicz, C. Pin (1994); E. Dubińska *et al.* (1995); E. Dubińska (unpubl. data); I. Kossowska, A. Maciejewski (1994); E. L. Metwally (1995)

Skład normatywny CIPW skał ultrazasadowych z masywów przyległych do bloku Gór Sowich; analizy pochodzą z następujących źródeł: P. Gunia (1992 i dane niepubl.); A. Majerowicz, C. Pin (1994); E. Dubińska i in. (1995); E. Dubińska (dane niepubl.); I. Kossowska, A. Maciejewski (1994); E. L. Metwally (1995)

— Braszowice–Brzeźnica massif (situated close to the southern apex of the Góry Sowie block),

— Szklary massif (eastern border of the Góry Sowie block, within Niemcza dislocation zone, close to tectonic border interpreted as terrane suture zone by Z. Cymerman and M. A. J. Piasecki, 1994).

The serpentinite massifs seem to display tectonic contacts with adjacent geological structures (Góry Sowie block, Variscan granitoids, Niemcza zone, A. Majerowicz, 1963, 1979; J. Niśkiewicz, 1993; A. Żelaźniewicz, 1995). Late Variscan granite-type apophyses locally invaded serpentinites and produced metasomatic-thermal contact zones reported from Jordanów–Gogołów and Szklary massifs. Contact schists between serpentinites and Variscan hybridal granitoid apophyses are composed of phlogopite and chlorite, and their various alteration products (e.g. vermiculite, smectite, different interstratified minerals), plus disseminated tremolite-to-pargasite amphiboles, and minor apatite (Tab.1; e.g., E. Dubińska, 1982*b*; A. Wiewióra, E. Dubińska, 1987; E. Dubińska, A. Wiewióra, 1988; J. Jelitto *et al.*, 1993; E. Dubińska *et al.*, 1995; J. Janeczek, M. Sachanbiński, 1995).

Mantle tectonites. Unaltered ultramafic rocks are scarce and irregularly distributed, while totally serpentinized rocks are common, e.g. Jordanów–Gogołów massif is extremely poor in untouched ultramafic rocks.

Despite heavy serpentinization the ultramafic rocks frequently represent porphyroclastic mantle tectonite textures with kink-banded porphyroclasts of pyroxenes, surrounded

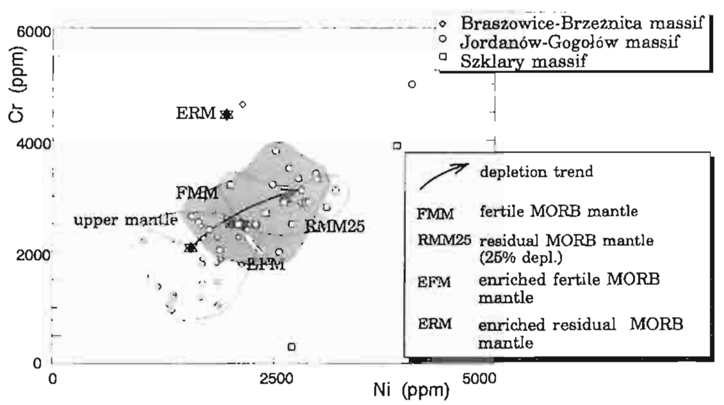

Fig. 4. Distribution of ultrabasic rocks from massifs adjacent to Góry Sowie block on Ni *vs* Cr diagram; compositions of upper mantle, EFM, ERM, FMM, and RMM25 according to J. A. Pearce, I. J. Parkinson (1993)

Diagram zawartości Ni *vs* Cr w skałach ultrazasadowych z masywów przylegających do bloku Gór Sowich; skład górnego płaszcza, EFM, ERM, FMM oraz RMM25 według J. A. Pearce'a, I. J. Parkinsona (1993)

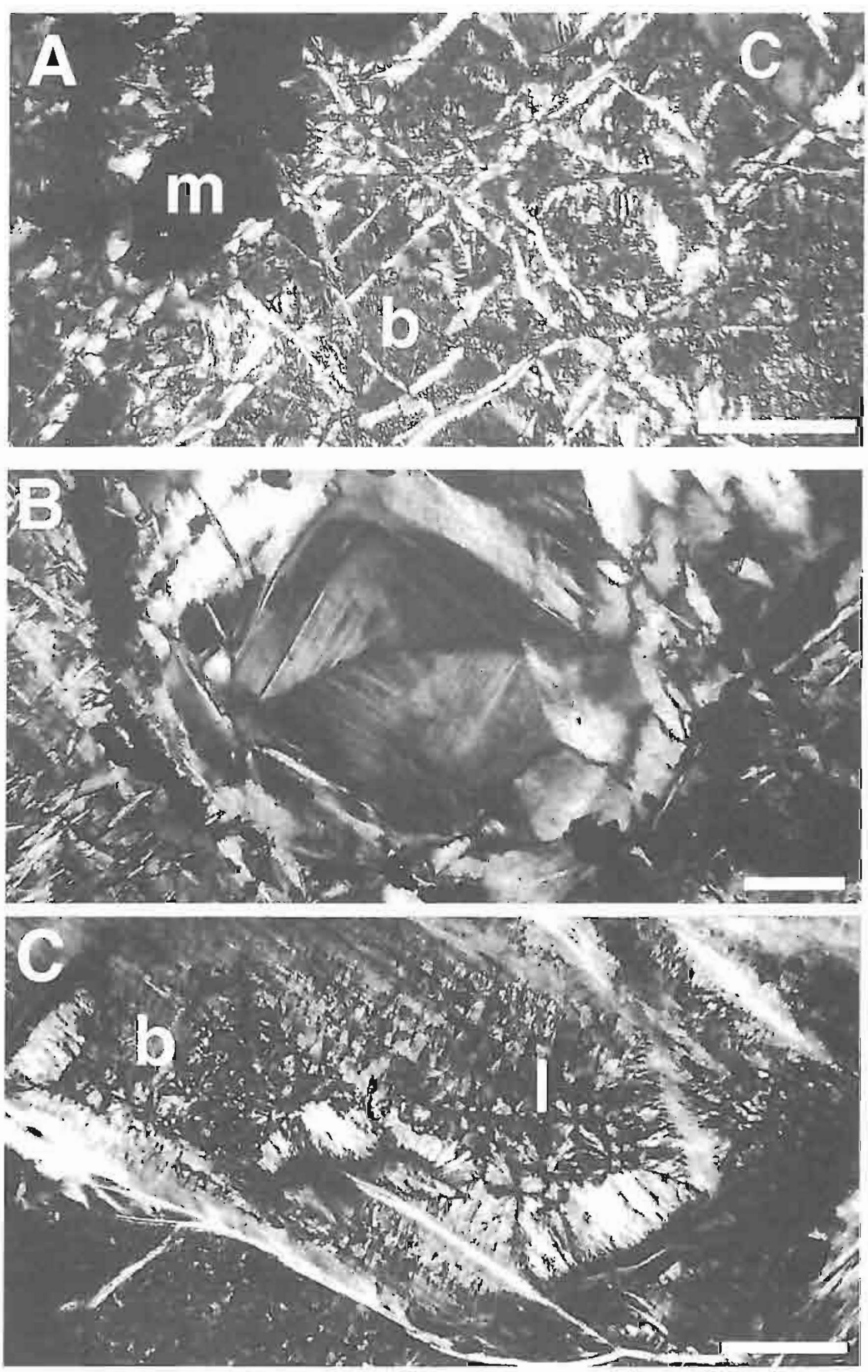

Fig. 5. **A** — photomicrograph of pseudomorphic serpentinite formed at the expense of mantle tectonite; b — bastite pseudomorph after pyroxene porphyroclast, m — magnetite pseudomorph after primary holly-leaf AlCr-spinel, c — chrysotile veinlet; scale bar = 100 μm; polarized light, crossed polars

B — photomicrograph of pseudomorphic serpentinite with hour-glass pseudomorph after olivine neoblast; scale bar = 20 μm; polarized light, crossed polars

C — photomicrograph of pseudomorphic serpentinite with dominal bastite (b) partly intergrown with late rosette lizardite (l); scale bar = 200 μm; polarized light, crossed polars

Serpentine polytypes identified on the basis of routine X-ray powder diffraction method as well as optically (F. J. Wicks, D. S. O'Hanley, 1988); serpentinite quarry at Nasławice, eastern part of Jordanów–Gogołów serpentinite massif

A — mikrofotografia serpentynitu pseudomorficznego, powstałego kosztem tektonitu płaszczowego; b — pseudomorfoza bastytowa po porfiroklaście piroksenu, m — pseudomorfoza magnetytowa po pierwotnym AlCr-spinelu o pokroju liścia ostrokrzewu, c — żyłka chryzotylowa; skala = 100 μm; światło spolaryzowane, polaryzatory skrzyżowane

B — mikrofotografia serpentynitu pseudomorficznego z pseudomorfozą klepsydrową po neoblaście oliwinu; skala = 20 μm, światło spolaryzowane, polaryzatory skrzyżowane

C — mikrofotografia serpentynitu pseudomorficznego z dominalnym bastytem (b), częściowo przerośniętym późnym lizardytem rozetkowym (l); skala = 200 μm; światło spolaryzowane, polaryzatory skrzyżowane

Odmiany politypowe serpentynów identyfikowano rutynową metodą dyfrakcji rentgenowskiej oraz optycznie, stosując kryteria zaproponowane przez F. J. Wicksa i D. S. O'Hanleya (1988); kamieniołom w Nasławicach, wschodnia część masywu serpentynitowego Jordanowa–Gogołowa

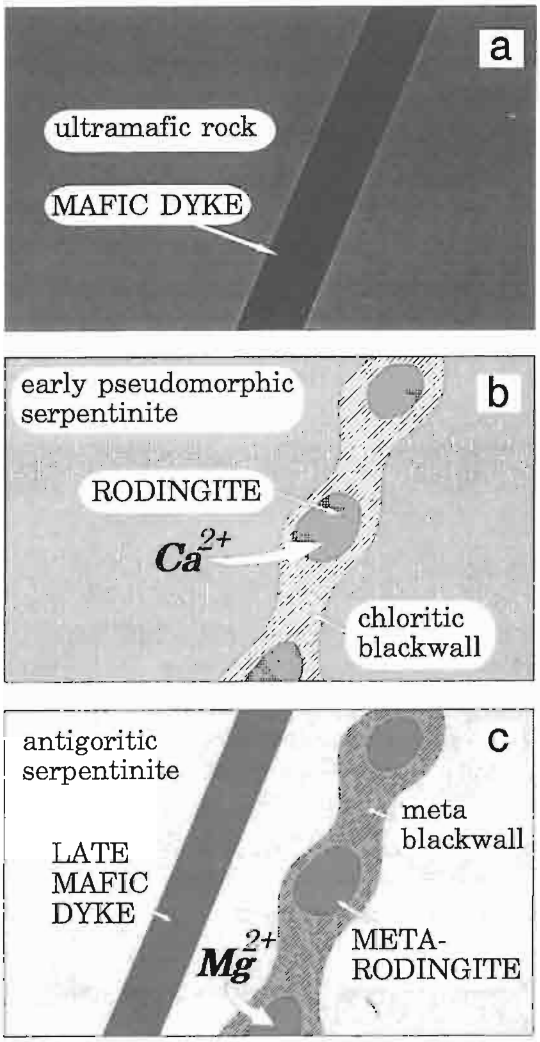

Fig. 6. Schematic sketch of relationship serpentinization-rodingitization
a — penetration of mafic dyke into ultramafic rock, **b** — formation of serpentinite and concomitant rodingitization of mafic material due to Ca^{2+}-ions release from pyroxenes in ultramafic rock; chloritic blackwall simultaneously develops at the expense of ultramafic rock owing to migration of alumina from mafic material towards ultrabasic rock, **c** — penetration of late mafic dyke into serpentinite enclosing rodingitized early mafic dyke; late mafic material does not evidence symptoms of rodingitization (Ca-metasomatosis)

Schematyczny szkic zależności między serpentynizacją i rodingityzacją
a — penetracja dajki maficznej do skały ultramaficznej, **b** — powstawanie serpentynitu i rodingityzacja materiału maficznego w wyniku uwolnienia jonów Ca^{2+} z piroksenów skały ultramaficznej; dzięki uruchomieniu Al_2O_3 ze skały maficznej i jej migracji do skały ultramaficznej kosztem tej ostatniej równocześnie rozwija się łupina chlorytowa, **c** — penetracja późnej dajki maficznej do serpentynitu zawierającego zrodingityzowaną wczesną dajkę maficzną; późny materiał maficzny nie wykazuje przejawów rodingityzacji (metasomatozy wapniowej)

by olivine neoblasts. Ultramafic rocks composed of polygonal olivine matrix enclosing olivine porphyroblasts was described by P. Gunia (1988) from Braszowice–Brzeźnica and Szklary massifs.

A primary tentative mineralogy of ultramafic rocks as deduced on the basis on CIPW norm calculations suggests that serpentinites were formed at the expense of harzburgites, lherzolites, and pyroxenites, the last are minor (Tab.1, Fig. 3). Their contents of Ni and Cr in the Braszowice–Brzeźnica ultrabasic rocks is lower than this in Jordanów–Gogołów (Tab. 2, Fig. 4). Ultrabasic rocks from Szklary massif display high Cr and Ni concentrations combined with high Al_2O_3 content, frequently ca. 10% weight, that is conspicuous and can be tentatively interpreted as crustal contamination or suggests unusual protolith, e.g enriched residual mantle.

Subsolidus recrystallization of the metamorphic peridotites was tentatively estimated at 620–715°C based on the olivine-spinel thermometer; this temperature can reflect solid-state plastic flow during upwell of the asthenospheric diapir (P. Gunia, 1995*a*).

Ultramafic cumulates. Up to the present these rocks were recognized on the basis of their major element chemistry, normative mineralogy close to pyroxenite, and gabbro and clinopyroxenite compositional layering (A. Majerowicz, C. Pin, 1994; P. Gunia, unpubl. data). The Ślęża diallagite palaeotemperature obtained using J.-J. C. Mercier (1980) single pyroxene geothermometer is close to ca. 1100°C and it is analogous to the Nowa Ruda gabbros (M. Borkowska, 1985).

Taking into account an occurrence of altered peridotite considered as ultramafic cumulate within tectonic contact zone between Jordanów–Gogołów serpentinites and Ślęża gabbros (Tąpadła pass), mantle tectonites of Jordanów–Gogołów massif were interpreted to be overthrusted on mafic

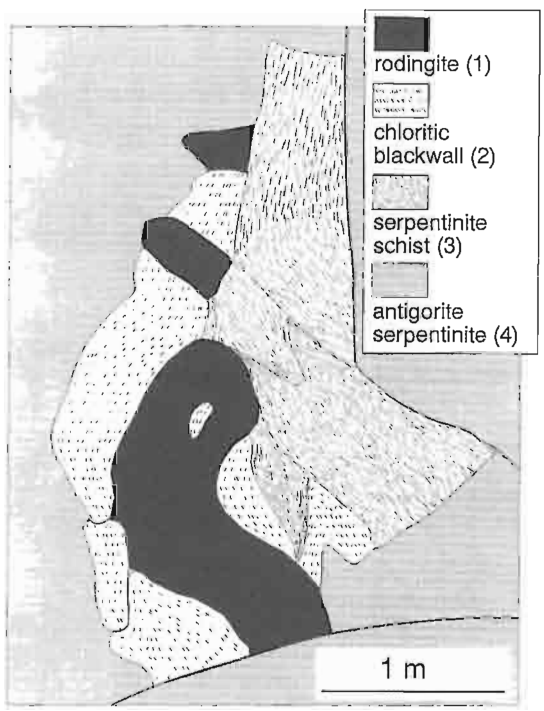

Fig. 7. Schematic sketch of tectonized boudine of rodingite; serpentinite quarry at Nasławice, eastern part of Jordanów–Gogołów serpentinite massif

Schematyczny szkic budiny tektonicznej rodingitu; kamieniołom serpentynitu w Nasławicach, wschodnia część masywu serpentynitowego Jordanowa–Gogołowa
1 — rodingit, 2 — chlorytowa łupina kontaktowa, 3 — łupek serpentynitowy, 4 — serpentynit antygorytowy

cumulates (M. P. Mierzejewski, 1993; A. Majerowicz, C. Pin, 1994). This explanation is vague because there is a strong similarity in texture and mineralogy between ultramafic cumulate section of the Penrose ophiolite stratigraphy and zones of extensive melting and/or melt penetration into mantle tectonites (e.g. R. Laurent *et al.*, 1991; P. B. Kelemen, H. J. B. Dick, 1995).

The pseudomorphic serpentinites with poikilitic bastites filling intercumulus space and perfect pseudomorphs after idiomorphic olivine analogous to orthocumulate described by K. Ozawa (1983) and P. Peltonen (1995) can be found as discrete layers or irregular bodies in different parts of Jordanów–Gogołów massif. These occurrences closely resemble zones of melt-rock reactions recently reported by J. E. Quick and R. T. Gregory (1995) and P. B. Kelemen and H. J. B. Dick (1995).

Serpentinites. The serpentinites from Jordanów–Gogołów massif represent different textural types: pseudomorphic lizardite-chrysotile serpentinites (Figs. 5A, B), non-pseudomorphic antigorite variety, chrysotile asbestos, lizardite rosette serpentinites, etc. The distribution of different varieties of serpentinites seems to be irregular; blocks and boudins of pseudomorphic serpentinites adjoin to a variety highly obliterated by antigorite blades and ubiquitous serpentinite mylonite wedges. The serpentinite textures suggest that early low-temperature serpentinization, located below brucite-lizardite or brucite-chrysotile invariant points in P-T space (see F. J. Wicks, D. S. O'Hanley, 1988 for details) produced lizardite-chrysotile pseudomorphic serpentinites and was extensive, while posterior recrystallization producing massive antigoritic serpentinites (greenschist facies) was less frequent (E. Dubińska, 1995). Serpentinites containing late rosette lizardite, formed at the expense of almost all previously described rocks (including antigorite varieties), were also found (Fig. 5C).

Serpentinites from the Braszowice–Brzeźnica massif are

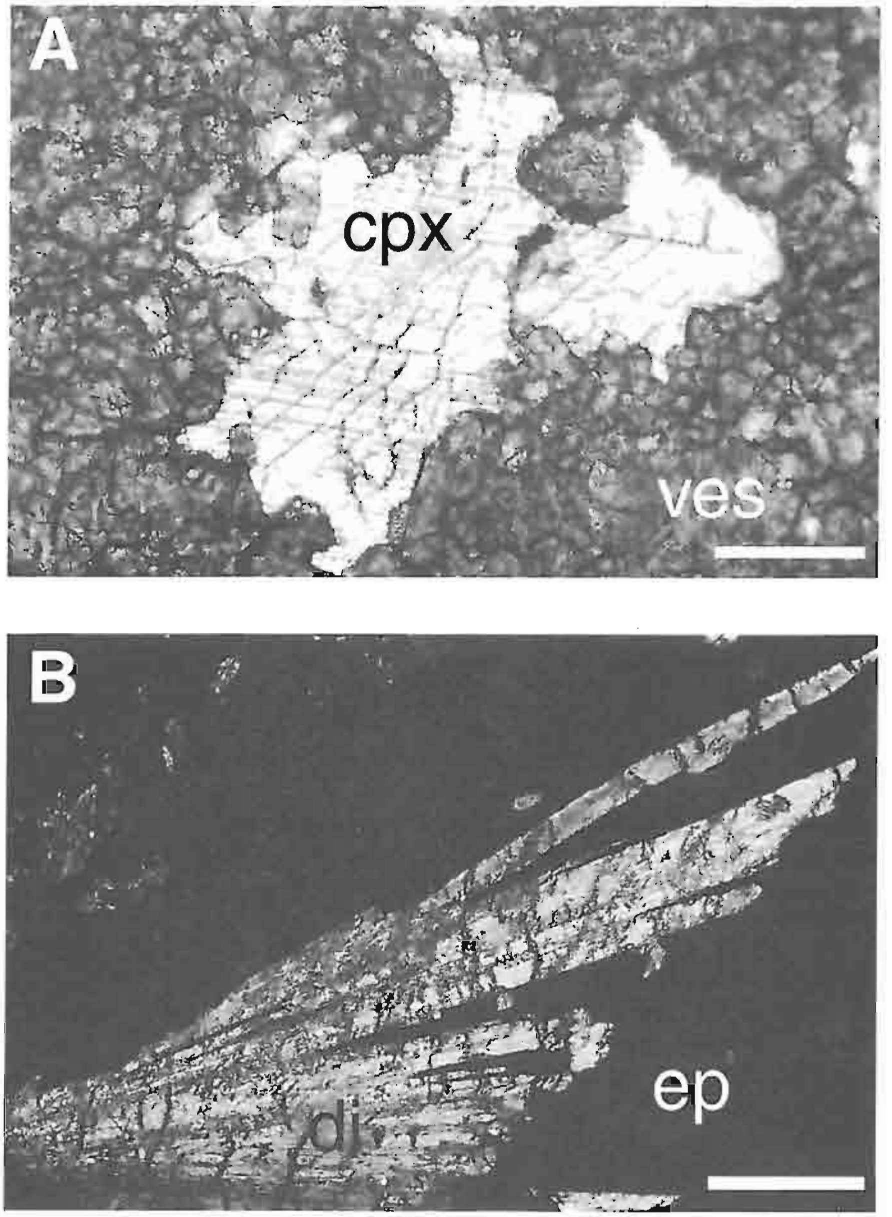

Fig. 8. **A** — photomicrograph of relict clinopyroxene (cpx) with (100) partings in vesuvianite (ves) rodingite from Przemiłów (central part of Jordanów–Gogołów serpentinite massif); scale bar = 200 μm; polarized light, one polar

B — photomicrographof rodingite from Szklary; di — neddles of newly formed (metasomatic) diopside, ep — epidote Ps 6-11 (P — piacite end member); scale bar = 400 μm; polarized light, crossed polars

A — mikrofotografia piroksenu reliktowego (cpx) z oddzielnością według (100) w rodingicie wezuwianowym (ves) z Przemiłowa (środkowa cześć masywu serpentynitowego Jordanowa–Gogołowa); skala = 200 μm; światło spolaryzowane, jeden polaryzator

B — mikrofotografia rodingitu ze Szklar; di — igły nowopowstałego (metasomatycznego) diopsydu, ep — epidot Ps 6-11 (Ps — człon pistacytowy); skala = 400 μm; światło spolaryzowane, polaryzatory skrzyżowane

Table 3

Representative whole-rock compositions of mafic rocks from serpentinites and massifs adjacent to Góry Sowie block

Component weight %	MAFIC MASSIFS**						MAFIC ROCKS FROM SERPENTINITES					
							RODINGITES					AMPHIBOLITE
	Nowa Ruda			Sobótka		Braszowice	Jordanów-Gogołów massif				Szklary massif	
	NR11*	NR7*	Wol	7G	II/21	Brasz	Na48D	Sw20	Pr1	Pr8*	739*	Sz67A*
SiO_2	48.20	51.40	47.40	50.55	46.00	50.90	37.88	39.72	36.14	39.27	40.1	36.6
TiO_2	3.30	2.30	0.59	0.90	2.75	0.50	0.27	0.12	0.04	0.04	0.05	0.02
Al_2O_3	12.35	14.60	17.40	14.75	15.15	15.50	14.76	17.99	16.86	14.23	16.2	33.15
Fe_2O_3	10.25	11.10	1.50	2.21	4.21	1.89	3.26	5.52	3.09	6.71	4.13	2.02
Cr_2O_3	tr.	tr.	tr.	tr.	tr,		0.01	0.05	tr.	tr.	0.10	tr.
FeO			2.61	4.50	12.33	3.61	0.25		1.55			
MnO	0.28	0.16	0.08	0.16	0.30	0.12	0.10	0.09	0.15	0.07	0.08	<0.01
MgO	5.30	7.80	12.30	8.75	10.30	8.80	0.52	13.55	10.55	5.59	13.2	5.05
NiO	tr.	tr.	tr.	tr.	tr.	tr.	0.02	0.03	0.01	0.07	0.07	0.04
CaO	8.05	6.30	13.85	13.30	4.30	15.20	30.59	22.51	27.04	33.65	22.6	19.18
Na_2O	2.50	4.30	1.70	3.20	2.40	2.50	0.22	tr.	0.06	tr.	0.10	0.51
K_2O	tr.	0.10	0.25	tr.	tr.	tr.	0.20	tr.	-	tr.	0.03	0.04
P_2O_5	n.d	0.02	n.d.	n.d.	n.d.	n.d.	0.01	n.d.	n.d.	n.d.	n.d.	n.d.
CO_2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.37	n.d.	0.22	n.d.	n.d.	n.d.
H_2O^+							3.44	n.d.	3.58	n.d.	n.d.	n.d.
Ign. loss	0.70	0.98	2.86	0.68	1.59	0.23					3.01	
Total	99.03	99.04	100.55	99.72	99.33	99.02	99.90	99.58	99.32	99.63	99.67	100.04

*Total iron as Fe_2O_3; **after C. Pin *et al.* (1988); - — not detected; n. d. — not determined; tr. — traces; NR11, NR7, Wol — gabbro; 7G, Brasz — metagabbro; II/21 — amphibolite; Pr1 — sample metasomatized, rich in vesuvianite; Pr8 — sample rich in relict clinopyroxene containing vesuvianite; NR11, NR7, Wol, 7G, II/21, Brasz, Na48D, Sw20, Pr1, Pr8, 739, Sz67A — sample numbers

Table 4

Representative trace elements compositions of mafic rocks from serpentinites and massifs adjacent to Góry Sowie block

Component [ppm]	MAFIC MASSIFS*						MAFIC ROCKS FROM SERPENTINITES				
							RODINGITES				AMPHIBOLITE
	Nowa Ruda			Sobótka		Braszowice	Jordanów-Gogołów massif			Szklary massif	
	NR11	NR7	Wol	7G	II21	Brasz	Sw20	Pr1	Pr8	739	Sz67A
Ti	15050	13790	3000	5400	16490	3000	720	270	241	282	112
V	485	290	n.d.	270	450	270	119	8	8	27	6
Cr	30	155	n.d.	95	340	590	346	12	15	650	14
Ni	20	35	n.d.	65	100	95	232	55	56	527	300
La	9.96	5.44	0.38	1.01	4.57	1.21	1.02	20.8	21.6	0.79	7.17
Ce	36.66	23.00	2.80	5.92	20.70	7.74	1.46	27.4	22.4	1.53	7.85
Pr	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.10	2.24	1.90	0.15	0.53
Nd	28.59	15.56	0.96	3.69	15.20	2.54	1.15	6.81	4.29	0.76	1.23
Sm	10.09	5.44	0.40	1.48	5.52	1.40	0.35	0.64	0.41	0.13	0.08
Eu	2.86	1.68	0.22	0.65	1.77	0.62	0.15	1.20	0.75	0.14	0.06
Gd	10.74	5.61	0.61	1.93	6.37	2.07	0.6	0.4	0.2	0.2	0.1
Tb	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.09	0.08	0.13	0.04	0.02
Dy	13.45	7.34	0.51	2.60	.87	2.35	0.85	0.30	0.16	0.24	0.10
Ho	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.17	0.04	0.01	0.04	0.02
Er	7.64	4.00	0.28	1.46	4.49	1.24	0.51	0.08	0.02	0.12	0.04
Tm	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.06	>0.01	0.05	0.01	0.01
Yb	8.35	4.15	0.24	1.40	4.64	1.15	0.57	0.17	0.09	0.14	0.12
Lu	1.29	0.62	0.03	0.19	0.73	0.16	0.08	0.03	0.02	0.03	0.03
Hf	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1.7	3.7	2.8	2.8	2.6
Zr	231	130	n.d.	30	157	n.d.	70	160	276	3	98
Nb	5	3	n.d.	n.d.	2	n.d.	0.4	1.6	0.6	0.7	0.9
Y	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	4.28	1.35	0.59	1.14	0.58
Th	n.d.	n.d.	n.d.	n.d.	0.17		0.8	0.9	1.1	0.6	0.9

*After C. Pin *et al*. (1988); other explanations as in Tab. 3

analogous to the Jordanów–Gogołów ones. Brittle-structure analysis suggest that serpentinization was succeeded by multi-stage brittle deformation (P. Gunia, S. Mazur, 1992).

Ultramafic rocks from Szklary massif are frequently veined and partly replaced by serpentines and intergrown by clinochlore, tremolite, talc, and anthophyllite, whereas both pseudomorphic and non-pseudomorphic antigorite serpentinite seem to be minor. The distribution of different varieties of ultrabasic rocks is wild: presumably it reflects tectonic displacements hidden owing to overprint of low temperature hydrothermal alteration and heavy Tertiary weathering.

The mineral parageneses in serpentinites from Jordanów–Gogołów and Braszowice–Brzeźnica massifs represent metamorphic assemblages formed at temperature 200–250°C as indicated by recrystallization of lizardite-chrysotile into antigorite without brucite (D. S. O'Hanley, F. J. Wicks, 1995). In Szklary, partially serpentinized ultramafic rocks are commonly overprinted by minerals (e.g. anthophyllite) typical of amphibolite-facies metamorphism (B. W. Evans, 1977). The age of amphibolite facies metamorphism is not clear (Variscan?). Such contrast between low-grade metamorphism of Jordanów–Gogołów and Braszowice–Brzeźnica serpentinites and medium-grade metamorphism recorded by ultrabasic rocks from Szklary is ambiguous.

MAFIC ROCKS; PETROGRAPHY

MAFIC MASSIFS

Mafic rocks from massifs surrounding Góry Sowie block are typical plutonic coarse-grained to fine-grained rocks which modal composition ranges from troctolites via olivine gabbros to gabbros (M. Borkowska, 1985; S. Maciejewski, 1968). The scarce hypabbysal rocks seem to represent sheeted dyke and extrusive sections (A. Majerowicz, 1994; R. Kryza, 1995). Their textures are variable from typical ophitic to porphyritic and aphanitic. The primary textures of mafic rocks are perfectly preserved despite intense hydrothermal alteration (e.g. saussuritization, uralitization, chloritization) and retrogressive metamorphism attributed to ocean-floor metamorphism (A. Majerowicz, 1994).

Chemistry of mafic rocks clearly reflects their different modal composition both in major and in minor elements (Tabs. 3, 4), e.g., in Nowa Ruda gabbros (Fig. 2) titanium and zircon concentrations range from 330 to ca. 20 000 ppm and from 1 to 230 ppm, respectively (M. Borkowska, 1985; C. Pin *et al.*, 1988).

RODINGITES AND AMPHIBOLITE DYKES FROM ULTRABASIC MASSIFS

Rodingites are Ca-rich, SiO_2-undersaturated rocks formed by metasomatism accompanying low-temperature serpentinization (e.g. R. G. Coleman, 1977; S. K. Mittwede, E. S. Schandl, 1992). Rodingites consist of Ca–Al and Ca–Mg silicates such as grossular, epidote, vesuvianite, and diopside. The rodingite protolith may vary from gabbros to granites and greywackes. At present, the term rodingite is used only in descriptive, genetical meaning, without chemical connotation.

Ca-metasomatism is largely ascribed to hydrothermal alteration, when Ca^{2+}-ions were released from primary pyroxenes, producing Ca^{2+}–OH^{-} type waters (I. Barnes, J. R. O'Neil, 1969; I. Barnes *et al.*, 1972, 1978; C. Neal, G. Stanger, 1985). Both serpentinization and rodingitization can be pro-

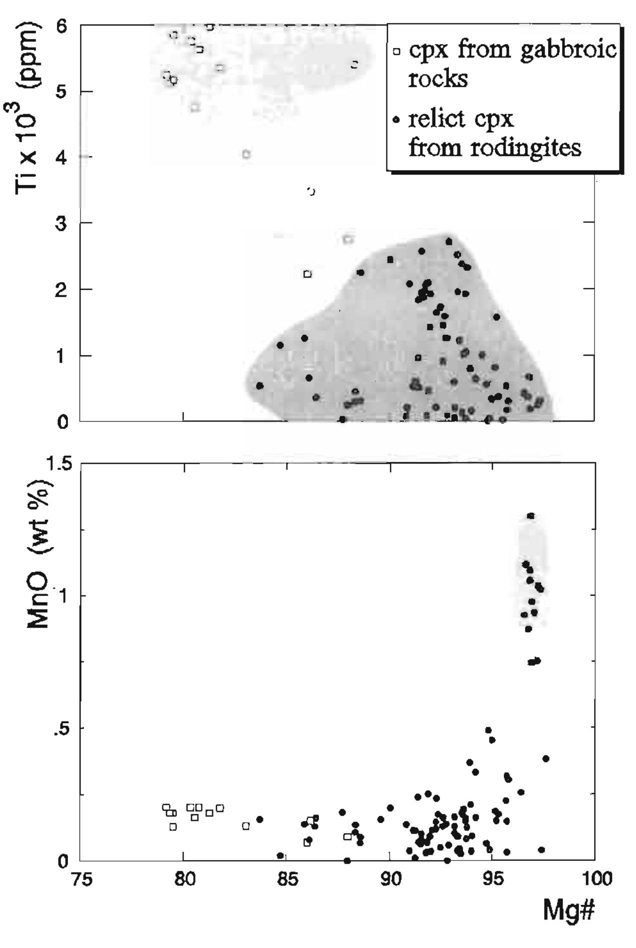

Fig. 9. Compositions of clinopyroxenes from gabbros (after M. Borkowska, 1985) and relict clinopyroxenes rodingites; MnO enrichment in some relict pyroxenes in rodingites probably derived from Mn release from subducted hydrothermal metaliferrous deposits

Składy piroksenów jednoskośnych z gabroidów (według M. Borkowskiej, 1985) i reliktowych piroksenów jednoskośnych w rodingitach: wzbogacenie w MnO niektórych piroksenów reliktowych w rodingitach może być związane z uwolnieniem Mn z subdukowanych metalonośnych utworów hydrotermalnych ducts of the oceanic and other stages of ophiolite evolution (e.g. J. Honnorez, P. Kirst, 1975; F. J. Wicks, D. S. O'Hanley, 1988; A. Nicolas, 1989; D. S. O'Hanley *et al.*, 1992; H. Bougault *et al.*, 1993; R. Hékinian *et al.*, 1993). Initial serpentinization of the peridotite and rodingitization of dykes and lithic inclusions usually occurred in an oceanic environment. Subsequent alteration, however, can take place in both oceanic and continental environments. Such serpentinization-rodingitization relationships, schematically shown at Figure 6, were found in numerous ophiolite suites ranging from Archean to Pleistocene (e.g. A. J. Coulton *et al.*, 1995; B. R. Frost, 1975; R. Laurent, 1980; D. S. O'Hanley, R. Offler, 1992; D. S. O'Hanley *et al.*, 1992; U. Rössli *et al.*, 1991; E. S. Schandl *et al.*, 1989, 1990; T.-F. Yui *et al.*, 1990).

Rodingite bodies from the studied area are usually small tectonic inclusions (from <0.5 to ≈ 20 m in length) within serpentinites (Fig. 7). Eight coherent mafic dykes were found within the serpentinites and they are metamorphosed and frequently tectonized. Rodingites involved in the study originated from undoubted mafic parent rocks as evidenced by high whole rock Al_2O_3 content (Tab. 3) combined with relict ophitic texture, and two varieties of relict pyroxenes: fresh clinopyroxene close to diopside end-member in composition (Tab. 5, Figs. 8A, 9) as well as bastite-like pseudomorphs containing unaltered exsolution lamellas formed at the expense of orthopyroxene (Fig. 10). Two generations of Ca-silicates are inferred from petrographic observations. The sequence, older CaAl-silicate, e.g. grossularite garnet or clinozoisite, to younger Mg-bearing silicates, e.g. vesuvianite, diopside, clintonite, is evident in undeformed samples (Fig. 8B). Formation of early

Table 5

Representative composition of clinopyroxene from gabbros and rodingites

Component	MAFIC MASSIFS**		RODINGITES: relict clinopyroxenes with (100) partings				RODINGITES: newly formed clinopyroxenes	
	$36bm_a$	$36bm_2$	Na53	Pr8	Sz90B	Sz106	Sz93A	Pr13
SiO_2	51.32	51.27	56.37	54.52	53.62	52.45	53.96	54.51
TiO_2	0.95	0.93	0.06	0.10	0.08	0.21	0.04	tr.
Al_2O_3	3.36	3.15	0.4	tr.	0.96	2.77	0.87	tr.
Cr_2O_3	0.80	0.47	tr.	0.02	0.02	0.71	0.06	0.06
FeO*	7.04	6.53	1.37	2.17	2.74	2.22	1.27	2.18
MnO	0.20	0.2	0.17	0.16	0.07	0.14	0.04	0.06
NiO	n.d.	n.d.	0.14	0.09	n.d.	0.02	n.d.	0.04
MgO	16.14	15.37	15.78	17.65	16.34	16.02	17.65	16.32
CaO	19.41	21.27	24.88	25.55	25.65	24.71	25.23	26.44
K_2O	n.d	n.d.	0.03	0.02	tr.	0.03	tr.	0.02
Na_2O	0.55	0.41	0.07	tr.	0.04	0.21	tr.	tr.
Total	99.77	99.6	99.27	100.28	99.52	99.49	99.12	99.63
	on the basis of 6 oxygens							
Si	1.90	1.90	2.05	1.98	1.97	1.92	1.97	2.00
Ti	0.03	0.03				0.01		
Al	0.15	0.14	0.02		0.04	0.12	0.04	
Cr	0.02	0.01						
Fe^{2+}*	0.22	0.20	0.04	0.07	0.08	0.07	0.04	0.07
Mn	0.01	0.01	0.01					
Mg	0.89	0.85	0.85	0.96	0.89	0.88	0.96	0.89
Ca	0.77	0.84	0.97	2.00	1.01	0.97	0.99	1.04
Na	0.04	0.03				0.01		
Mg#	0.80	0.81	0.95	0.94	0.91	0.93	0.96	0.93

*Total iron FeO and Fe^{2+}, respectively; **after M. Borkowska (1985); 36bma, 36bm2, Na53, Pr8, Sz90B, Sz106, Sz93A, Pr13 — sample numbers; other explanations as in Tab. 3

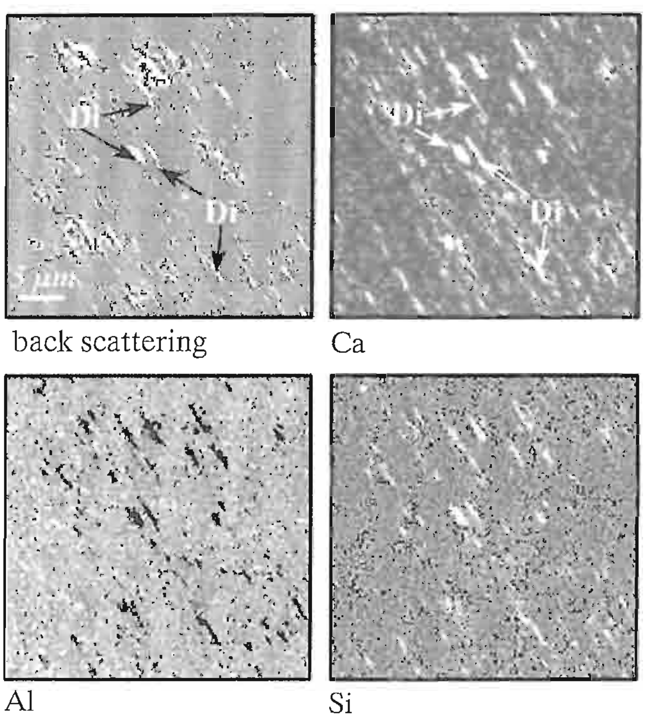

Fig. 10. Back scattered electron picture and electron beam image of chlorite bastite-like pseudomorph after orthopyroxene, rodingite from Świątniki; eastern part of Jordanów–Gogołów serpentinite massif

Di — unaltered exolution lamellae of diopside at the bastite-like chloritic background (formed at the expence of orthopyroxene)

Mapping elektronów wstecznych i rozmieszczenie pierwiastków w podobnej do bastytu pseudomorfozie chlorytowej po piroksenie rombowym; rodingit ze Świątnik, wschodnia cześć masywu serpentynitowego Jordanowa–Gogołowa

Di — niezmienione lamelki odmieszań o składzie diopsydu w tle chlorytowym podobnym do bastytu, który powstał kosztem piroksenu rombowego

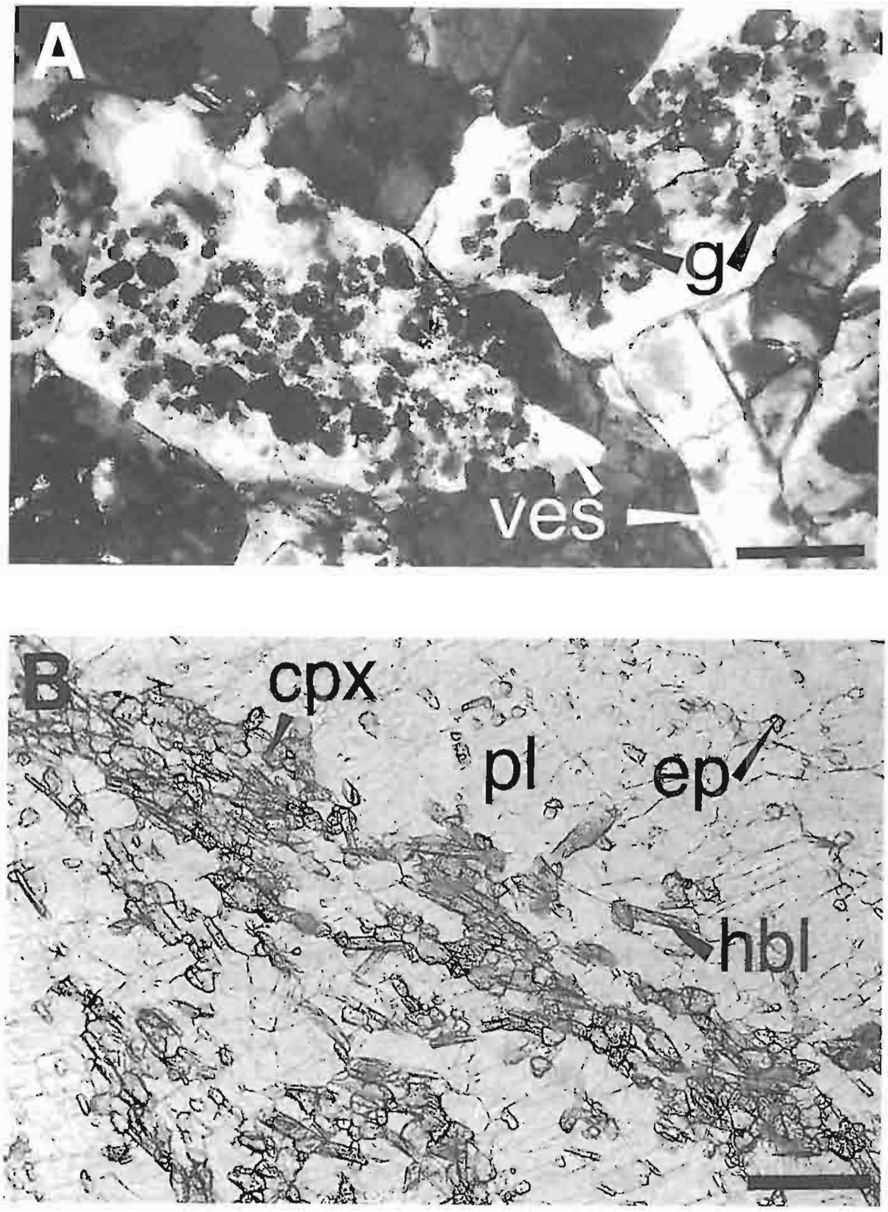

Fig. 11. **A** — photomicrograph of rodingite from Jordanów (eastern part of Jordanów–Gogołów serpentinite massif); late idiomorphic vesuvianite (ves) blasts enclose earlier tectonic breccia composed of grossularite garnet (g) fragments; scale bar = 200 μm; polarized light, crossed polars

B — photomicrograph of amphibolite from tectonized dyke cross-cutting ultrabasic rock in Szklary; tectonized plagioclase (pl) overprinted with small prisms of epidote (ep) and streak composed of hornblende (hbl) and clinopyroxene (cpx); scale bar = 200 μm; polarized light, one polar

A — mikrofotografia rodingitu z Jordanowa (wschodnia część masywu Jordanowa–Gogołowa); późne automorficzne blasty wezuwianu (ves) obrastają okruchy brekcji tektonicznej złożonej z granatu bogatego w grossular (g); skala = 200 μm; światło spolaryzowane, polaryzatory skrzyżowane

B — mikrofotografia amfibolitu ze stektonizowanej dajki przecinającej skały ultrazasadowe masywu Szklar: stektonizowany plagioklaz (pl) przerośnięty drobnymi słupkami epidotu (ep) oraz smugą złożoną z hornblendy (hbl) i piroksenu jednoskośnego (cpx); skala = 200 μm; światło spolaryzowane, jeden polaryzator

Ca-silicates in the rodingites is probably related to low-temperature oceanic metamorphism, related to formation of lizardite±chrysotile pseudomorphic serpentinites, when Ca^{2+}-ions were released from pyroxenes. CaMg-silicates in rodingites seem to be products of younger greenschist facies continental metamorphism (Variscan?) that can be correlated with formation of antigorite variety of serpentinites.

The rodingites typically exhibit textures indicative of brittle deformation. Several episodes of brittle deformation initiated at an early episode of rodingitization, via completely mylonitized zones and minerals formed during posterior episodes (Fig. 11A), to cementation of previously formed breccias and mylonites by late minerals, e.g. andradite, are observed (Fig. 12; E. Dubińska, 1995).

There is a strong similarity in major elements abundances in relict and newly formed pyroxenes, nevertheless, they can be easily distinguished due to (100) partings well pronounced in relict variety (see Figs. 8A, B, and 9 for comparison). Relict pyroxenes from rodingites are characterized by lower Mg# [Mg/(Mg+Fe)] and titanium contents that clinopyroxenes from Nowa Ruda gabbros (Tab. 5, Fig. 9).

Amphibolites from the Szklary massif were formed from anorthosite-type protolith with highly anorthitic relict plagioclase (An 93-100). There are two varieties of metamorphic assemblages:

— hornblende + newly formed clinopyroxene + newly formed plagioclase (An 65-75), Fe-rich epidote, and accessory garnet (Fig. 11B). Temperature of garnet and pyroxene, newly formed plagioclase and hornblende, and garnet and hornblende formation was estimated at 720–760°C (E. Dubińska *et al.*, 1991)

— hornblende, clinochlore, Fe-rich epidote, magnetite, Fe-Mg-Al-spinel, and accessory pirophanite-geikielite.

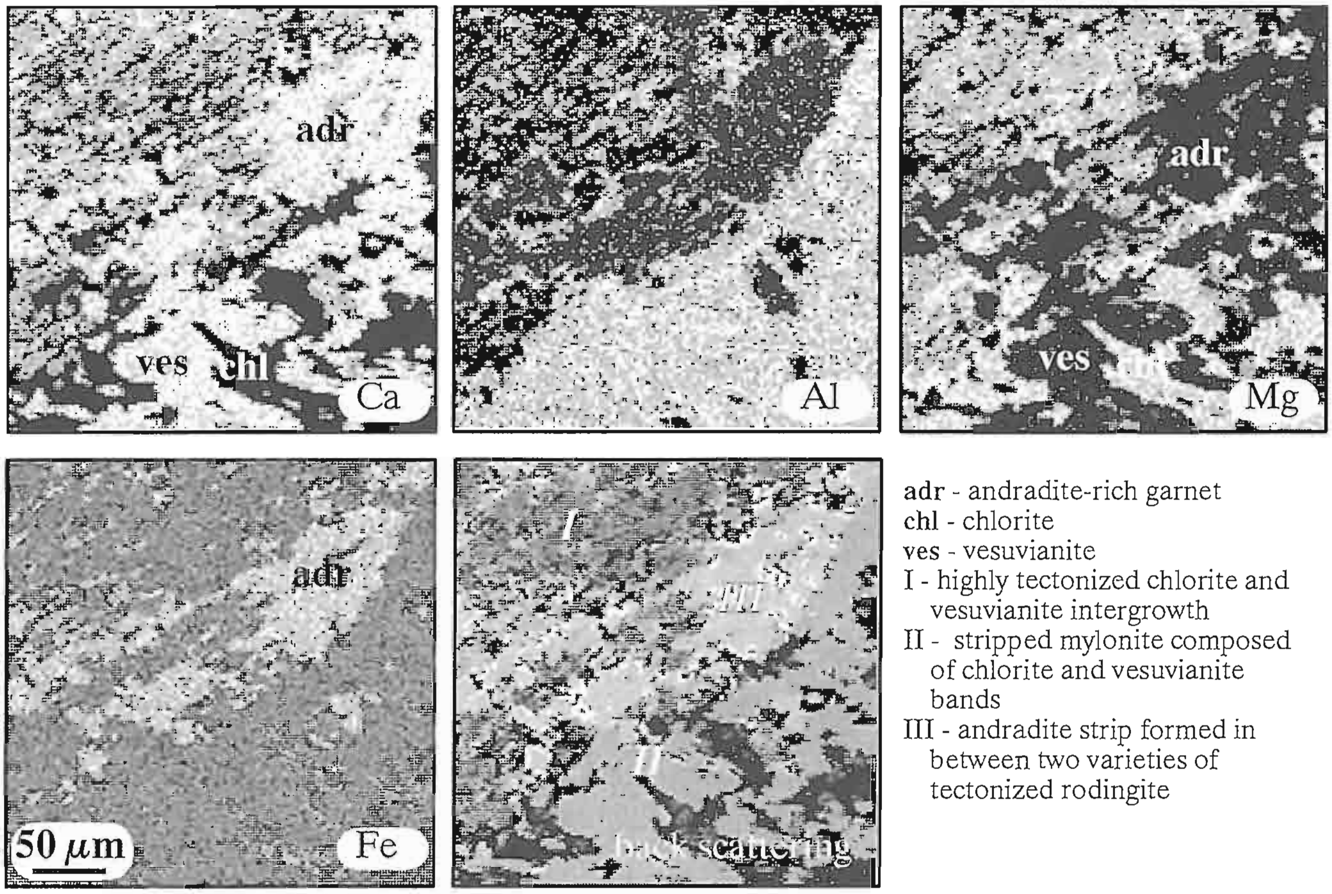

Fig. 12. Back scattered electron picture and electron beam image of andradite (adr) formed in between two varieties of highly tectonized chlorite (chl) and vesuvianite (ves) intergrowths; rodingite from Przemiłów, central part of Jordanów–Gogołów serpentinite massif

Mapping elektronów wstecznych i rozmieszczenie pierwiastków w rodingicie z Przemiłowa (środkowa część masywu serpentynitowego Jordanowa–Gogołowa); późny andradyt (adr) powstały między dwiema odmianami stektonizowanego przerostu chlorytu (chl) i wezuwianu (ves)

I — silnie stektonizowany smużysty przerost złożony z chlorytu i wezuwianu, II — mylonit złożony ze smug chlorytowo-wezuwianowych, III — strefa andradytu między dwiema odmianami stektonizowanego rodingitu

GEOCHEMISTRY OF TRACE ELEMENTS IN MAFIC ROCKS

Trace element geochemistry of mafic rocks from massifs adjacent to Góry Sowie block implies their N-MORB or N-MORB coherent affinity (flat spider-diagram of chondrite normalized analyses) as suggested by C. Pin *et al.* (1988), although bimodal characteristics is evident (Fig. 13): I-type mafic rocks includes Al_2O_3- and Mg#-low and rich in REE (rare earth elements) and HFSE (high field strength elements) variety, and II-type mafic rocks involves Al_2O_3- and Mg#-high and REE- and HFSE-poor variety. Samples from both groups derived from three considered massifs and are randomly distributed. In ophiolitic gabbros from Bridge River (Canada), B. N. Church *et al.* (1995) described gabbros that showed geochemical signature similar to the II-type gabbros and inferred their formation from partial melting of MORB-type source. Origin of the I-type gabbros (rich in incompatible elements) remains obscure.

Petrographic observations of studied rodingites support the very low mobility of REE and HFSE during serpentinization, rodingitization, and alteration in highly alkaline environment (e.g. B. W. Evans *et al.*, 1981; W. G. Ernst *et al.*, 1983; F. V. Holub *et al.*, 1984; N. A. Suturin, R. S. Zamaletdinov, 1984; A. Michard, 1989; E. S. Schandl *et al.*, 1989; M. A. Menzies *et al.*, 1993).

A significant depletion of Ti, Y and HREE's (heavy rare earth elements) when compared with N-MORB rocks was found in rodingites and amphibolites from ultrabasic massifs. Their HREE and Y abundances are below or close to those of undifferentiated mantle composition.

The rodingites and amphibolites from ultrabasic massifs can be roughly categorized by their REE patterns (Fig. 14) and Zr/Hf ratio (not shown):

— group I includes samples relatively rich in Zr and LREE (light rare earth elements),

— group II includes samples with low Zr/Hf ratio and low content of LREE.

Gradual enrichment in LREE's and Zr-enrichment within group I is accompanied by HREE depletion and a positive Eu anomaly.

Low Ti contents together with low HREE abundance (Fig. 15) and composition of relict pyroxenes in rodingites are critical for genetic interpretations. It suggests an extremely depleted source character, typical for boninite-suite rocks (see

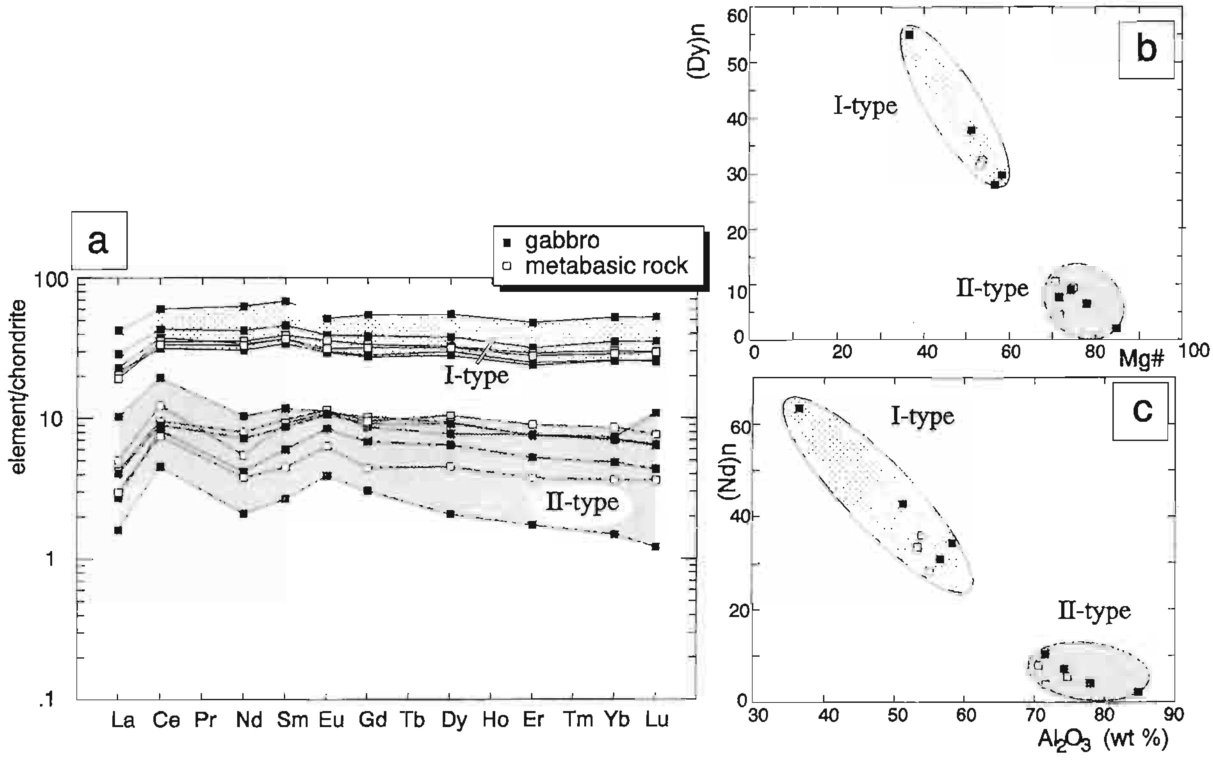

Fig. 13. Diagrams for gabbros and metabasic rocks from mafic massifs surrounding Góry Sowie block; data after C. Pin *et al.* (1988): **a** — chondrite normalized REE distribution pattern, normalization according to W. F. McDonough and F. A. Frey (1989); **b** — distribution on Mg# *vs* (Dy)n diagram; **c** — distribution on Al_2O_3 *vs* (Nd)n diagram

Diagramy dla gabroidów i metabazytów z masywów zasadowych wokół bloku Gór Sowich; dane C. Pina i in. (1988): **a** — diagramy „pajęcze" pierwiastków ziem rzadkich (REE), normalizacja na chondryt według W. F. McDonougha, F. A. Freya (1989); **b** — diagram Mg# *vs* (Dy)n (zawartość dysprozu po normalizacji na chondryt); **c** — diagram Al_2O_3 *vs* (Nd)n (zawartość neodymu po normalizacji na chondryt)

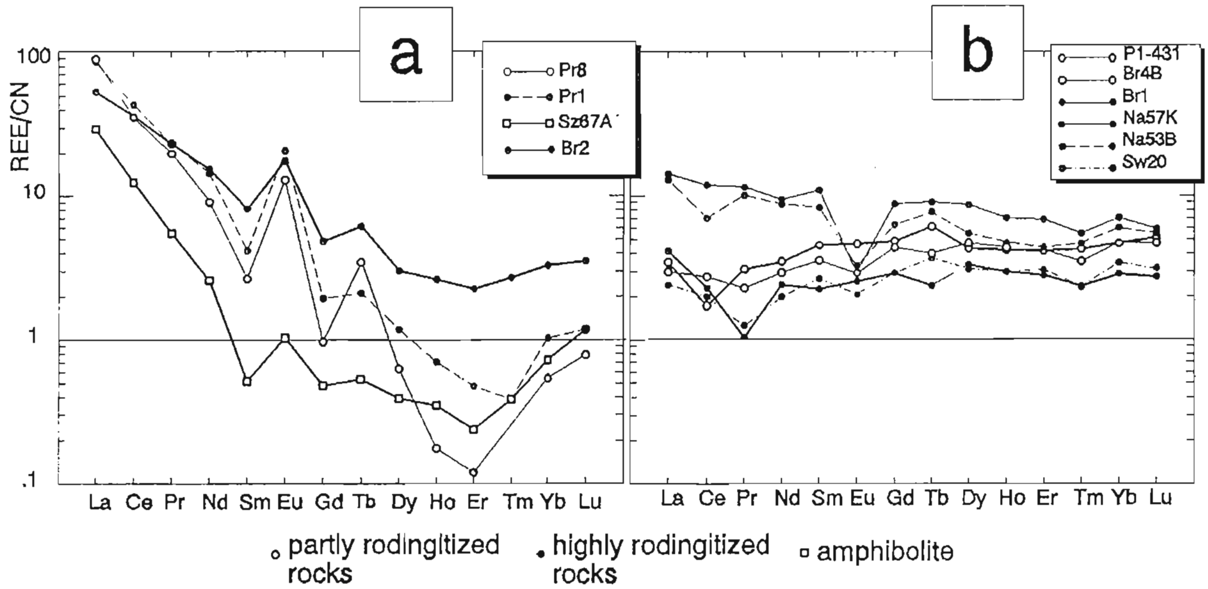

Fig. 14. Chondrite normalized REE distribution patterns of rodingites; normalization after W. F. McDonough and F. A. Frey (1989): **a** — rodingites and amphibolite enriched in LREE, all of them display positive Eu anomaly; **b** — rodingites non-enriched in LREE, some of them display negative Eu anomaly; Pr8, Pr1, Sz67A, Br2, P1-431, Br4B, Br1, Na57K, Na53B, SW20 — sample numbers

Diagramy „pajęcze" rozmieszczenia REE w rodingitach, normalizacja na chondryt według W. F. McDonougha i F. A. Freya (1989): **a** — rodingity i amfibolit wzbogacony w lekkie REE (LREE), z dodatnią anomalią Eu; **b** — rodingity nie wykazujące wzbogacenia w LREE, niektóre z ujemną anomalią Eu; Pr8, Pr1, Sz67A, Br2, P1-431, Br4B, Br1, Na57K, Na53B, SW20 — numery próbek

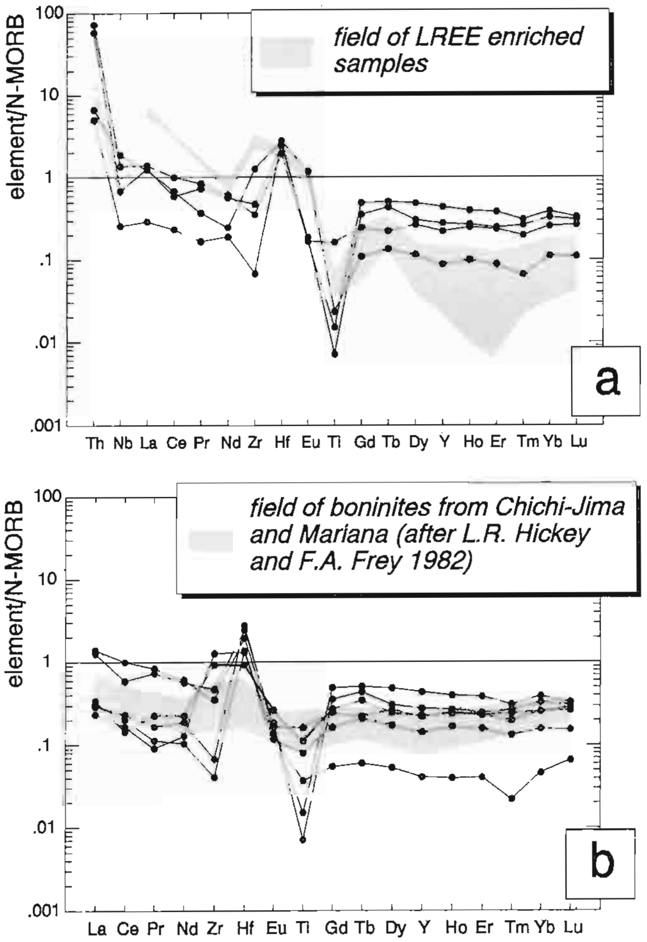

Fig. 15. N-MORB normalized trace element distribution patterns, normalization according to S.-S. Sun and W. F. McDonough (1989); **a** — two groups of rodingites (enriched and non-enriched in LREE), **b** — non-enriched rodingites as compared with classic boninites

Diagramy „pajęcze" pierwiastków śladowych, normalizacja na N-MORB według S.-S. Suna, W. F. McDonougha (1989); **a** — dwie grupy rodingitów — wzbogacone i ubogie w LREE; **b** — porównanie charakterystyki geochemicznej rodingitów ubogich w LREE i boninitów z typowych wystąpień

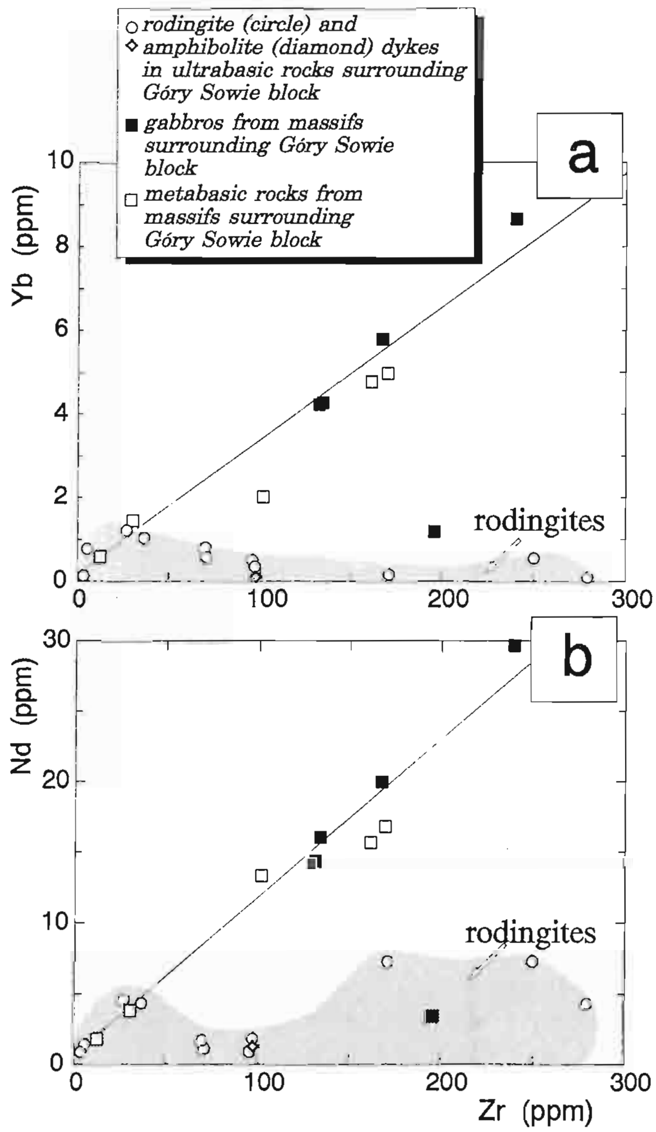

Fig. 16. Distributions of Zr *vs* Yb (**a**) and Zr *vs* Nd (**b**) of mafic rocks from massifs adjacent to Góry Sowie block (data after C. Pin *et al.*, 1988) and from occurrences in ultrabasic rocks (rodingites and amphibolite)

Diagramy zależności Zr *vs* Yb (**a**) i Zr *vs* Nd (**b**) w skałach maficznych z masywów przylegających do bloku Gór Sowich (dane według C. Pina i in., 1988) oraz z wystąpień skał maficznych w skałach ultrazasadowych (rodingitów i amfibolitów)

Fig. 15) i.e. rocks distinctive for fore-arc magmatism or back-arc spreading environments (e.g. L. Beccaluva, G. Serri, 1988; A. J. Crawford *et al.*, 1989; D. Elthon, 1991; A. V. Brown, G. A. Jenner, 1989; S. J. Edwards, 1995; J. N. Lytwyn, J. F. Casey, 1993; A. V. Sobolev, L. V. Danyushevsky, 1994; L. V. Danyushevsky *et al.*, 1995).

Progressive enrichment in both LREE's and Zr in modern boninites as well in boninite-like rock from ophiolites is usually ascribed to source metasomatism, e.g. by influx of hydrous fluids released from a subducting slab and/or crustal contamination in a supra-subduction zone (e.g. R. L. Hickey, F. A. Frey, 1982; D. R. Nelson *et al.*, 1984; A. J. Crawford, W. E. Cameron, 1985; R. N. Taylor, R. W. Nesbitt, 1988; A. J. Crawford *et al.*, 1989). Similar process can be responsible for LREE's and Zr enrichment of group II of the rodingites, e.g. crustal contamination due to penetration of hydrous fluids released from subducted oceanic lithosphere into Góry Sowie block(?).

Immobile trace-element concentrations in both groups of mafic rocks evidence two different magmatic sources (Fig. 16): MOR-type source for gabbros and metabasites from massifs and a metasomatized depleted source for rodingites and amphibolites from ultrabasic massifs.

GEODYNAMIC IMPLICATIONS

The following geodynamic situation of the Sudetic ophiolite can be deduced on the basis of integrated field, petrographic, mineralogical, and geochemical study, in particular on the basis of the inhomogeneity and N-MORB affinity of mafic rocks from massifs adjacent to Góry Sowie block geochemical data of C. Pin *et al.* (1988) combined with characteristics of ultrabasic rocks (Fig. 17):

1. Formation of mafic rocks (N-MORB-affinity) at a mid-ocean ridge. An active ocean hydrothermal system affected mafic rocks (A. Majerowicz, 1994); furthermore, plagiogranite-derived rodingites recorded such activity (E. Dubińska, 1995). This effect suggests that early serpentinization started immediate to spreading centre, supposedly close to ridge-fracture zone intersection. Fresh and altered mafic rocks as well as rodingitized plagiogranites, together with partly serpentinized metamorphic peridotites were transported away from the mid-ocean spreading centre.

2. The majority of the Palaeozoic oceanic lithosphere was probably consumed by a subduction zone; however, the "surviving" fragments (ultrabasic and mafic massifs) were thrust onto the mantle wedge. Boninite-like rocks should have been formed at the fore-arc setting, simultaneously with obduction of oceanic crust. Their formation at the back-arc setting is implausible, since there are not unequivocal evidences of synchronous arc-related rock series.

3. Bulk serpentinization of ultramafic rocks and simultaneous rodingitization of mafic rocks took place up to the final stage of oceanic crust obduction. However, late mafic dykes penetrated previously serpentinized ultramafic bodies and these dykes are not rodingitized, hence rodingitization (and serpentinization) died away during penetration of boninite-affinity dykes. Protolith of the late boninite-type dykes represent modified geochemical signature probably modified due to continental contamination of the source (Góry Sowie block influence?).

4. Several episodes of continental metamorphism of serpentinites and rodingites produced antigoritic serpentinites and metarodingites, amphibolite-facies ultrabasic rocks and amphibolites, and numerous tectonic breccias. Most of these episodes can be roughly correlated with Variscan HT-LP metamorphism.

The variability of ultramafic and mafic rocks, rodingites and serpentinites in the immediate vicinity of Góry Sowie block can be explained as the result of rock displacement which formed a chaotic structure of the Lower Silesia ophiolite.

The current data reveal potential link between ultramafic-mafic rock series occurring within Góry Sowie unit and those neighbouring to Góry Sowie block. Our data are compatible with the hypothesis that ultramafic-mafic assemblages from Góry Sowie can be relics of either MOR-ophiolite sequence or small sections of supra-subduction zone (SSZ) mantle wedge. Crustal contamination of both rodingite and amphibolite protoliths seemingly reflects pre-Variscan change of plate configuration and emplacement of the Góry Sowie unit into mantle peridotite section.

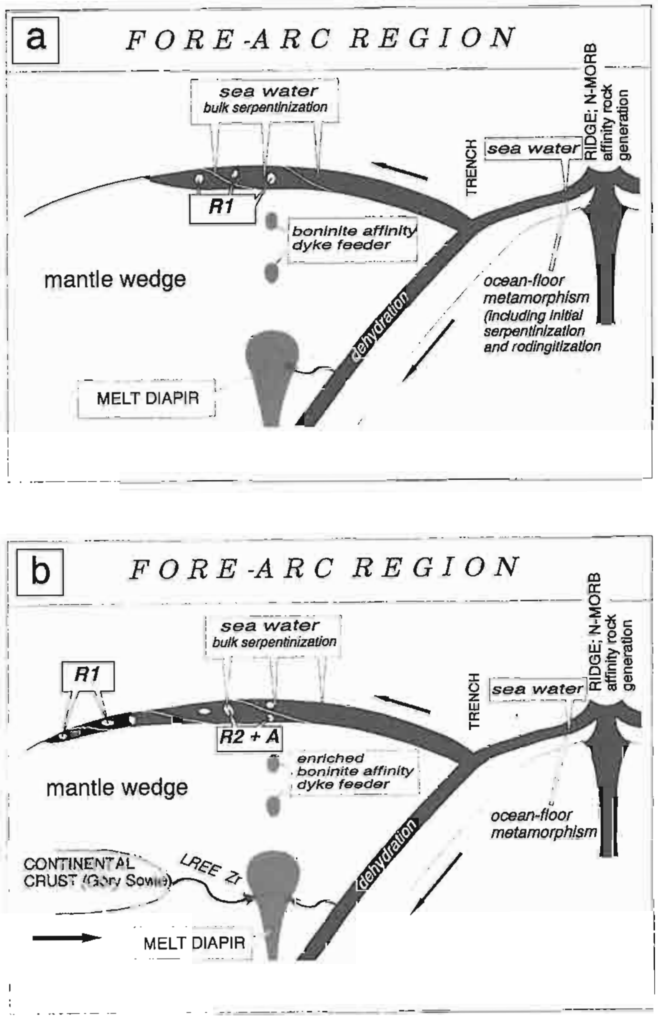

Fig. 17. A possible geodynamic model of the Sudetic ophiolite (not to scale): **a** — formation of oceanic crust comprising N-MORB affinity mafic rocks, their ocean floor metamorphism and initial serpentinization, obduction of the oceanic crust onto supra subduction mantle wedge, penetration of early boninite-affinity mafic feeder dykes and their rodingitization simultaneous with bulk serpentinization of ultramafic rocks; **b** — formation of late boninite- affinity dykes (LREE and Zr enriched protolith), seemingly related to crustal contamination of mantle source; serpentinization died away during penetration of these dykes; model of boninite petrogenesis according to R. N. Taylor *et al.* (1992)

R — rodingite protolith and rodingite (R1 — rodingites formed from non-evolved protolith, R2 — rodingites formed from enriched protolith), A — protolith of amphibolite dykes within ultrabasic rock

Przypuszczalny model geodynamiczny ofiolitu Sudetów (bez skali): **a** — powstanie skorupy oceanicznej zawierającej skały maficzne o pokrewieństwie N-MORB, ich metamorfizm w warunkach dna morskiego oraz inicjalna serpentynizacja, obdukcja skorupy oceanicznej na klin płaszcza nad strefą subdukcji, penetracja wczesnych dajek o pokrewieństwie boninitowym do obdukowanego ofiolitu, ich rodingityzacja równoczesna z masową serpentynizacją skał ultrazasadowych; **b** — powstanie późnych dajek o pokrewieństwie boninitowym (protolit wzbogacony w LREE i Zr); przypuszczalnie modyfikację tę spowodowała kontaminacja materiałem skorupowym; serpentynizacja zamierała podczas penetracji tych dajek; model petrogenetyczny boninitów według R. N. Taylora i in. (1992)

R — protolit rodingitów i rodingity (R1 — rodingity powstałe z niezmodyfikowanego protolitu, R2 — rodingity powstałe ze zmodyfikowanego (wzbogaconego) protolitu, A — protolit dajek amfibolitowych w skałach ultrazasadowych

The observed relations between the Góry Sowie and adjacent serpentinites seem to be similar to these of Granulitgerbirge massif/serpentinites and gabbro from Saxothuringian zone (C. D. Werner, 1981); both suggest that some Palaeozoic ophiolites of Central Europe overlie granulite-massifs (likely emplaced into their SSZ-zones).

S. Speczik and W. Olszyński (1993) and J. Niśkiewicz and M. Sachanbiński (1995) reported evidences of PGE (platinum group elements)-mineralization from Jordanów–Gogołów and Szklary massifs. Boninite affinity of rodingite protolith and frequent occurrence of "ultramafic cumulates" both shed new light on the PGE potential of ultrabasic rocks from Sudetic ophiolite (e.g. S. Tanguay *et al.*, 1990; M. Leblanc, 1991; M. Ohnenstetter, 1992; R.-B. Pedersen *et al.*, 1993; N. B. J. Kieser, 1994; T. Augé, P. Maurizot, 1995; M. Economou-Eliopoulos, I. Vacondios, 1995; R. B. Larsen, T. Grenne, 1995; K. Yang *et al.*, 1995; M.-F. Zhou *et al.*, 1996).

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OFIOLIT SUDETÓW: NOWY MODEL GEODYNAMICZNY

Streszczenie

Ofiolit Sudetów obejmuje tektonity płaszczowe, skały intepretowane jako kumulaty ultramaficzne, kumulaty maficzne oraz dajki pakietowe, tj. prawie kompletny zespół skał zgodnych z umowną stratygrafią ofiolitową Penrose.

Tektonity płaszczowe tworzą trzy odrębne masywy ultrazasadowe wokół bloku Gór Sowich. Mimo intensywnej serpentynizacji czytelne są tekstury porfiroklastyczne typowe dla tektonitów płaszczowych i poikilitowa budowa tzw. kumulatów ultramaficznych. Charakterystyka chemiczna skał ultrazasadowych rejestruje zmienny stopień zubożenia źródła płaszczowego. Rozmieszczenie różnych odmian skał ultramaficznych i serpentynitów jest chaotyczne.

Człony maficzne ofiolitu są reprezentowane przez gabroidy i, podrzędnie, przez dajki pakietowe. W obu grupach skał zwykle widoczne są niskotemperaturowe zmiany hydrotermalne, przypisywane metamorfizmowi dna oceanicznego. Zapis geochemiczny skał maficznych ofiolitu dolnośląskiego wskazuje na pokrewieństwo do N-MORB (normalnych bazaltów grzbietu oceanicznego), jest jednak bimodalny: obok skał o charakterystyce typowej dla N-MORB lub zubożonych w pierwiastki inkompatybilne zdarzają się próbki wyraźnie wzbogacone w te pierwiastki.

Z innego rodzaju protolitu powstały rodingity (skały wapniowo-krzemianowe będące produktami ubocznymi serpentynizacji) i amfibolity z trzech masywów serpentynitowych wokół bloku Gór Sowich (Jordanów–Gogołów, Braszowice–Brzeźnica i Szklary). Cechują się one wyjątkowo niskimi zawartościami pierwiastków ziem rzadkich oraz tytanu, co sugeruje ich pokrewieństwo do serii boninitowej (skały typowe dla obszarów przedłukowych). W części próbek obserwuje się stopniowe wzbogacenie w pierwiastki z grupy lekkich ziem rzadkich, równoczesną zmianę stosunku Zr/Hf i pojawienie się dodatniej anonalii Eu. Zróżnicowanie to można przypisać procesom metasomatozy źródła magmowego na skutek dopływu fluidów uwolnionych z subdukowanej płyty oceanicznej i ich przypuszczalnej kontaminacji skorupowej nad strefą subdukcji.

Ponieważ człony ultrazasadowe i zasadowe ofiolitu dolnośląskiego wykazują charakterystykę skał powstałych w środowisku grzbietu oceanicznego, a protolit rodingitów i amfibolitów z dajek w skałach ultrazasadowych cechuje się pokrewieństwem boninitowym, można uznać skały ultrazasadowe z otoczenia bloku Gór Sowich za fragmenty obdukowanej skorupy oceanicznej. Przyczyną kontaminacji skorupowej protolitu amfibolitów i części rodingitów jest przypuszczalnie przedwaryscyjska zmiana konfiguracji płyt i wmontowanie bloku Gór Sowich w zespół skał płaszczowych.

Serpentynizacja skał ultramaficznych ofiolitu Sudetów i związana z nią rodingityzacja odbywały się prawdopodobnie dwustopniowo: została zainicjowana w pobliżu grzbietu śródoceanicznego, a następny jej etap zachodził na obszarze przedłukowym, równocześnie z powstawaniem nasunięcia ofiolitowego.

Mozaikowa budowa masywów serpentynitowych otaczających blok Gór Sowich jest rezultatem licznych epizodów tektoniki kruchej, których odbiciem jest również zróżnicowanie metamorficznych zespołów mineralnych rodingitów i amfibolitów.