The Middle Austro-Alpine Sieggraben structural complex – new data on geothermobarometry

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Stredno Austro-Alpínsky Sieggrabenský štruktúrny komplex – nové geotermobarometrické údaje

Abstract: The Sieggraben structural complex is located in the Eastern Alps and went through complicated tectonothermal evolution. Lithotypes are represented by metabasic rocks, metacarbonates, metapelites, and serpentinites. Metabasites consist of amphiboles and eclogites. The whole unit underwent two MP/HP metamorphic stages – a D1 prograde burial stage and a D2 exhumation stage. The D1 prograde burial stage resulted in the forming of Omp with over 30 % of Jd component, Am1, Pl1. *P-T* conditions of the D1 stage were calculated at 610–650 °C (Grt-Cpx geothermometer) and 16–17 kbar (Grt-Cpx-Pl-Qtz geobarometer). The D2 exhumation stage resulted in the forming of Am2, Pl2, and Cpx2 mineral association. *P-T* conditions of the D2 stage were set to 700 °C at 12 kbar by Grt-Bt geothermometer and Grt-Pl-Ky-Qtz geothermobarometer. Previously published *P-T* path was recalculated using new geothermobarometry calculations.

Key words: Eastern Alps, Sieggraben structural complex, metamorphic stages, geothermobarometry, *P-T* path, microstructures, symplectites

1. INTRODUCTION

This paper studies the Sieggraben structural complex (SSC) from the *P-T* evolution point of view through petrologic study of mineral parageneses D1 – D2, chemical rock compositions and geothermobarometry data. Based on the previous works by authors dealing with the Sieggraben structural complex (e.g. Tollmann, 1980; Frank et al., 1987; Frisch & Neubauer, 1989; Dallmeyer et al., 1992; Neubauer et al., 1992; Thöni & Jagoutz, 1993; Putiš & Korikovsky, 1993, 1995; Putiš et al., 1994, 2000; Korikovsky et al., 1998) and on the *P-T* path suggested by Putiš et al. (2002), in this paper we recalculated established *P-T* conditions and tried to model new evolution *P-T* path of the study area.

2. GEOLOGY OF STUDY AREA

The study area occurs in the Eastern Alps, about 80 km S of Vienna in Austria (Fig. 1). The Eastern Alps are located on the north side of the European Alpine chains and form about 500 km long belt with E – W direction (Gaidies et al., 2006). Geological boundaries include the Greywacky Zone to the north, the Periadriatic lineament to the south, and the margin of Cenozoic infill of the Vienna and Styrian basins to the east.

The Austroalpine (AA) basement units represent a complex napple pile composed of pre-Variscan metasediments with intrusion of pre-Variscan, Variscan, Permo-Triassic and Cenozoic magmatic rocks which experienced various grade of metamorphism of the Variscan, Permo-Triassic and Eo-Alpine ages (Schuster & Thöni, 2001). The whole basement consists of the several subunits, which are characterized by differences in lithology, mineralogy, ages, geochemistry, and their evolution. These subunits lack generally accepted subdivision and nomenclature but according to Schuster & Thöni (2001), subdivision can be expressed as follows: (i) from north to south and from bottom to top – the Wechsel, Waldbach, Semmering, Strallegg, and Sieggraben complexes; (ii) west – the Seckau-Troiseck-Floning, Speik, Wölz, Rappolt, Saualpe-Koralpe, and Plankogel complexes.

As shown above, the Sieggraben structural complex belongs to the Austroalpine structural complexes of the Eastern Alps, more accurately to the Austroalpine basement units. The eclogite-bearing complex is located on the south-eastern margin of the Eastern Alps, or within the internal part of the Alpine orogenic belt. Tollmann (1980) ascribed it to the Middle Austroalpine structural complex. The study area is located near villages of Sieggraben and Schwarzenbach, about 80 km south of Vienna.

Tectonostratigraphy of the Middle Austroalpine (MAA) and Lower Austroalpine (LAA) structural complexes is based on the work of Tollmann (1980). The top of the tectonostratigraphic profile is occupied by the MAA SSC, overlaying the LAA Grobgneiss and Wechsel structural complexes as the result of Lower Cretaceous collision. The MAA Sieggraben eclogitic lenses are commonly located within the ductile banded amphibolites or marbles and belong to a gneiss-amphibole-serpentine-marble lithological complex with some concordant

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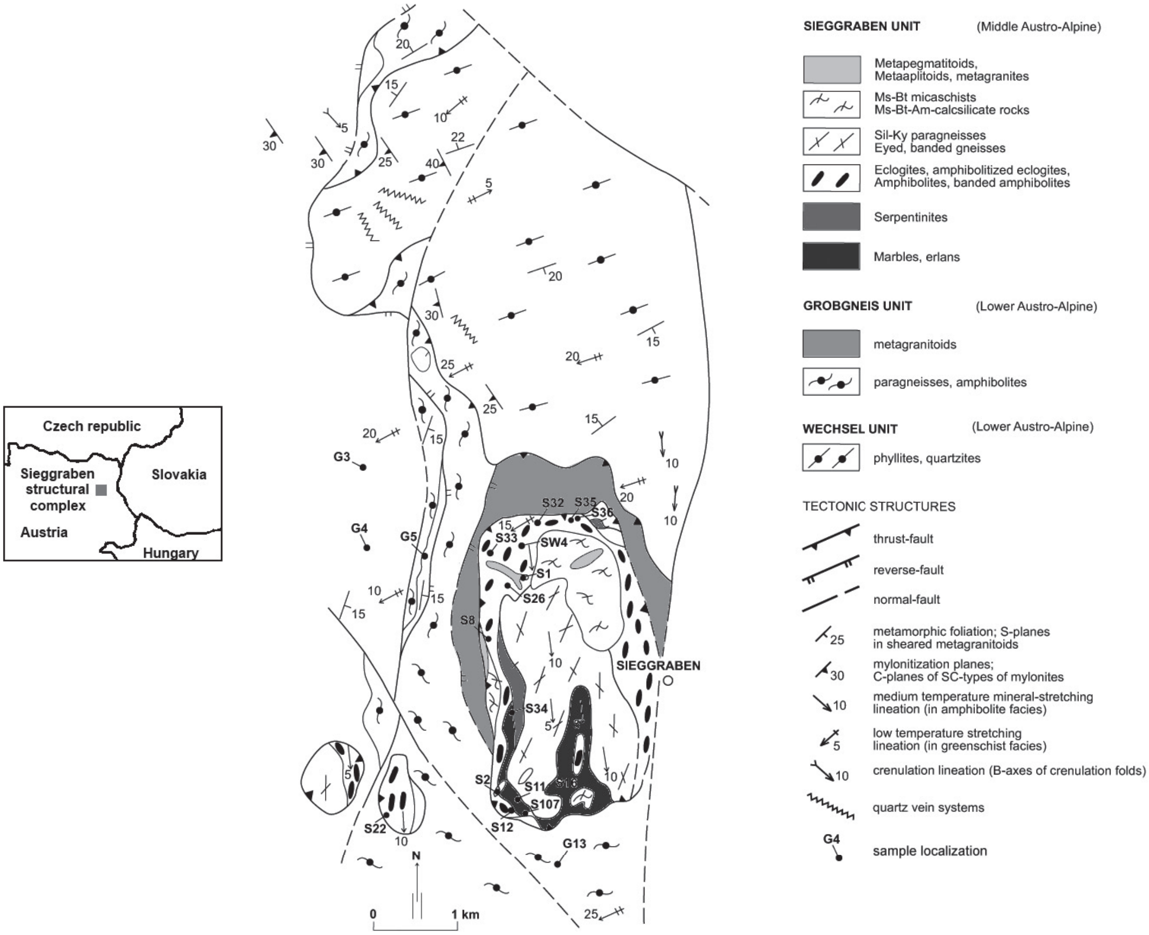

Fig. 1. Geological-tectonic sketch-map of the Sieggraben area (Putiš et al., 2000) with sample location.
Obr. 1. Geologicko-tektonická situačná mapa Sieggrabenu (Putiš et al., 2000) s lokalizáciou vzoriek.

to discordant veins of granitic-pegmatic orthogneiss, easily seen in outcrops (Putiš et al., 2002)

Based on the previous results and views, the Sieggraben structural complex (as the whole MAA basement itself), is derivated to have formed as a part of the Koriden terrane (Frisch & Neubauer, 1989; Neubauer & Frisch, 1993). It represents an accretional wedge, derived from the flysch-like sediments and the ocean fragments near a trench located on the upper (northern) Variscan plate (Matte, 1986, 1991).

There could be recognized two types of faults (Putiš et al., 2002): (i) younger (probably Late Cretaceous – Early Cenozoic structures) low-angle normal faults – in the footwall of the SSC and Grobgneiss structural complexes; top-to WSW movement along low-temperature stretching lineations defined by newly formed white mica, biotite, and chlorite; (ii) older (Early Cretaceous) higher-temperature extensional fabric, formed by parallel NNW – SSE directed D1 mineral and D2 stretching lineations and ductile layered structures; only recognizable in the internal part of the MAA Sieggraben structural complex (SSC).

The zircon-monazite U-Pb upper discordia intercept and whole-rock Rb-Sr isotope ages of the Sieggraben orthogneisses, 321 ± 8 Ma or 289 ± 16 Ma (Putiš et al., 2000), an Early Palaeozoic age is derivated for the MAA Sieggraben lithological complex as a minimum age. No relics of the pre-Alpine metamorphism have been preserved (Putiš et al., 2002). The U-Pb lower discordia intercept age of zircon and monazite of granitic orthogneisses of the Alpine reactivation of the SSC is about 105 Ma. It is interpreted to either date of the cooling of the SSC during the thrusting along a deep crustal detachment fault (between 750-500 °C), or to indicate the achieved maximum reactivation temperatures at around 770 °C (Putiš et al., 2000). The underlying LAA Wechsel structural complex (Wiesmath orthogneiss) has a similar intercept age and it is interpreted to date of coincidental Alpine metamorphism of the buried LAA structural complexes with the maximum temperatures slightly over 500 °C at 10 kbar, calculated by Grt-Chl and Grt-Bt thermometers and Phg barometer (Korikovsky et al., 1998). This time superimpose with the shortening period within the Meliata-Hallstatt basin passive continental margin (Putiš et al., 2002).

The SSC involves wide range of rock lithotypes: (i) metabasites – eclogites, amphibolites, and their mylonites; (ii) metaultramafites – serpentinites; (iii) metagranitoids and orthogneisses; (iv) metapelites – micaschists; (v) metacarbonates – marbles.

3. METHODS OF RESEARCH

Thin sections of collected samples were measured on electron probe micro-analyzer at Dionýz Štúr State Geological Institute, Bratislava, Slovakia (CAMECA – SX100) and at Eberhard Karls Universität Tübingen, Tübingen, Germany (JEOL 8900). Selected samples were shipped for whole-rock analyses to ACME Analytical Laboratories in Vancouver, Canada.

Based on the previous information for purpose of this paper, these geothermobarometers were chosen: (i) D1 burial stage: Grt-Cpx geothermometer, Grt-Cpx-Pl-Qtz geobarometer; (ii) D2 exhumation stage: Grt-Bt geothermometer, Grt-Pl-Ky-Qtz geobarometer.

For geothermobarometric calculations, analyses from this paper and some analyses published in the previous work were used (Putiš et al., 2000, 2002).

For the calculations Theriak-Domino v.140205 with its internal thermodynamic data set JUN92.bs was used (de Capitani & Petrakakis, 2010). Database JUN92.bs is almost identical to the Berman's data set (Berman et al., 1985). For some calculations, internal unpublished Microsoft Excel worksheets and c++ programs were used.

Grt-Cpx geothermometer

Due to the common appearance of garnet and clinopyroxene in high-grade metamorphic rocks, garnet-clinopyroxene geothermometer is one of the most widely used (Ravna & Paquin, 2003).

The principal chemical reaction involved in this geothermometer could be described as follows:

$$CaFeSi_2O_6 + \frac{1}{3}Mg_3Al_2Si_3O_{12} = CaMgSi_2O_6 + \frac{1}{3}Fe_3Al_2Si_3O_{12}$$

with derivated distribution constant for this reaction:

$$K_D = \frac{\left(\frac{Fe^{2+}}{Mg}\right)^{grt}}{\left(\frac{Fe^{2+}}{Mg}\right)^{cpx}}$$

where K_D is distribution coefficient. The calibration of Ravna (2000) was used in this paper.

Grt-Cpx-Pl-Qtz geobarometer

Based on the work of Newton & Perkins (1982), Eckert et al. (1991) recalibrated original garnet-pyroxene-plagioclase-quartz geobarometer to new more accurate version. Same input parameters were used, but enthalpy of reaction ΔH_R was replaced with new values based on the calorimetric experimental results (Eckert et al., 1991):

GAPES reaction:

$$P = 3.47 + 0.01307T + 0.003504T\ln K_A \ (\pm 1.55 \text{ kbar})$$

GADS reaction:

$$P = 2.60 + 0.01718T + 0.003596T\ln K_B \ (\pm 1{,}90 \text{ kbar})$$

These geobarometric calibrations are based on the following reactions:

$$CaAl_2Si_2O_8 + Mg_2Si_2O_6 = \frac{2}{3}Mg_3Al_2Si_3O_{12} + \frac{1}{3}Ca_3Al_2Si_3O_{12} + SiO_2$$

$$CaAl_2Si_2O_8 + CaMgSi_2O_6 = \frac{2}{3}Ca_3Al_2Si_3O_{12} + \frac{1}{3}Mg_3Al_2Si_3O_{12} + SiO_2$$

Grt-Bt geothermometer

The garnet-biotite geothermometer is ion exchange type thermometer based on the Fe-Mg exchange. After Holdaway et al. (1997) it is the most widely used thermometer for *T* estimation in medium-grade pelitic metamorphic rocks. The last revised and published equation is (Holdaway et al., 1997):

$$T(K) = \frac{41952 + 0{,}311P + G + B}{10{,}35 - 3R\ln K_D}$$

where $R = 8.31441\ J\cdot mol^{-1}\cdot K^{-1}$ is universal gas constant, T is temperature in Kelvin, P is pressure in bar, K_D is distribution coefficient, parameters G and B are given by evaluation in terms of Margules parameters:

$$G = 3RT\ln\left(\frac{\gamma\frac{Grt}{Mg}}{\gamma\frac{Grt}{Fe}}\right) \qquad B = 3RT\ln\left(\frac{\gamma\frac{Bt}{Fe}}{\gamma\frac{Bt}{Mg}}\right)$$

Grt-Pl-Ky-Qtz geobarometer

The end-member reaction for this geobarometer has been calibrated in many studies (e.g. Newton & Haselton, 1981; Hodges & Spear, 1982; Ganguly & Saxena, 1984; Hodges & Crowley, 1985; Koziol, 1989). This geobarometer is based on the following equilibrium reaction:

$$Ca_3Al_2Si_3O_{12} + 2Al_2SiO_5 + SiO_2 = 3CaAl_2Si_2O_8$$

The calibration could be described as:

$$7635 - 19.66T + 0.7963(P\text{-}1) + 3T\ln(X_{Ca,Pl}/X_{Ca,Grt}) = 0$$

where T is temperature in Kelvin, P is pressure in bar, $X_{Ca,Pl}$ is concentration of calcium in plagioclase and $X_{Ca,Grt}$ is concentration of calcium in garnet. Uncertainty on pressure calculated by this geobarometer is about ±1.3 kbar.

Tab. 1. Mineral description of selected samples.
Tab. 1. Mineralogický opis vybraných vzoriek.

Sample	Mineral association	Lithotype	Localization
Metabasites			
S-35	Omp, Grt, Rt, Ilm	Eclogite	Sieggraben
Metaultramafites			
EG-S	Ol, Opx, Tr, Atg	Serpentinite	Egenbuch – road cut
Metagranitoids and orthogneisses			
S-28B	Qtz, Kfs, Pl, Ms, Grt, Tur	Metagranitoid/orthogneiss	Sieggraben
S-28A	Qtz, Pl, Bt, Tur, Ky	Orthogneiss	Sieggraben
Metapelites			
23c	Tur, Qtz, Phe, Pl	Micashist	Sieggraben
Metacarbonates			
24c	Cal, Grt, Am, Bt, Ep, Cpx	Calc-silicate rock	Sieggraben - Calvary

4. RESULTS

Collected representative samples (some of them are later used in descriptions) are presented in the Tab. 1 with location on Fig. 1.

Description of individual lithotypes is based on the macroscopic observations, microscopic study and electron microprobe analysis. Based on the mentioned methods mineral associations were divided, according to their *P-T* conditions, into several tectonometamorphic stages. The first D1 stage corresponds to burial event of the Sieggraben structural complex and the second D2 stage corresponds to exhumation event with dynamic recrystallization of primary mineral associations.

4.1. Metabasites

Metabasic rocks in the study area are represented by HP amphibolites, eclogites, and transitional types, e.g. eclogitized gabbros. The HP amphibolites have association of Am1-Pl1-Grt. This association is product of the D1 burial stage. The HP amphibolites show signs of transitional textures to eclogites accompanied by forming of Omp and also growing of Prp-rich rims in garnet crystals. The D2 retrograde stage resulted in recrystallization of prismatic Am1 into fine-grained aggregates of Am2 and Pl2. During the D2 stage symplectitic intergrowth of Cpx2 and Pl2 replaced primary pyroxene (Cpx1) and amphibole (Am1) (Fig. 2).

Eclogites comprise association of Omp-Grt-Zo-Rt. Omphacites are presented as large prismatic crystals surrounded by matrix with Am (Am1), garnet, zoisite, rutile, and rare plagioclase (Pl1). Omphacite is overgrowing remaining minerals which are presented as inclusions. Overgrowing omphacite is the result of the D1 stage and along with Am1 defines metamorphic lineation D1 in eclogites and amphibolites. The D2 exhumation stage is represented by newly created symplectites formed with Cpx2 and Pl2 by replacing Omp and Am1.

Distinct generations of minerals display different chemical composition. Am1 has a composition of magnesio-hornblende; Am2 is verging to tschermakite with increasing barroisite

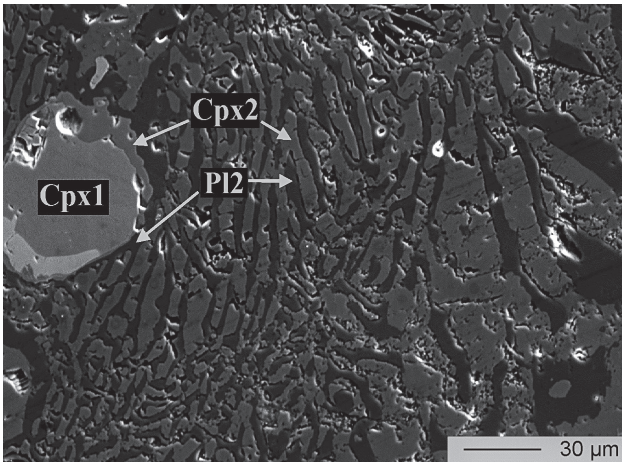

Fig. 2. Sample S-35; Symplectitic intergrowth of clinopyroxene and plagioclase after omphacite.
Obr. 2. Vzorka S-35; Symplektitické prerastanie klinopyroxénu a plagioklasu po omfacite.

component. Cpx1 has higher proportion of jadeite component (>30 %) than Cpx2 and in classification diagrams; their fields can be clearly distinguished (Cpx1 mainly in the QUAD field, Cpx2 in the field of Ca-Na pyroxenes). Feldspar is represented by albite with An_{10-20}. Garnet has composition of almandine (50-60 %) with minor proportion of grossular (20-30 %) and pyrope (10-20 %). Garnets display weak chemical zoning with increasing pyrope (Mg) and decreasing spessartine (Mn component) from the core to the rim as it is documented by two composition profiles of garnets. It suggests prograde trend of garnet evolution.

The D2 stage resulted in deformation of amphibolites, which were transformed into mylonites. In process of dynamic recrystallization, primary Omp-Am1-Pl1 assemblage was surrounded by newly created mylonitic matrix which is composed of Am2 and Pl2. Omphacite crystals were fractured without significant recrystallization. Degree of mylonitization displays in the proportion of dynamically recrystallized matrix. The newly created fine-grained matrix with Am2 and Pl2 indicates the D2 exhumation stage.

Mineral composition of mylonites is similar to eclogites and amphibolites. Am1 is also of magnesio-hornblende composition with increasing tschermakite component in Am2. Cpx2 has jadeite component below 20 % and belong to QUAD field.

4.2. Metaultramafites

Remnants of olivine and orthopyroxene crystals are 0.5-1 mm in size and are surrounded by serpentinized matrix with Atg.

4.3. Metagranitoids and orthogneisses

Orthogneisses in the study area have coarse-grained texture with signs of ductile deformation. Primary mineral association is represented by Qtz-Kfs-Pl-Ms-Grt-Tur and corresponds to granitic or pegmatitic protolite. Ductile deformation resulted in the formation of younger mica and also in deformation of feldspars and quartz.

Quartz from the primary association of granite/pegmatite was forming veins surrounded by coarse-grained feldspar. Deformation of quartz aggregates developed several generations of ribbons: the first generation (Qtz1) as a result of stretching in longitudal direction, and the second generation (younger, Qtz2) ribbons as a result of forming deformation bands within the older ribbons. Later migration of mentioned ribbons resulted in development of new quartz aggregates (Qtz3) (Fig. 3).

Feldspars are represented by porphyroclasts of the first generation K-feldspars (Kfs1) and plagioclase (Pl1), fine-grained aggregates of younger plagioclase (Pl2), and K-feldspars (Kfs2) as a result of dynamic recrystallization (Pl1 → Pl2, Kfs1 → Kfs2). Plagioclase Pl2 and K-feldspars Fsp2 develop grain matrix surrounding Pl1 and Kfs1.

Micas are represented by muscovite and phengite (Phe1) forming larger tabular crystals, which are sporadically replaced by muscovite and phengite (Phe2) in form of fine-grained aggregates.

Newly formed quartz, feldspars and micas represents the D2 lineation of these rocks.

4.4. Metapelites

Micaschists of the SSC have fine-grained texture. Primary mineral association is represented by Qtz-Ms-Bt±Pl±Grt±Tur±Rt.

Primary medium grained quartz (Qtz1) is partly replaced by fine-grained quartz (Qtz2) as a result of ductile deformation, which corresponds to the D2 stage. Most of the primary quartz (Qtz1) shows significant undulose extinction and forms large ribbons along mica crystals. Large mica crystals are partly deformed to mica fish structures (Fig. 4). The D2 exhumation stage is also indicated by replacement of garnet with biotite and kyanite or sillimanite. Garnet has almandine composition with almandine component over 70 %, pyrope component between 15-20 % and spessartine component between 3-5 %. Grossular component is very low; below 2 %.

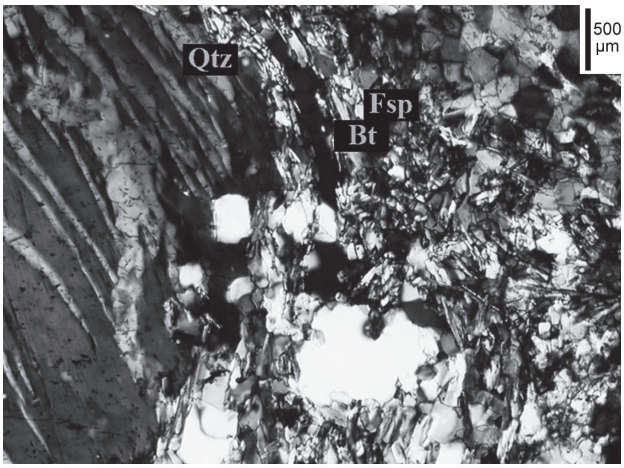

Fig. 3. Sample S-28b; Migration of ribbons resulted in development of new quartz aggregates.

Obr. 3. Vzorka S-28b; Migrácia ribónov ako výsledok vývoja nových agregátoch kremeňa.

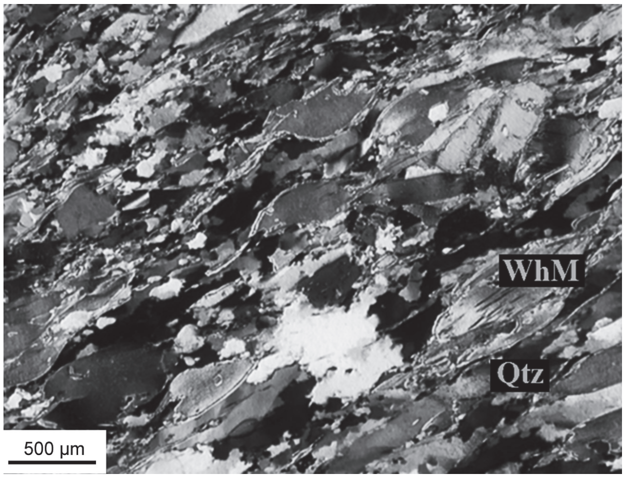

Fig. 4. Sample 23c; Large mica crystals - partly deformed to mica fish structures. WhM – White Mica.

Obr. 4. Vzorka 23c; Veľké kryštály sľudy - čiastočne zdeformované do "fish" štruktúr. WhM – svetlá sľuda.

Tab. 2. Representative chemical analyses of garnet and clinopyroxene in eclogites (sample 35).

Tab. 2. Reprezentatívne chemické analýzy granátu a klinopyroxénu v eklogitoch (vzorka 35).

	35	35	35	35		35	35	35	35
	rim	core	rim	core		cpx1	cpx1	cpx2	cpx2
SiO_2	38.10	38.05	37.97	37.93	SiO_2	52.66	53.44	53.32	53.29
TiO_2	0.08	0.43	0.06	0.06	TiO_2	0.17	0.19	0.06	0.07
Al_2O_3	21.42	21.37	21.78	21.32	Al_2O_3	8.72	8.91	1.40	1.71
Cr_2O_3	0.03	0.02	0.02	0.00	Fe_2O_3	4.59	4.75	3.96	4.94
Fe_2O_3	0.62	0.13	0.70	0.59	FeO	4.10	4.59	6.53	6.39
FeO	24.81	24.13	24.44	24.27	MnO	0.02	0.02	0.05	0.02
MnO	0.82	2.63	0.93	2.85	MgO	7.68	7.56	12.41	12.27
MgO	3.84	3.35	3.87	2.89	CaO	14.29	13.97	21.26	21.01
CaO	9.99	9.80	9.97	9.74	Na_2O	5.84	6.05	1.69	1.85
Na_2O	0.07	0.12	0.09	0.13	K_2O	0.06	0.02	0.01	0.01
Suma	99.77	100.03	99.82	99.78	F	0.00	0.00	0.00	0.00
					Cl	0.13	0.02	0.00	0.02
Si^{4+}	2.99	2.99	2.98	3.00	suma	98.26	99.52	100.68	101.58
Al^{3+}	0.01	0.01	0.02	0.00	O=F	0.00	0.00	0.00	0.00
Σ	3.00	3.00	3.00	3.00	O=Cl	-0.06	-0.01	0.00	-0.01
Ti^{4+}	0.00	0.03	0.00	0.00	suma	98.20	99.51	100.68	101.57
Al^{3+}	1.97	1.97	1.99	1.98					
Cr^{3+}	0.00	0.00	0.00	0.00	Si^{4+}	1.95	1.95	1.97	1.96
Fe^{3+}	0.02	0.00	0.01	0.01	Al^{3+}	0.05	0.05	0.03	0.04
Fe^{2+}	0.00	0.00	0.00	0.00	Ti^{4+}	0.00	0.01	0.00	0.00
Σ	2.00	2.00	2.00	2.00	Al^{3+}	0.33	0.34	0.03	0.03
Fe^{3+}	0.02	0.00	0.03	0.02	Fe^{3+}	0.13	0.13	0.11	0.14
Fe^{2+}	1.63	1.59	1.60	1.60	Mg^{2+}	0.42	0.41	0.68	0.67
Mn^{2+}	0.05	0.18	0.06	0.19	Fe^{2+}	0.12	0.12	0.17	0.16
Mg^{2+}	0.45	0.39	0.45	0.34	Mn^{2+}	0.00	0.00	0.00	0.00

	35	35	35	35		35	35	35	35
	rim	**core**	**rim**	**core**		**cpx1**	**cpx1**	**cpx2**	**cpx2**
Ca^{2+}	0.84	0.83	0.84	0.82	**Fe^{2+}**	0.01	0.02	0.03	0.04
Na^{+}	0.01	0.02	0.01	0.02	**Mn^{2+}**	0.00	0.00	0.00	0.00
Σ	3.00	3.00	3.00	3.00	**Mg^{2+}**	0.00	0.00	0.00	0.00
Pyr	15.04	13.16	15.14	11.42	**Ca^{2+}**	0.57	0.55	0.84	0.83
Spess	1.81	5.87	2.06	6.40	**Na^{+}**	0.42	0.43	0.12	0.13
Alm	55.03	53.30	54.76	54.50	**K^{+}**	0.00	0.00	0.00	0.00
And	1.05	0.22	0.38	0.74	**F^{-}**	0.00	0.00	0.00	0.00
Gross	26.99	27.37	27.61	26.93	**Cl^{-}**	0.01	0.00	0.00	0.00
					Jd =	32.87%	33.42%	4.43%	4.82%

Tab. 3. Representative chemical analyses of garnet and biotite in gneisses (sample 28).
Tab. 3. Reprezentatívne chemické analýzy granátu a biotitu v rulách (vzorka 28).

	28	28	28	28		28	28
	rim	**core**	**rim**	**core**			
SiO_2	38.05	37.65	37.86	37.83	**SiO_2**	35.86	36.33
TiO_2	0.00	0.08	0.03	0.02	**TiO_2**	3.00	3.73
Al_2O_3	21.69	21.60	21.66	21.74	**Al_2O_3**	18.30	18.19
Cr_2O_3	0.00	0.00	0.03	0.01	**FeO**	18.12	17.56
Fe_2O_3	0.05	0.23	0.53	0.12	**MnO**	0.06	0.03
FeO	33.89	34.24	33.76	33.81	**MgO**	9.95	10.07
MnO	1.54	1.65	1.69	1.72	**CaO**	0.05	0.00
MgO	5.07	4.53	4.71	4.79	**Na_2O**	0.09	0.08
CaO	0.75	0.64	0.78	0.81	**K_2O**	9.32	9.48
Na_2O	0.01	0.06	0.10	0.03	**H_2O***	3.54	3.58
suma	101.05	100.68	101.14	100.88	**F**	0.00	0.00
					Cl	0.47	0.44
Si^{4+}	2.99	2.98	2.98	2.99	**suma**	98.76	99.49

	28	28	28	28		28	28
	rim	core	rim	core			
Al^{3+}	0.01	0.02	0.02	0.01	**O=F**	0.00	0.00
Σ	3.00	3.00	3.00	3.00	**O=Cl**	-0.23	-0.22
Ti^{4+}	0.00	0.00	0.00	0.00	**suma**	98.52	99.26
Al^{3+}	2.00	2.00	1.99	2.01			
Cr^{3+}	0.00	0.00	0.00	0.00	**Si^{4+}**	2.73	2.73
Fe^{3+}	0.00	0.00	0.00	0.00	**$Al^{3+}T$**	1.27	1.27
Fe^{2+}	0.00	0.00	0.00	0.00	**Ti^{4+}**	0.17	0.21
Σ	2.00	2.01	2.00	2.01	**$Al^{3+}Z$**	0.37	0.34
Fe^{3+}	0.00	0.01	0.03	0.01	**Fe^{2+}**	1.15	1.10
Fe^{2+}	2.23	2.27	2.22	2.23	**Mn^{2+}**	0.00	0.00
Mn^{2+}	0.10	0.11	0.11	0.11	**Mg^{2+}**	1.13	1.13
Mg^{2+}	0.59	0.54	0.55	0.56	**Ca^{2+}**	0.00	0.00
Ca^{2+}	0.06	0.05	0.07	0.07	**Na^{+}**	0.01	0.01
Na^{+}	0.00	0.01	0.01	0.00	**K^{+}**	0.90	0.91
Σ	3.00	2.99	3.00	2.99	*I··*	0.08	0.08
Pyr	19.86	17.94	18.53	18.88	**F^{-}**	0.00	0.00
Spess	3.43	3.71	3.78	3.85	**Cl^{-}**	0.06	0.06
Alm	74.60	76.53	75.50	74.99	**OH^{-}**	1.94	1.94
And	0.00	0.00	0.08	0.00			
Gross	2.11	1.82	1.92	2.20			

4.5. Metacarbonates

Metacarbonates in the study area are represented by calc-silicate rocks and marbles. Calc-silicate rocks comprise mineral association of Cal-Am-Bt-Pl-Ep-Grt-Scp-Cpx or Fo-Phl-Grt-Spl-Cal with strongly serpentinized Fo to Atg.

Olivine in metacarbonates is highly magnesian forsterite (forsterite molecule ratio is higher than 0.9). Clinopyroxene belongs to QUAD pyroxenes and has the diopside composition; it is typically amphibolitized. Amphibolization of Cpx and serpentinization of Fo in metacarbonates is related to the D2 exhumation stage. Calcite shows characteristic twin lamellae fabric.

4.6. Geothermobarometry

As mentioned in the previous chapters, acquired whole-rock chemical analyses and microprobe analyses of minerals (Tab. 2 and 3) from selected lithotypes were used in geobarometric and geothermobarometric calculations. Acquired results are presented in Tab. 4 sorted by stage of metamorphism. Only valid values are presented in the table. New calculated data were used

Tab. 4. *P-T* **estimation of burial (D1) and exhumation (D2) stages of metamorphism – the metabasic rocks (S35, S35b, S35c) and gneisses and orthogneisses (S28, S21, 23c).**

Tab. 4. Odhad *P-T* **podmienok prográdneho (D1) a exhumačného (D2) štádia metamorfózy – metabázické horniny (S35, S35b, S35c), ruly a ortoruly (S28, S21, 23c).**

Sample	Mineral association	T [°C]	P [kbar]	Indicated stage of metamorphism
		Grt-Bt (Holdaway et al., 1997)	Grt + Pl + Ky + Qtz (Koziol, 1989)	
S28	Qtz, Grt, Ky, Fsp, Pl, Ms	700 ± 30	12	D2 stage
S21	Phe, Ms, Bt, Qtz, Kfs, Pl	630 ± 30	6	D2 stage
23c	Qtz, Grt, Ky, Fsp, Pl, Ms	600 ± 30	4	D2 stage
Sample	**Mineral association**	**T [°C]**	**P [kbar]**	**Indicated stage of metamorphism**
		Grt-Cpx (Ravna, 2000)	Grt-Cpx-Pl-Qtz (Eckert et al., 1991)	
S35	Grt, Cpx, Qtz, Pl, Rt, Zo	620-650 ± 34	17	D1 stage
S35b	Grt, Cpx, Qtz, Pl, Rt	610-620 ± 34	16-17	D1 stage
S35c	Grt, Cpx, Qtz, Pl, Rt	620-630 ± 34	17	D1 stage

for precising of the estimated *P-T* path of the Sieggraben structural complex (Fig. 5) by Putiš et al. (2000, 2002).

5. DISCUSSION

The Sieggraben structural complex shows the great variability of lithologies. The major lithotypes are represented by metabasic rocks in association with metapelites, metacarbonates with variable proportion of siliceous matter, and serpentinites. The whole lithological sequence is cut by veins of leucocrate granite to pegmatite metamorphosed to orthogneiss. This is likely an Early Palaeozoic basement complex with an unknown Variscan metamorphic grade after a strong Alpine reactivation (Neubauer, 1994; Dallmeyer et al., 1996; Froitzheim et al., 1996, Putiš et al., 2000). Metabasites are represented by amphibolites to eclogites and their mylonites but as suggested by the whole rock composition, they have the MORB protolith.

The rocks of the Sieggraben structural complex underwent two MP/HP metamorphic stages. The first stage was induced by continental subduction of a pre-Alpine basement fragment and led to the formation of HP rocks in eclogite facies (Putiš et al., 2002). Eclogites and HP-amphibolites with Pl are products of this stage. The D1 prograde burial stage from the amphibolites to eclogite facies resulted in the forming of a mineral association with clinopyroxene omphacite with over 30 % of jadeite component. It is also documented on the increasing pyrope component in garnet rims.

The D2 exhumation stage displays in the forming of a new mineral association with the second generation of Am, Pl and Cpx. Ductile D2 deformation led to forming of layered textures, mylonites, and also symplectites. Prismatic Cpx1 and Am1 were dynamically recrystallized into fine grained aggregates of Cpx2+Zo2 and Am2+Pl2, respectively. The beginning stage of exhumation also resulted in the forming of symplectitic intergrowth of Cpx2+Pl2 replacing Cpx1 and Am1. Lower pressure is documented by the increased content of barroisite component in Am2 and decreased content of jadeite (<20 %) in Cpx2. Prograde zoning of garnet indicates slight increase of the temperature during the D2 stage but decrease of Jd in Cpx2 is the evidence of decreasing pressure during the exhumation.

Continuing exhumation displays in the increasing of tschermakite component in amphibole. This Al-rich tschermakite was described in previous works as rimming overgrowths on garnet (Putiš et al., 2002). It also led to serpentinization of olivine and amphibolization of clinopyroxene in calc-silicate rocks.

The *P-T* path calculated on basis of geothermobarometric data from this paper (Fig. 5) is a little different to the previous model of the *P-T* path from the work of Putiš et al. (2002). Peak conditions of the D1 burial stage were calculated to 610-650 °C and 16-17 kbar with Grt-Cpx geothermometer (Ravna, 2000) and Grt-Cpx-Pl-Qtz geobarometer (Eckert et al., 1991) on eclogite. In comparison to previous model the temperature of eclogite-facies metamorphism is lower while the pressure is higher.

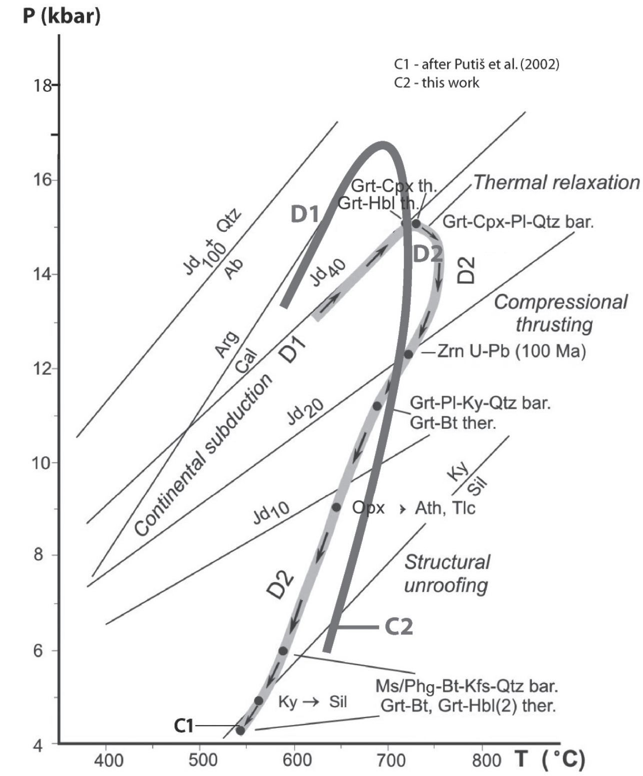

Fig. 5. Estimated *P-T* path. C1 – after Putiš et al. (2002), C2 – this work; PT-1 – peak D1 stage, PT-2 – D2 stage, PT-3 – lower D2 stage.

Obr. 5. Odhadnutá *P-T* cesta. C1 – podľa Putiš et al. (2002), C2 – táto práca; PT-1 – vrcholné D1 štádium, PT-2 – D2 štádium, PT-3 – nižšie D2 štádium.

Calculated *P-T* path indicates a rapid uplift of the SSC probably by an obduction-like process in form of a collision-driven extension exhumation (Putiš et al. 2000). At the first stage of exhumation, the temperature increased and is set to 700 °C at 12 kbar by Grt-Bt geothermometer (Holdaway et al., 1997) and Grt-Pl-Ky-Qtz geothermobarometer (Koziol, 1989) on orthogneiss. Another point on the *P-T* path is defined by Grt-Bt geothermometer (Holdaway et al., 1997) and Grt-Pl-Ky-Qtz geothermobarometer (Koziol, 1989) to 600 °C at 4 kbar on micaschist. The slope of the D2 stage on the calculated *P-T* path is steeper in comparison to previous model by Putiš et al. (2000, 2002). It indicates faster rate of exhumation as proposed by previous model (Putiš et al., 2000, 2002), but a little slower cooling rate.

The Sieggraben structural complex formed during the Cretaceous orogeny induced by collision of the Austro-Alpine continental crust and the Tisia continent in the south-eastern direction after closure of the Middle Triassic-Early Jurassic Meliata-Halstatt Ocean basin in the Middle to Late Jurassic at ca. 150 Ma (Dallmeyer et al., 1996). In the Western Carpathians, this orogeny resulted in the formation of the Meliatic Unit with HP metamorphosis up to blueschist facies (Faryad, 1997). The presence of eclogite facies rocks in the SSC suggests a shortening and continental subduction of some AA basement fragments within the passive continental margin (Neubauer 1994; Putiš et al., 2000).

In the AA units the eclogite-facies, metamorphism took place only in the MAA unit. LAA unit also underwent LT(MT) – MP(HP) metamorphism during the Early Cretaceous (Korikovsky et al. 1998) but the Upper AA unit escaped from the zone of continental subduction and was stacked over thickening wedge of the continental collision (Platt, 1993). This indicates that the suture zone after the closure of the Meliata-Halstatt Ocean could be located between the root zone of the Upper AA unit and the Southern Alps (Putiš et al., 2002). The continental underthrusting zone that includes eclogite-facies metamorphosed MAA unit with the SSC can be located between the Upper AA unit root zone and the northern margin of the AA unit (Putiš et al., 2002).

6. CONCLUSIONS

The rocks of the Sieggraben structural complex (metabasic rocks, metagranitoids, metapelites, metacarbonates and serpentinites) underwent two MP/HP metamorphic stages.

The D1 prograde burial stage from the amphibolites to eclogite facies resulted in the formation of a mineral association with Omp with over 30 % of Jd component, Pl1 and Am1. Peak conditions of the D1 burial stage were calculated to 610-650 °C and 16-17 kbar with Grt-Cpx geothermometer (Ravna, 2000) and Grt-Cpx-Pl-Qtz geobarometer (Eckert et al., 1991) on eclogite.

The D2 exhumation stage displays in the forming of a new mineral association with the second generation of Am, Pl, and Cpx. Ductile D2 deformation led to forming of layered textures, mylonites and also symplectites. Prismatic Cpx1 and Am1 were dynamically recrystallized into fine grained aggregates of Cpx2+Zoi2 and Am2+Pl2, respectively. The beginning stage of exhumation also resulted in the forming of symplectitic intergrowth of Cpx2+Pl2 replacing Cpx1 and Am1. Prograde zoning of garnet indicates slight increase of the temperature during the D2 stage but decrease of Jd in Cpx2 is the evidence of decreasing pressure during the exhumation.

Calculated *P-T* path indicates a rapid uplift of the Sieggraben structural complex probably by an obduction-like process in form of a collision-driven extension exhumation (Putiš et al. 2000). At the first stage of exhumation the temperature increased and is set to 700 °C at 12 kbar by Grt-Bt geothermometer (Holdaway et al., 1997) and Grt-Pl-Ky-Qtz geothermobarometer (Koziol, 1989) on orthogneiss. Another point on the *P-T* path is defined by Grt-Bt geothermometer (Holdaway et al., 1997) and Grt-Pl-Ky-Qtz geothermobarometer (Koziol, 1989) to 600 °C at 4 kbar on micaschist. The slope of the D2 stage on the calculated *P-T* path is steeper in comparison to the previous model by Putiš et al. (2000, 2002). It indicates faster rate of exhumation as proposed by the previous model (Putiš et al., 2000, 2002), but a little slower cooling rate. These differences between old and new calculations arise from newly calibrated geothermobarometers.

New petrological and geothermobarometric data confirm and in some aspects precise the model of the polyphase development of the Sieggraben structural complex with the phase of burial during the compression wedge formation (D1 stage) and later phase of the unroofing and exhumation (D2 stage) as proposed by Putiš et al. (2000, 2002).

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Resumé: Horniny sieggrabenského štruktúrneho komplexu sú reprezentované niekoľkými litologickými suitami. Dajú sa rozdeliť na metabáziká (eklogity, amfibolity a ich mylonity), metaultramafity (serpentinity), metagranitoidy a ortoruly, metapelity (svory, pararuly), metakarbonáty (mramory). Metabáziká majú typickú minerálnu asociáciu s niekoľkými generáciami Cpx, Am, Pl, Grt, Zo. Serpentinity s Ol a Opx sú serpentinizované za vzniku Atg. Metagranitoidy a ortoruly s asociáciou Qtz-Kfs-Pl-Ms-Grt-Tur majú granitový až pegmatitový protolit. Metakarbonáty majú minerálne asociácie Cal-Am-Bt-Pl-Ep-Grt-Scp-Cpx alebo Fo-Phl-Grt-Spl-Cal, pričom Fo je výrazne serpentinizovaný na Atg.

Horniny sieggrabenského štruktúrneho komplexu boli metamorfované v dvoch MP/HP metamorfných štádiách. V prográdnom štádiu D1 v amfibolitovej až eklogitovej fácii viedlo k vzniku minerálnej asociácie s Omp ($Jd_{0,30}$), Pl1 a Am1. Amfibol má zloženie hornblendu. *P-T* podmienky štádia D1 boli vypočítané na 610-650 °C a 16-17 kbar pomocou Grt-Cpx geotermometra (Ravna, 2000) a Grt-Cpx-Pl-Qtz geobarometra (Eckert et al., 1991) na eklogite. Metapelity obsahujú asociáciu Qtz-Ms-Bt±Pl±Grt±Tur±Rt.

Exhumačné štádium D2 viedlo k vzniku metamorfnej asociácie s Am2, Pl2 a Cpx2. Podiel jadeitového komponentu v Cpx2 klesá výrazne pod 30%. Am2 sa zložením posúva k tschermakitu, pričom stúpa podiel barroisitového komponentu. Duktílna deformácia spôsobila vznik páskovanej textúry, mylonitov a symplektitov. Prizmatický Cpx1 a Am1 dynamicky rekryštalizovali za vzniku jemnozrnných agregátov Cpx2+Zoi2 a Am2+Pl2. Počiatočná fáza exhumácie viedla tiež k vzniku symplektitických prerastaní Cpx2+Pl2 z pôvodných Cpx1 a Am1. Prográdna zonalita granátu s nárastom pyropového a poklesom spessartínového komponentu od stredu k okraju indikuje nárast teploty v iniciálnej fáze štádia D2, avšak pokles jadeitovej zložky v Cpx2 dokazuje pokles tlaku počas exhumácie. Vypočítaná *P-T* dráha indikuje prudký výzdvih sieggrabenského komplexu pri procese typu obdukcie vo forme exhumácie (Putiš et al. 2000). V prvej fáze exhumácie teplota stúpla a bola vypočítaná na 700 °C pri 12 kbar pomocou Grt-Bt geotermometra (Holdaway et al., 1997) a Grt-Pl-Ky-Qtz geotermobarometra (Koziol, 1989) na ortorule. Ďalší bod na *P-T* dráhe bol definovaný pomocou Grt-Bt geotermometra (Holdaway et al., 1997) a Grt-Pl-Ky-Qtz geotermobarometra (Koziol, 1989) na 600 °C pri 4 kbar na svore. Sklon novovypočítanej *P-T* dráhy je strmší oproti modelu podľa Putiš et al. (2000, 2002), čo indikuje väčšiu rýchlosť exhumáciu pri pomalšom ochladzovaní.

Nové petrologické a geotermobarometrické údaje potvrdzujú a v niektorých aspektoch spresňujú model polyfázového vývoja sieggrabenského štruktúrneho komplexu s fázou pochovania počas vzniku akrečného klinu počas kolízie austro-alpínskej kontinentálnej kôry s kontinentom Tisia po uzatvorení strednotriasovo-spodnojurského meliatsko-halstattského oceána v strednej až vrchnej jure (štádium D1) a fázou odstrešenia a exhumácie (štádium D2), ktorý bol vytvorený v starších prácach (Putiš et al., 2000, 2002).

Appendix

Mineral abbreviations

Recommendations by the IUGS Subcommission on the Systematics of Metamorphic Rocks: Web version 01.02.07:

Ab – Albite
Am – Amphibole
Arg – Aragonite
Atg – Antigorite
Ath – Anthophyllite
Bt – Biotite
Cal – Calcite
Chl – Chlorite
Cpx – Clinopyroxene
Ep – Epidote
Fo – Forsterite
Fsp – Feldspar
Grt – Garnet
Hbl – Hornblende
Ilm – Ilmenite
Jd – Jadeite
Kfs – K-feldspar
Ky – Kyanite
Ms – Muscovite
Ol – Olivine
Omp – Omphacite
Opx – Orthopyroxene
Phl – Phlogopite
Phg – Phengite
Pl – Plagioclase
Prp – Pyrope
Qtz – Quartz
Rt – Rutile
Scp – Scapolite
Sil – Sillimanite
Spl – Spinel
Srp – Serpentinite
Tlc – Talc
Tur – Tourmaline
Zo – Zoisite
Zrn – Zircon
WhM – White Mica