Microscopy and Microanalysis of Corona Textures in Eclogitic Greenschists from the Eastern Alps, Austria

Robert Sturm
Salzburg, Austria
Robert.Sturm@sbg.ac.at

Introduction

Metamorphic rocks formed under conditions of high temperature (>600°C) and high lithological pressure (>1 GPa) and being subject to a subsequent tectonic uplift commonly include a remarkable number of fascinating mineral textures. One type of these well known and extensively described high-grade metamorphic textures are the so-called corona structures or reaction rims which, by definition, are primarily based on metamorphic reactions that cause the formation of concentric layers of new mineral phases separating an older and unstable mineral core from a newer and equally unstable mineral matrix.[1,2] In other words, corona structures in metamorphic rocks preserve evidence of changes in the environmental conditions (temperature, pressure, fugacity of H_2O) experienced by the rock during its tectonometamorphic history.[3]

Within the Eastern Alps in Austria, relics of high-pressure, high-temperature rocks belonging to the blueschist or eclogite metamorphic facies can be found in the central part of the so-called Tauern Window, where the rocks of a lower tectonic unit (Penninicum) penetrated through the superposed nappes (East-Alpine). During this uplift of the Penninic rocks, high-grade mineral assemblages were subject to a retrograde metamorphism, or diaphthoresis, resulting in the formation of different types of greenschists and amphibolites that are characterized by the predominance of chlorite and hornblende, respectively.[4] Preservation of glaucophanitic and eclogitic minerals such as garnet, omphacite, paragonite, glaucophane or barroisite took place partly by the formation of reaction rims around these phases that mainly consisted of clinozoisite/epidote, and in the case of a surplus of Fe^{3+}, magnetite.[5] With the help of these corona textures, complete pressure-temperature paths can be modelled for specific rock units of the Penninicum, which at last not only help to understand the development of the Tauern Window, but also give significant insights into the evolution of the alpine mountain belt as a whole.

In the contribution presented here, several results obtained from a recently conducted microscopic and microanalytical study of corona structures in eclogitic greenschists and amphibolites are presented. The work may be likewise of interest for microscopists and mineralogists/chemists, because, besides the application of different microscopic techniques chemical analyses were carried out on the µm-scale using an EMPA system.

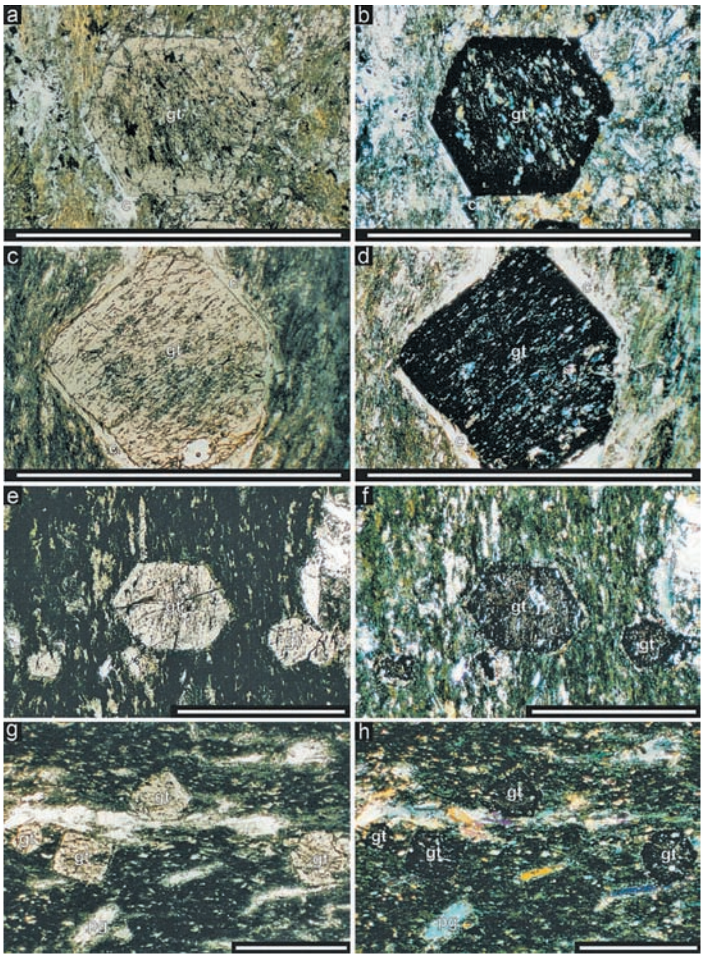

Fig. 1. *Lightmicroscopy of central-alpine greenschists with typical epidote coronas (c) around relictic garnet (gt) and paragonite (pg). Garnets have a high number of inclusions originating from the eclogitic rock-forming event. Bars represent a length of 2 millimetres, respectively.*

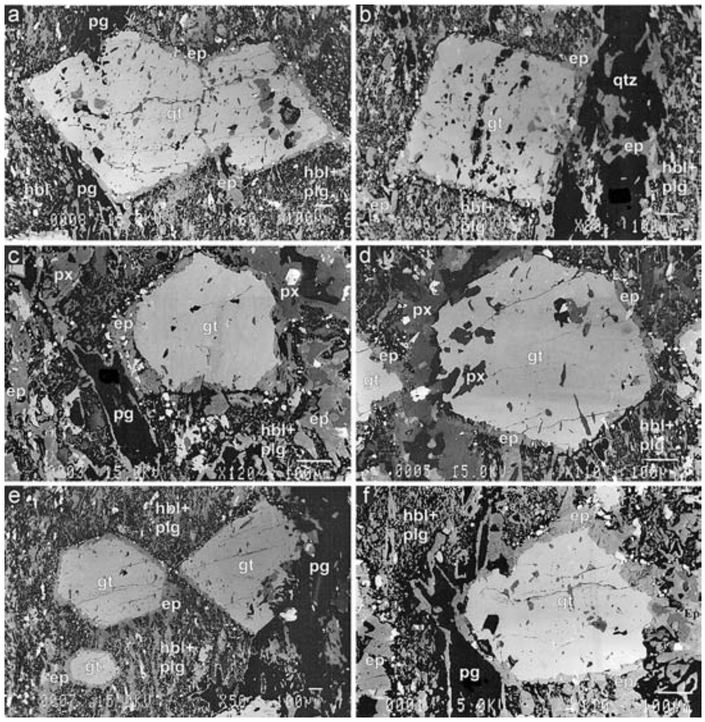

Fig. 2. *BSE images exhibiting the main mineral phases that occur in the eclogitic greenschists. Coronas around garnet (gt) and paragonite (pg) are commonly composed of epidote (ep) and magnetite (white phases). Omphacitic pyroxene (px) represents a further constituent of the originally formed eclogite. The newer matrix of the greenschists chiefly includes the mineral phases hornblende (Mg-Ca-amphibole, hbl), plagioclase (plg) and quartz (qtz).*

Light microscopy and electron microprobe analysis

For light microscopy (LM), backscattered electron imaging (BSEI), and electron microprobe analysis (EMPA) of the corona textures, polished thin sections of the respective host rocks were produced. LM was conducted with a Zeiss Polyvar microscope

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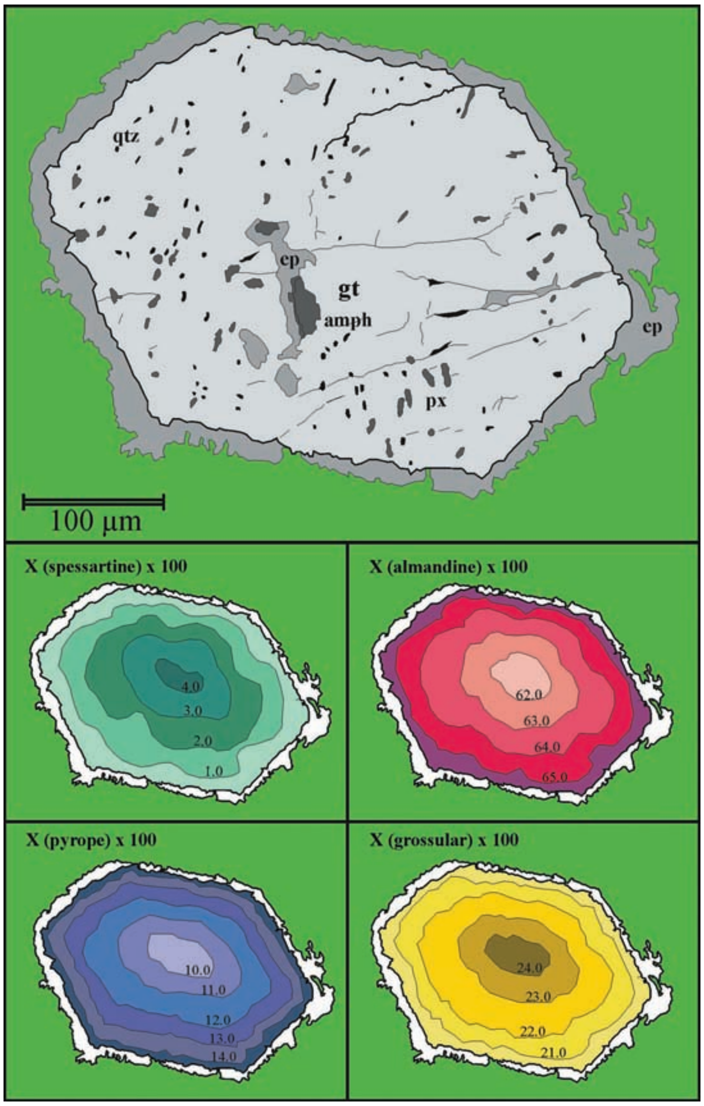

Fig. 3. *Mineral inclusions and chemical composition of the relictic garnet occurring in the greenschists of this study. Besides omphacitic pyroxene (px) used for geothermobarometric calculations, main inclusions are Na-amphibole (amph), epidote (ep) and quartz (qtz). Most garnets are characterized by a concentric chemical zoning, whereby spessartine (Mn-garnet) and grossular (Ca-garnet) continuously increase from rim to core, while almandine (Fe-garnet) and pyrope (Mg-garnet) exhibit a contrary tendency.*

that was appropriately equipped for petrographic investigations (bright field and dark field). For BSEI and EMPA, thin sections were coated with a carbon layer. Subsequent documentation of the samples was carried out with the help of a Jeol JXA-8600 microprobe at the former Institute of Geology and Palaeontology, University of Salzburg. For the production of BSE images of the coronas and adjacent mineral assemblages, an accelerating voltage of 15 kilovolts, a beam current of 20-40 nanoamperes (depending upon the desired contrast of the images), and a beam diameter of about 1 µm were selected. Micro-chemical measurement of the mineral phases of interest took place by using the wavelength-dispersive analysis system including the three spectrometer crystals LiF, PET, and TAP. Except for the beam current, which was set to a constant value of 20 nanoamperes, the same device setup as for BSEI was used. Counting times for the element peaks uniformly amounted to 10 seconds, those for the background to 3 seconds, respectively. Natural quartz (SiO_2), albite ($NaAlSi_3O_8$), adulare ($KAlSi_3O_8$), wolla-stonite ($CaSiO_3$), pyrolusite (MnO_2), rutile (TiO_2) as well as synthetic Al_2O_3, MgO, and Fe were selected as standards for the main element analysis.[6] Correction of the analysis raw data was conducted by the integrated computer system using the widely applied ZAF method. The subsequent determination of chemical mineral formulae and the quantification of important mineral components like those of garnet or epidote were acomplished with the help of specific computer programs running under MS Excel©.

Appearance and development of the corona textures

In the investigated greenschists from the Tauern Window, garnet, omphacite, and paragonite, which represent the relics of an eclogitic rock formed at 600 °C and ≥ 1.2 GPa, are commonly included into coronas of epidote ± magnetite. These reaction rims caused a remarkable preservation of the high-pressure, high-temperature mineral assemblage and separated the mineral phases from a fine-grained symplectitic matrix of hornblende, plagioclase, and quartz that was formed during the retrograde metamorphic event. The contrast in grain size between the old mineral relics and the newer matrix is illustrated in the light-microscopic images

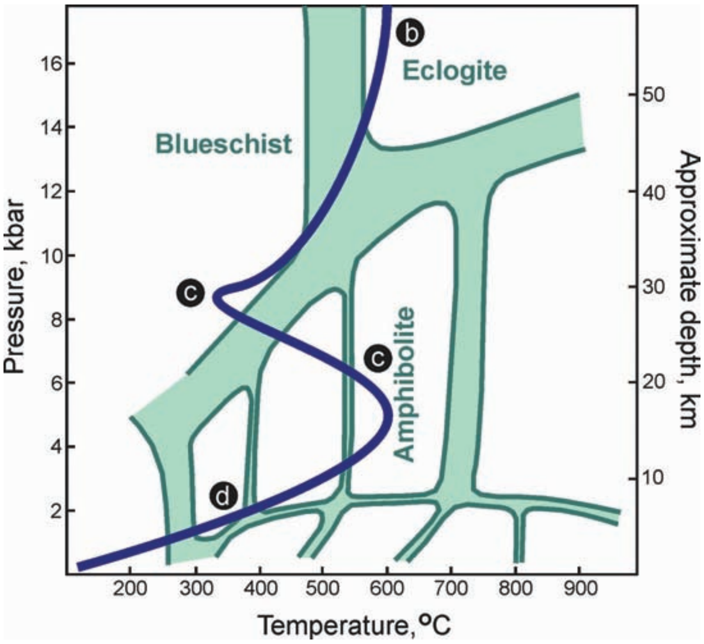

Fig. 4. *p-T-diagram and p-T-path (blue) illustrating the main stages of greenschist evolution. Thus, an initial eclogitic stage is followed by a medium-to-high-pressure/low-temperature event resulting in the formation of mineral phases belonging to the blueschist facies. Enhancement of temperature due to the superposition of tectonic rock units causes an amphibolite metamorphic overprint of the rocks. During the final uplift, the rocks passed through different low-grade metamorphic stages, which, e.g., resulted in the crystallization of chlorite (Table. 1). Letters in black circles refer to the respective tectonometamorphic stages illustrated in Fig. 5.*

of Fig. 1. While euhedral garnet crystals reach a maximum size of a few millimetres and paragonite platelets a length of up to 0.5 millimetres, grain size of the symplectitic matrix is on the order of several tens of micrometers. Thickness of the epidotic reaction rim ranges from about 20 to 100 micrometers and depends upon how wide the corona reaction has proceeded during the uplift of the rock. As clearly exhibited by the light-microscopic artwork, both inclusion phases of garnet (mainly omphacite, amphibole, and quartz) and minerals of the fine matrix are subject to a sig-

Table 1 EMP analyses of relictic and matrix mineral phases from the corona-textured greenschist.

	Relictic mineral phases				Matrix mineral phases			
	grt	px	amph	pg	amph/hbl	ep	plag	chl
SiO_2	38.14	54.84	57.02	46.33	49.47	38.87	68.98	26.64
TiO_2	0.08	0.03	0.05	0.05	-----	0.18	-----	0.06
Al_2O_3	21.07	8.31	11.37	39.78	8.31	27.67	19.14	21.76
Fe_2O_3	-----	6.80	-----	-----	-----	8.17	-----	-----
FeO	28.91	7.28	12.77	0.98	14.83	-----	0.42	17.53
MgO	2.82	4.85	8.83	0.07	12.51	0.02	-----	19.30
MnO	0.67	0.08	0.01	-----	0.13	0.22	-----	-----
CaO	8.12	9.84	0.95	1.03	10.49	23.47	0.87	0.03
K_2O	-----	-----	0.04	0.12	0.12	-----	0.06	0.02
Na_2O	0.03	7.98	6.93	6.82	1.61	-----	10.71	0.03
total	**99.84**	**100.04**	**98.07**	**95.34**	**97.47**	**98.60**	**100.18**	**85.37**
oxygen	12	6	23	22	23	12.5	8	28
Si	3.020	2.010	7.850	5.928	7.117	3.009	3.000	5.610
Ti	0.002	0.001	0.008	0.005	-----	0.009	-----	0.010
Al	1.980	0.359	1.844	6.045	1.410	2.520	0.990	5.350
Fe^{3+}	-----	0.187	0.306	-----	0.638	0.476	-----	-----
Fe^{2+}	1.920	0.223	1.167	0.105	1.145	-----	0.020	3.030
Mg	0.330	0.260	1.811	0.013	2.681	0.002	-----	5.950
Mn	0.050	0.002	0.008	-----	0.017	0.013	-----	-----
Ca	0.690	0.386	0.141	0.141	1.617	1.948	0.060	0.010
K	-----	-----	0.008	0.020	0.026	-----	0.008	0.010
Na	0.001	0.567	1.853	1.732	0.449	-----	0.920	0.010
total	**8.003**	**4.000**	**14.996**	**13.988**	**15.099**	**7.977**	**4.998**	**19.980**

nificant rectification, indicating a shearing process during earlier eclogitization (s_1) and later formation of the greenschists (s_2).

As revealed by the BSE micrographs of Fig. 2, mineral phases are characterized by different grey levels, *i.e.* the brighter a mineral occurs on the respective image, the higher is its content of elements with enhanced atomic weight (*e.g.* ^{56}Fe or ^{55}Mn). Thus Magnetite (Fe_3O_4) within the epidotic corona appears as an almost white phase, garnet ($(Mg,Fe,Mn,Ca)_3Al_2Si_3O_{12}$) and epidote ($Ca_2(Al,Fe)_2Si_3O_{11}$) as light-grey phases, and plagioclase ($NaAlSi_3O_8$ – $CaAl_2Si_2O_8$), quartz (SiO_2), and paragonite ($NaAl_2(OH)_2AlSi_3O_{10}$) as dark-grey to black phases. Magnetite, which is partly included in the epidote corona, forms subhedral crystals with a maximum size of 50 micrometres. Inclusions in garnet are either evenly distributed over the whole host grain (Fig. 2 a, b) or accumulated in the inner or outer zones of the garnet crystal. This rather inconspicuous characteristic has a noticeable effect on geothermobarometric analyses and the related formulation of p-T paths (see below).

From a thermodynamic point of view, corona textures may be regarded as the result of diffusion-controlled reactions that preferentially take place between well-defined mineral zones exhibiting sharp changes in composition at the zone boundaries. Concerning the greenshists of this study, retrograde formation of the reaction rims around eclogitic mineral relics was probably realized in the following way: *garnet + omphacite + paragonite = epidote + albite + Ca-Mg-hornblende ± magnetite.* Thereby, the increased production of hornblende and magnetite indicated 1) the enhanced participation of H_2O and 2) the course of alteration under oxidizing conditions.

Chemistry of the mineral components

Concerning the chemistry of the older and newer mineral phases included in the greenschists, several interesting phenomena can be observed. As illustrated in Fig. 3, chemical composition of relictic garnet is subject to a significant zoning: while in the mineral's core the average composition almandine$_{58}$ grossular$_{24}$ pyrope$_5$ spessartine$_{13}$ can be measured, at the rim the chemistry changes to almandine$_{63}$ grossular$_{23}$ pyrope$_{11}$ spessartine$_3$, indicating a continuous increase of Fe^{2+} and Mg but, at the same time, a decrease of Ca and Mn from the innermost to the outermost growth zones. Results of the remaining mineral analysis are summarized in Table. 1. Within the group of those minerals originating from the eclogitic rock, omphacite is commonly characterized by high contents of jadeite ($NaAlSi_2O_6$) and aegirine ($NaFe^{3+}Si_2O_6$). Relictic amphibole differs from that in the matrix of the greenschist in so far, as its content in Na_2O and therefore its glaucophanitic component is remarkably enhanced, while MgO and CaO (tremolitic/actinolitic components) are significantly lower. Paragonite is not characterized by its ideal stoichiometric formula noted above but exhibits valuable contents of CaO and FeO. Mineral phases, including high contents of Na, are worthwhile indicators of high pressure, and the so-called jadeite-in-omphacite geobarometer has found numerous applications in the past.

Epidote from the coronas and the matrix is usually marked by a clear predominance of Al_2O_3 (clinozoisite) over Fe_2O_3 (epidote s.s.), whereby the ratio of the two oxide components is subject to respective fluctuations, depending upon whether the mineral phase resulted from the decomposition of garnet, paragonite or omphacite. Plagioclase occurring within the symplectitic texture of the matrix is almost exclusively composed of albite, thereby acting as an important sink for the Na that is released from the decomposition of the eclogitic relics. Chlorite represents the youngest mineral phase that commonly forms from amphibole/hornblende and epidote in higher crustal niveaus ($T < 500$ °C, $p < 0.5$ GPa). Similar to the amphibolitic phase, MgO and FeO are on the same order of magnitude (Table 1), underlining the genetic relationship between the two mineral phases.

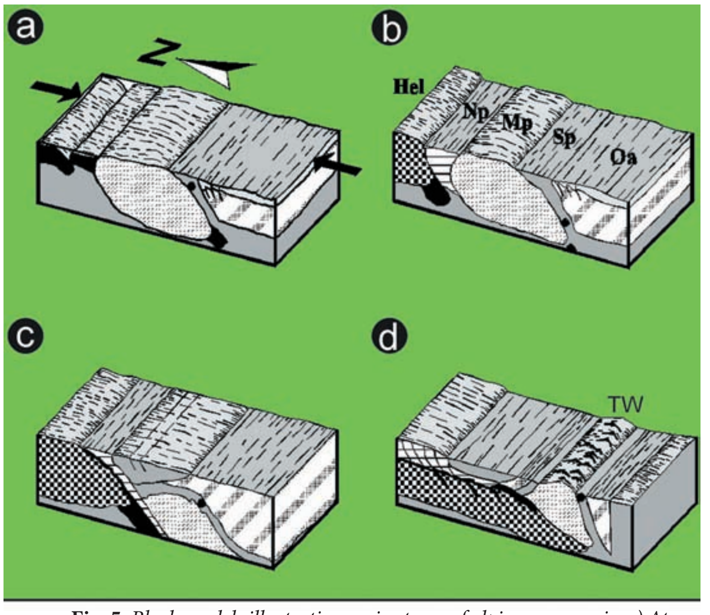

Fig. 5. *Block models illustrating main stages of alpine orogenesis; a) At the initial stage (Cretaceous) pre-alpine nappes are subject to a convergence due to the northward movement of the African continent; b-c) Movement of the continental plate causes the subduction of oceanic crust, continental collision, and the superposition of one continental plate by another; d) At the end of the orogenic event (Tertiary), Penninic rock units penetrate the superposed nappes forming the so-called Tauern Window (TW); Abbreviations: Hel: Helveticum, MP: Middle Penninicum, NP: North Penninicum, SP: South Penninicum, Oa: East-Alpine.*

In geothermobarometric respects, besides the jadeite-in-omphacite geobarometer, the garnet-omphacite as well as the garnet-amphibole geothermometers may be applied in the exemplary case introduced here. For p-T calculations, respective mineral inclusions in garnet, being representative for the eclogitic conditions, were used. For estimating pressure and temperature during matrix formation, stable mineral assemblages were plotted into available p-T grids.[7] For the garnet illustrated in Fig. 4, a p-T path was constructed that is characterized by a typical beta shape, starting with high-pressure high-temperature conditions (eclogite), followed by a subsequent glaucophanitic event (high-pressure low to medium temperature) and a final amphibolitic event (medium-pressure high-temperature). After this last event, the rocks are subject to a continuous uplift, thereby running through different retrograde stages, one of which is characterized by an extensive chloritization.

Conclusion

Due to their textural and chemical diversity, alpine greenschists including eclogitic relics represent interesting research objects for both the microscopist and the geoscientist. With the help of the electron mircoprobe and subsequent geothermobarometric calculation routines, the principle phases of rock evolution may be decoded, representing the greenschists as valuable indicators for understanding alpine orogenesis. In the exemplary case presented here, the respective rocks can be included into a well functioning, theoretical model of the alpine mountain belt formation (black dot in Fig. 5).[8] According to present knowledge, at the beginning of orogenesis the Penninic unit, including the rocks of this study, was subject to a subduction event, resulting in the production of high-grade metamorphites (eclogites). During their uplift, the eclogites underwent a retrograde metamorphism with the formation of blueschists. Superposition of tectonic units from the South caused an increase of the thermal component which resulted in an amphibolite-facies metamorphic event. Due to the final uplift, low- to medium-grade metamorphic mineral assemblages were formed. ■

References

(1) Foster, C. T. (1986): Thermodynamic models of reactions involving garnet in a sillimanite/staurolite schist. *Min. Mag.* 50, 427-439.

(2) Foster, C. T. (1999): Forward modelling of metamorphic trextures. *Can. Min.* 37, 415-429.

(3) Griffin, W. L. & Heier, K. S. (1973): Petrological implications of some corona structures. *Lithos* 6, 315-335.

(4) Dachs, E. & Proyer, A. (2001): Relics of high-pressure metamorphism from the Grossglockner region, Hohe Tauern, Austria: Paragenetic evolution and PT-paths of retrogressed eclogites. *Eu. J. Min.* 13, 67-86.

(5) Sturm, R., Dachs, E. & Kurz, W. (1997): Untersuchung von Hochdruckrelikten in Grüngesteinen des Großglockner-Gebietes (zentrales Tauernfenster, Österreich): Erste Ergebnisse. Zentralbl. *Geol. Paläontol.* 3/4, 345-363.

(6) Sturm, R. (2003): Die Granate in eklogitischen Reliktgesteinen des zentralen Tauernfensters (Penninikum, Ostalpen): Chemismus, Zonierung und Reaktionsgefüge. *Carinthia* II 113, 515-526.

(7) Carswell, D. A. (1990): Eclogite Facies Rocks. Blackie and Son Ltd., Glasgow, London.

(8) Selverstone, J. (1985): Petrologic constraints on imbrication, metamorphism and uplift in the SW Tauern Window, Eastern Alps. *Tectonics* 4, 687-704.