Table 4.1 *Deformation history of granulites and adjacent rocks*

	granulites	orthogneisses	migmatites
D_1	S_1 G facies boudinage HP partial melts in shear zones	S_1 intrafolial folds ? A - G facies	
D_2	S_2 amphibolite facies coaxial with S_1		
D_3	ductile folds F_3		
D_4			S3 shear bands
	ductile-brittle shear zones		

granulite - facies, and reactivated under amphibolite - facies conditions. The foliation is generally east-west trending (Fig. 3.2), parallel to the lithological boundaries, and steeply north-dipping (dip 65-80°).

Lineations - mineral lineations (Ms, Qtz), fold axes, and striations - are generally subparallel, with E-W direction; their plunge is variable, ranging from subhorizontal to 40° (Málkov) up to 70° (Zelená).

5. Crustal assemblages

5.1 Petrology, mineralogy

Polyphase heterogeneous deformation (see below) resulted in formation of many structurally variable rock types. Based on lithological criteria, three main groups of granulite rocks have been distinguished: felsic (light, quartzo-feldspathic), metapelitic (darker), and pyroxene-bearing (dark) ones. The three rock types have acid, sub-acid and intermediate to basic chemistry, respectively (Kotková 1992; Tab. 5.1). Each of them includes several types, differing mainly in mineral proportions (ibid.).

A typical feature is the alternation of felsic and metapelitic rock layers. Dominant felsic granulites commonly form separate morphologically distinct and isolated outcrops with rather conspicuous jointing. They are generally massive and devoid of any macroscopic foliation. Granulites of the area B are exceptional, being very well foliated. Metapelitic rocks occur in several cm-m thick layers, parallel to the regional foliation. At places, biotite is quite abundant, forming clusters with garnet, or parallel bands with or devoid of garnet. Pyroxene-bearing granulites and amphibole-biotite-rich rocks are subordinate rock types in the areas investigated. The former one occurs in the České středohoří basement (borehole T38), both the types were newly described from Stráž nad Ohří quarry.

A special rock type occurring in minor amounts in the Ohře crystalline area represent kyanite ± garnet-bearing melts (Photo 6), which might be considered as a result of dehydration melting, and

Table 5.1 *Nomenclature of granulites used in the work*

petrology	geochemistry (SiO_2,group)	typomorphic minerals
felsic	acid (>69 %; A)	Qtz,Pl,Kfs,Grt,Ky
metapelitic	subacid (<69 %; B_2)	ditto
pyroxene-bearing	intermediate - basic (<69 %; B_1)	Pl,Grt,Cpx

garnet-kyanite-bearing migmatitic gneisses.

Felsic granulites (Photo 1,2) are characterized by less abundant garnet and kyanite, predominance of K-feldspar over plagioclase and the general absence of micas. The rocks described as metapelitic (Photo 3) contain high garnet ± biotite (muscovite) abundances, and more plagioclase. Increasing amounts of biotite

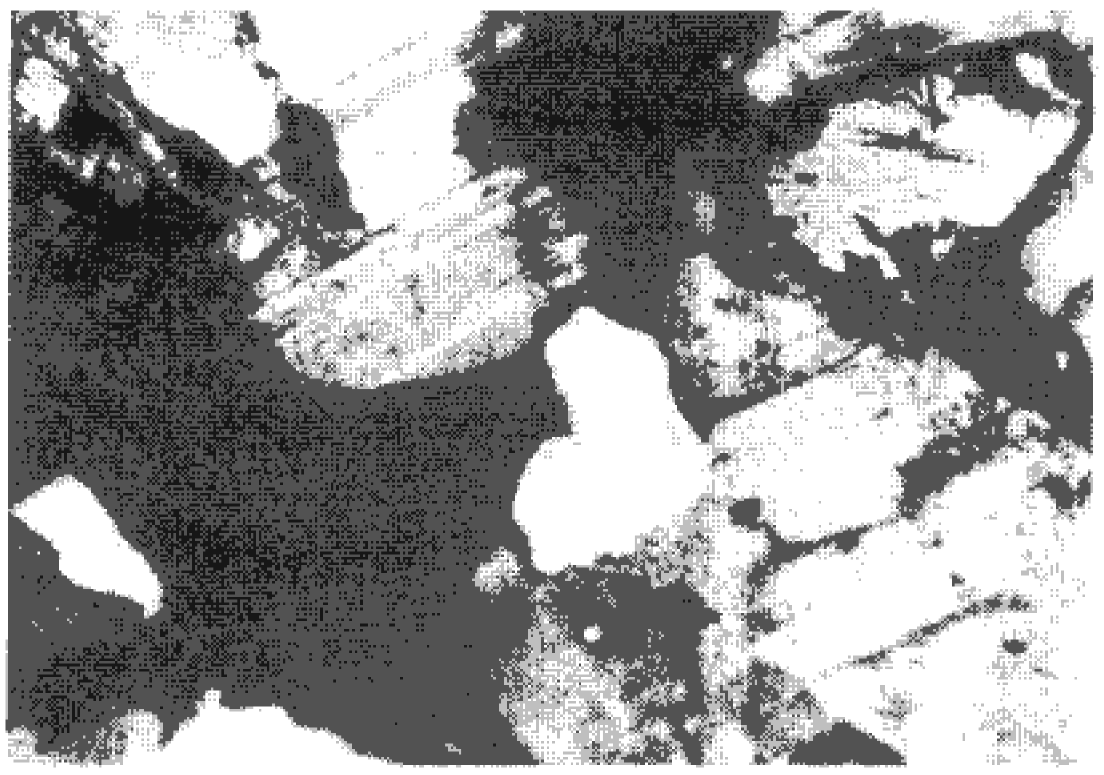

Photo 1 *Felsic granulite, Stráž nad Ohří quarry; Grt II nucleating on kyanite; mult. 64x, // nicols*

indicate the transition to granulite gneisses (cf. Kopecký & Sattran 1966), that have banded structure and reduced grain size (Photo 4). Characteristic feature of granulites is generally well-preserved high P-T mineral assemblage (in low-deformed rocks, see below). Peak mineral assemblage of the two types is garnet-kyanite-mesoperthite-quartz, that of pyroxene-bearing granulites garnet-clinopyroxene-antiperthite-quartz (Photo 5).

5.2 Deformation and paragenetic history of the granulitic rocks

Granulites are texturally heterogeneous on mesoscopic scale. Coarse-grained granulites, with only slight preferred orientation of minerals (kyanite, quartz) are juxtaposed to finer-grained granulitic gneisses (Bt ± Ms-bearing) with a strong mesoscopic planar-linear fabric (L-S tectonites). Transitions between these two rock types allow one to regard their coexistence as the result of the heterogeneity of finite strain distribution, which is a common feature in naturally deformed rocks (Ramsay & Graham 1970,

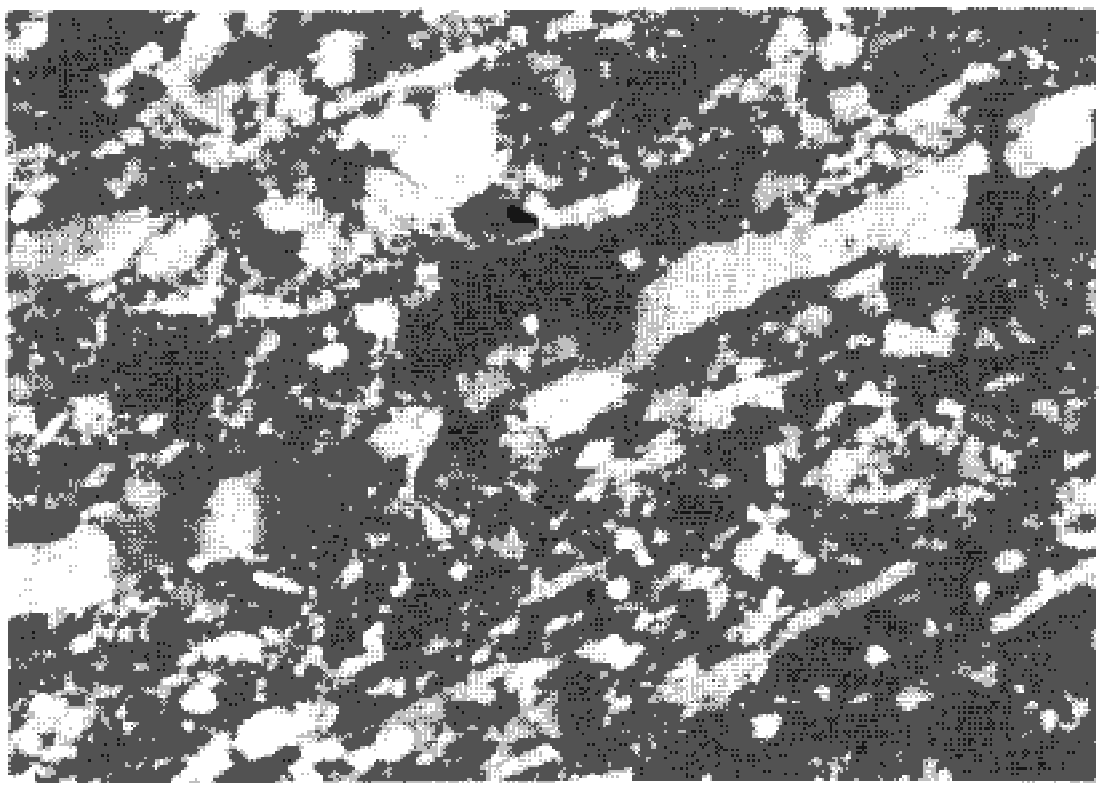

Photo 2 Felsic granulite, Málkov; quartz ribbons; mult. 20.5x, x nicols

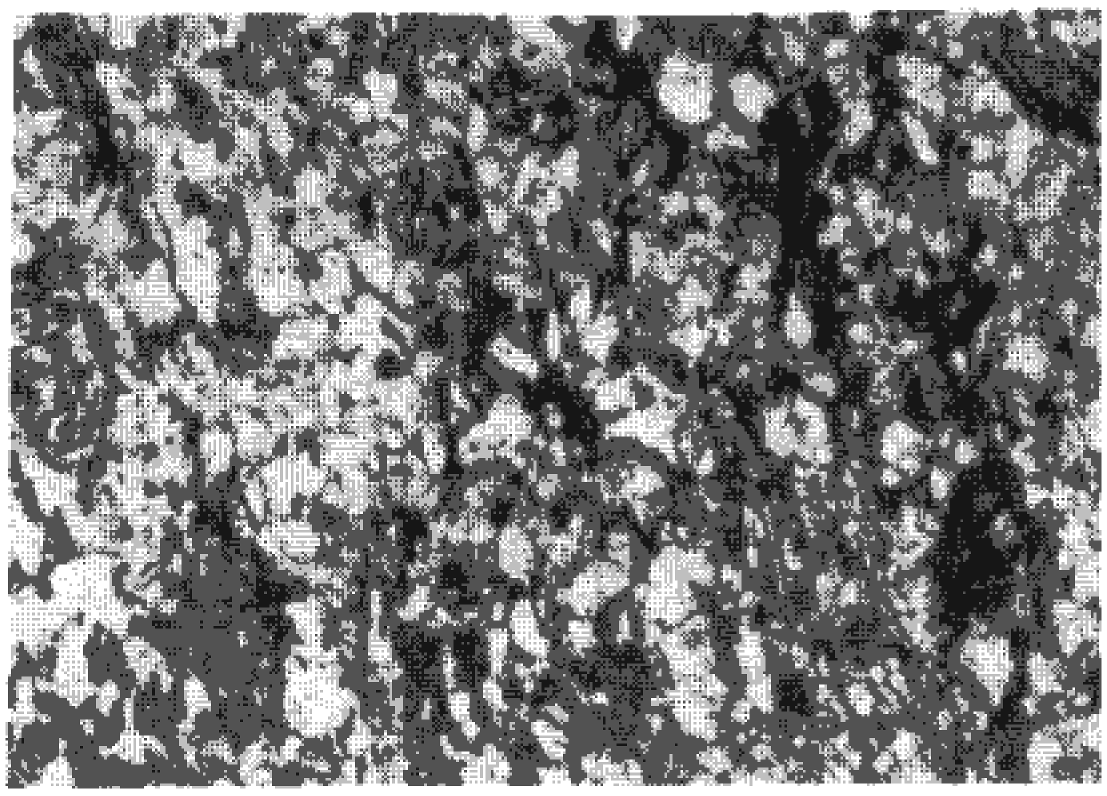

Photo 4 Biotite-rich granulite gneiss, Stráž nad Ohří; Bt in the foliation; mult. 20.5x, x nicols

Ramsay 1980, Bell et al. 1986, Lardeaux 1987). In low-strain domains, early structures and metastable early minerals have been preserved because of lack of intracrystalline deformation with catalytic effects on metamorphic reactions (see Rubie & Thompson, 1985, for discussion).

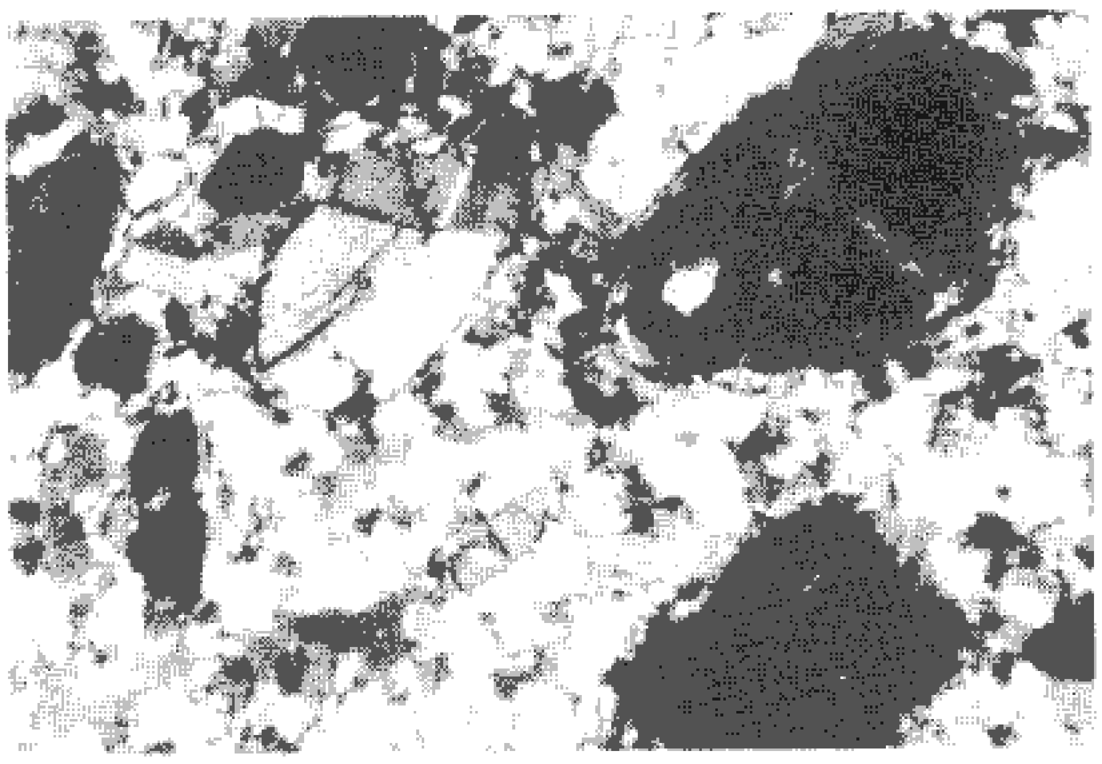

Photo 3 Metapelitic granulite, Stráž nad Ohří quarry; large GrtI and KyI grains; mult. 25x, x nicols

Six main stages of the evolution have been distinguished, including two phases of ductile and one of ductile-brittle to brittle deformation. The successive parageneses observed in granulites, correlated with the deformational stages, allow to reconstruct the metamorphic evolution of the rocks.

I. Granulite stage I

This stage is represented by relatively coarse-grained rocks (preserved in low-strain domains) with weakly deformed matrix of quartz and feldspars, containing large porphyroblasts of garnet and kyanite (Photo 3). The mineral assemblage

garnet I + kyanite I + ternary feldspar + rutile

corresponds to the early high-pressure metamorphism of this stage.

Presence of ternary feldspar is only hypotethic, indicated by the composition of extensively preserved mesoperthite (especially in felsic lithologies, e.g. $Ab_{44}Or_{54}An_3$).

II. Granulite stage II (deformation D1)

The rocks underwent successive heterogeneous deformation D1 under high-grade metamorphic conditions. These conditions are documented by deformation (slight elogation of large grains of perthite, microclinization of Pe, deformation of KyI - Photo 7), segregation of quartz and feldspars without recrystallization, and crystallization of GrtII (Photo 1) and KyII in subparallel bands. The assemblage

garnet II + kyanite II + mesoperthite + plagioclase + rutile

indicate persisting granulite-facies conditions of metamorphism. Unmixing of ternary feldspar (perthitic Kfs, and Pl, formation) proceeded during this or even successive stages. Stability of the assemblage

garnet + clinopyroxene + plagioclase + quartz

and absence of Opx implies that the rocks are situated on the high pressure side of the reaction

$$Opx + Pl = Grt + Cpx + Qtz \qquad (1)$$

during all the retrograde evolution.

III. Amphibolite stage (deformation D2)

Succesive hydration with mica crystallization occurred under either static or dynamic conditions; the latter led to the development of Bt ± Ms foliation in more pelitic compositions (Photo 4). Dynamic recrystallization of feldspar (formation of fine-grained mozaic, decomposition of perthite) and development of platy and ribbon Qtz is attributed to this rather than the preceding stage, also because of an observed discordance between the preferred orientation of kyanite and quartz ribbons (elongated grains). However, earlier quartz deformation cannot be ruled out.

Retrograde rock evolution is marked by hydration reactions. Garnet destabilization into biotite ± muscovite (Photo 8), aligned

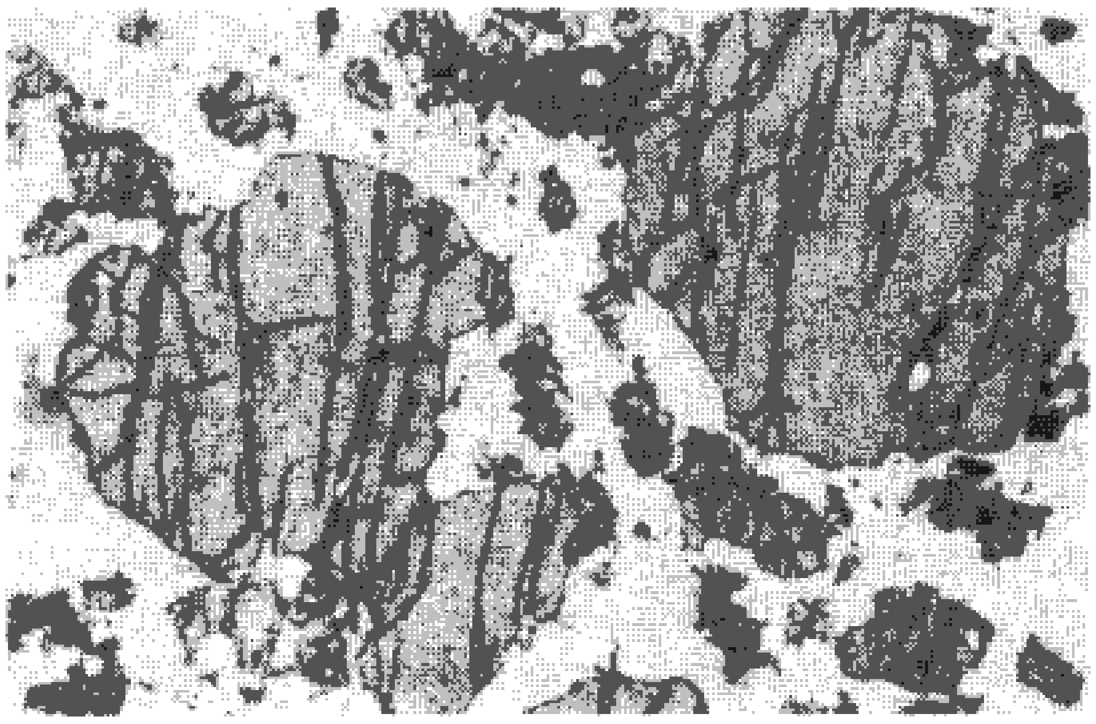

Photo 5 *Pyroxene-bearing granulite, Stráž nad Ohří quarry; large Grt and smaller Cpx grains; mult. 25x, // nicols*

in the S_{1-2} rock foliation, suggests retrogression according to the reactions

$$garnet + K\text{-}feldspar + H_2O = biotite + SiO_2 \quad (2)$$

and

$$garnet + K\text{-}feldspar + H_2O = biotite + muscovite + SiO_2 \quad (3)$$

Reaction rim of Pl around Bt in Grt implies a different mechanism of Grt destabilization, giving rise to the second Pl generation:

$$garnet + K\text{-}feldspar + H_2O = biotite + plagioclase + quartz \quad (4)$$

Photo 6 *Kyanite-bearing felsic melt, Kamenec; large Ky grains in Qtz-dominated matrix; mult. 20.5x, // nicols*

Larger recrystallized grains of Pl II with higher An concentrate also around kyanite.

Kyanite breakdown into muscovite and quartz observed in the rocks is consistent with the reaction

Photo 7 *Felsic granulite, Stráž nad Ohří; deformation of Kyl; mult. 25x. x nicols*

$$K\text{-}feldspar + Al\text{-}silicate + H_2O = muscovite + SiO_2 \quad (5)$$

It is assumed that association of biotite and kyanite results from simultaneous operation of reactions (2), resp. (3), and (4).

Oval aggregates present in dark-colored rock types formed by zoisite, muscovite and quartz probably represent pseudomorphoses after kyanite; the following balanced reaction is suggested for their development:

$$2\,Ky + 2\,Pl + 2Kfs + 2\,H_2O = Zoi + 2\,Ms + 2\,Qtz \quad (6)$$

which corresponds to simultaneously operating reactions (5) and

$$An + H_2O = Zoi \quad (7)$$

Absence of kyanite or garnet relics in the aggregates may indicate that alternative reaction

$$An + Kfs + H_2O = Zoi + Ms + Qtz \quad (8)$$

was responsible for their formation, especially in rocks where kyanite destabilization into muscovite biotite was observed.

In other subacid samples, concentric aggregates consisting of large zoisite, quartz and abundant biotite form at the expense of garnet, which indicates the reaction

$$Grt + Kfs + H_2O = Bt + Zoi + Qtz \quad (9)$$

Symplectites of zoisite and quartz, present in basic compositions, probably formed by reaction

$$An + Grs + H_2O = Zoi + Qtz \quad (10)$$

Relics of kyanite surrounded by zoisite, muscovite, garnet and biotite imply that garnet as well as kyanite and biotite took part in the reaction. This composite reaction can be expressed as a set of reactions, consisting of (2), (5), and (7) or (10), written together as

$$Ky + Pl + Grt\,s.s. + Kfs + H_2O = Zoi + Ms + Bt + Qtz \quad (11)$$

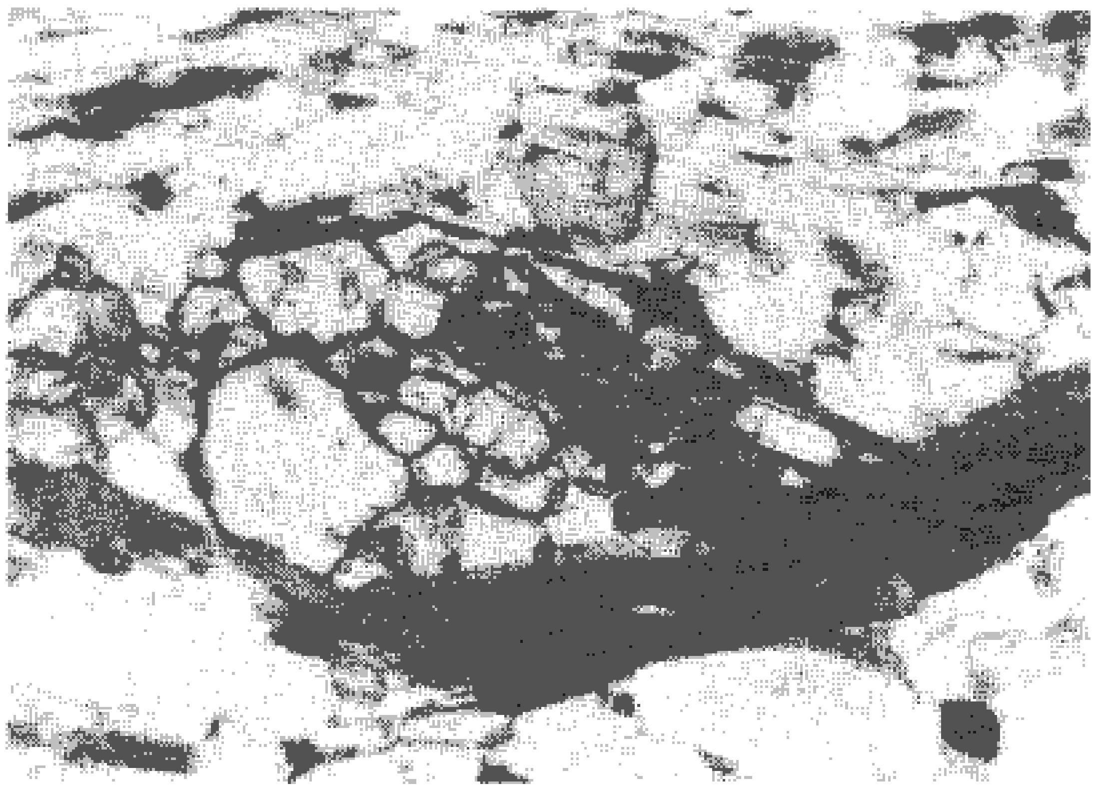

Photo 8 Felsic granulite, borehole RPZ31; garnet destabilization in biotite and muscovite; mult. 100x, // nicols.

Lower grade conditions are documented also by presence of titanite instead of rutile.

Reactions (2) to (11) give rise to amphibolite-facies assemblagegarnet + biotite muscovite zoisite titanite in acid and subacid compositions, and assemblage

garnet + zoisite + amphibole + biotite muscovite

in intermediate to basic compositions.

IV. High temperature recrystallization

Some rock textures display signs of successive high-temperature recrystallization (annealing, recovery, with formation of triple points), destroying any preferred orientation in the rocks (if it existed).

V. Greenschist stage

This stage is characterized by largely static crystallization of chlorite either at the expense of garnet, or in the matrix. Lower-temperature destabilization of garnet via reaction

$$garnet + H_2O = chlorite + quartz \qquad (12)$$

and retrogression of biotite into chlorite led to development of the greenschist-facies assemblage

muscovite + chlorite + plagioclase.

VI. Brittle deformation

Lower-grade deformation created parallel cracks in GrtI, KyI and platy quartz (in quartz, the cracks are filled in with fluid inclusions), oriented oblique to the foliation.

Retrogression of garnet to biotite and of kyanite to muscovite in the study area have been described e.g. by Sattran (1967) and Hokr et al. (1974). Reactions (3) and (5) are common in other granulite complexes (in the Bohemian Massif e.g. Fediuková 1978, Matějovská 1967, Jakeš 1969, and elsewhere e.g. Vielzeuf 1984, Libourel 1985, Rötzler K. 1992). Reaction (4) was described by Vrána (1989). Balanced reactions (8), (9) and (10) were derived by LeGoff & Ballévre (1990a,b) for Fe-Bt endmembers and $X_{Ca}^{Grs} < 0.3$ in orthogneisses.

All the reactions can be interpreted using the petrogenetic grids for granulite facies conditions in pelitic systems (KFMASH), derived by Thompson (1976a, 1982), Vielzeuf & Boivin (1984) and Vielzeuf (1984), for meta-igneous rocks in system KCFMASH composed by LeGoff & Ballévre (1990 a,b), and for system CASH (Boettcher 1970). The retrogression observed is consistent with transition from granulite to amphibolite and greenschist - facies metamorphic conditions, characterized by temperature and pressure decrease. Cooling proceeded still in the kyanite stability field, as documented by preservation of kyanite in the rocks, and absence of sillimanite and cordierite (Fig. 8.1). Persisting high pressure conditions are also indicated by stability of the assemblage zoisite + quartz instead of garnet + anorthite (cf. Newton 1966), and stability of the assemblage garnet + clinopyroxene in intermediate lithologies. All the retrograde reactions reflect an increase in X_{H2O} in the system.

5.3 Minerals and their chemistry

Analytical technique

Chemical composition of minerals was determined making use of Cameca-type microprobe (BRGM Orléans, Clermont-Ferrand, Czech Geological Survey Prague), in the assistance of V.Johan, Ch.Gilles, J.Frýda and Z.Kotrba. Several samples were analysed by R.Schumacher (University Münster; JEOL 8600 SX) and V.Gallagher (Geological Survey of Ireland, Philips 505B SEM equipped with an EDAX energy dispersive spectrometer and analyser).

Analytical conditions: Accelerating voltage 15kV, counting time 20s (Münster) and 10s (elsewhere) per element on peak, natural silicates as standards in a modified ZAF and Bence & Albee (1968) correction programmes.

Garnets

Large garnets (Grt I, up to 3 mm in size; Photo 3) are equant or slightly elongated, both euhedral and corroded. They are commonly poikiloblastic, with inclusions of kyanite, plagioclase, perthite, rutile and biotite. Some garnet grains have an atol or framboidal structure.

Small isometric grains of Grt II are concentrated in subparallel trails and in clusters associated with small kyanite II. Garnets II also form polycrystalline coronas and continuous rims around KyI (Photo 1).

Composition (Fig. 5.1) and also abundance of garnets relate to whole-rock chemistry. Dark garnets of pyroxene-bearing

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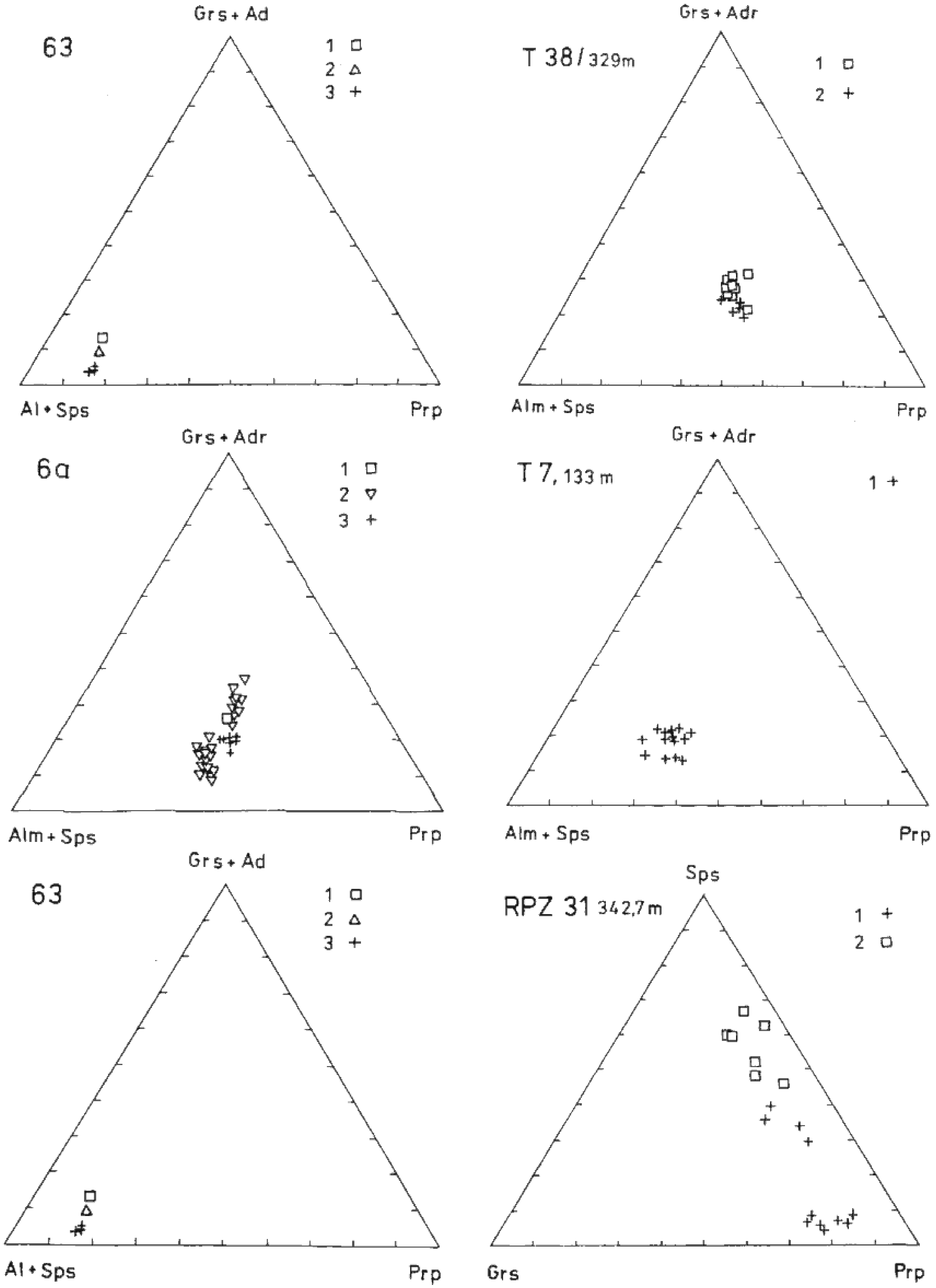
Fig. 5.1 Chemical composition of garnets. 63 - acid granulite, Stráž nad Ohří : 1 - large Grt I, 2 - medium-sized Grt, 3 - small Grt II (all cores); 6a - subacid granulite, Stráž nad Ohří: 1 - rim, 2 - internal part, 3 - core of large Grt I; 6 - basic amphibole-biotite-rich rock, Stráž nad Ohří: symbols as 6a; T38 - pyroxene-bearing granulite, borehole T38: 1 - core, 2 - rim of large garnet; T7 - subacid granulite, borehole T7: large garnets; RPZ31 - acid granulite, borehole RPZ31: 1 - core, 2 - rim of large garnet I.


Grs + Ad
63
1 □
2 △
3 +
Al + Sps
Prp
Grs + Adr
T 38 / 329m
1 □
2 +
Alm + Sps
Prp
Grs + Adr
6a
1 □
2 ▽
3 +
Alm + Sps
Prp
Grs + Adr
T 7, 133 m
1 +
Alm + Sps
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63
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granulites are relatively rich in Grs and poor in Alm (20-30mol% of Grs, up to 35mol% of Alm, 37-44mol% Prp). Orange-brown Prp(Grs)-rich garnets are abundant in sub-acid rock compositions (X_{Prp} up to 44mol%, X_{Grs} up to 23mol%), while relatively low amounts of pink or violet Alm-rich garnets (X_{Alm} up to 80mol%, X_{Prp} 15mol% at maximum) are typical of the felsic ones. Sps content in garnets is generally low (below 3mol%). An exception represent large garnets I from RPZ31 borehole, which contain 6-20mol% of Sps in their cores.

There is a systematic decrease of Grs content from Grt I cores to their rims and - sometimes with a certain compositional gap - to GrtII grains.

Zonation

Several types of garnet zonation were observed. Some garnets have rather flat zoning profiles, sometimes with a slight MgO decrease and MnO increase at their rims. Grs profiles are commonly flat. In some garnets, however, Grs slightly decreases from core to rim.

MgO + CaO increase from core to rim is typical of RPZ borehole and Blahuňov - Málkov area felsic rock garnets, in the former ones accompanied by steep MnO decrease at garnet rims. Steep Prp increase and Grs decrease in the marginal zone (Fig. 5.2) is a striking feature of large garnets of metapelitic and pyroxene-bearin rocks from the Ohře crystalline. The same trend, but less pronounced, display garnets of pyroxene granulites from T38 borehole. Thin 'retrograde' MgO rim was observed in some cases.

Rather complex are zoning patterns of large inclusion-rich garnets of metapelitic and especially basic rocks (Fig. 5.3). It is characterized by contemporaneous change of MgO, FeO and MnO, compensated by change of CaO.

Largely flat zoning profiles are typical of high-grade (temperatures above 615-665°C) garnets, where the growth zoning is obliterated through volume diffusion (Anderson & Olympio 1977, Yardley 1977, Tracy 1982). However, Ca zonation observed in the cores of large garnets indicates that earlier (prograde) zoning can be preserved even at high temperatures. Ca- (and Mn-) rich relict cores in high-grade pelitic gneisses were observed also by Petrakakis (1986) and Tucillo et al. (1990). MgO decrease and MnO increase at garnet rims reflect a retrograde effect of diffusion (e.g. Tracy et al. 1976), documenting a post-peak cooling of these rocks.

Preservation of Ca zonation is assumed to be caused by lesser diffusivity of Ca relative to other elements. Similar behaviour of Fe, Mg and Mn contrasting to that of Ca results from the different processes that rule the distribution of these elements - temperature-dependent exchange reactions (Fe,Mg,Mn) vs. net transfer equilibria (Ca; see Tucillo et al. 1990 for discussion).

I suggest that the reaction

Grs + Al-sil + Qtz = An (GASP)

is responsible for development of Ca-zonation, as supported by the present assemblage (Pl inclusions in Grt). It can be then assumed that large garnets began to crystallize before the peak metamorphic pressure, during the prograde stage. Similar opinion expressed Pin & Vielzeuf (1988) for acid high-pressure granulites of the European Variscan belt. Steep Ca decrease at the rim of large garnet are then indicative of decompression.

Garnet zoning of granulites from the RPZ borehole and the zone Blahuňov - Málkov can be considered as a record of prograde evolution, in the second case followed by the retrograde one, provided that Fe-Mg exchange between garnet and biotite and GASP reactions were operating during its formation. Pronounced MgO increase and Grs decrease typical of metapelitic (area A) and basic rock garnets might reflect high temperature effects associated with decompression.

Plagioclase

Plagioclase of felsic granulites has An_{2-10} (max. An_{12}), the one of subacid rocks contains 15-27, in some samples even 33mol% An. In pyroxene-bearing granulites, plagioclase in the matrix of the T38 borehole sample has An_{25-26}. Pl intergrown with Cpx (see below) in matrix and isolated inclusion in Grt have An_{27-28}, while Pl associated with Cpx in garnet contain 33-34mol%An. Inclusions of Pl in garnets have similar or slightly higher An proportion, in some cases displaying slight increase of An from core to rim of the inclusion.

Larger grains of plagioclase occurring in the fine-grained matrix and around kyanite grains have higher An contents than the matrix ones, and represent the second (retrograde) plagioclase generation.

Pyroxene

In addition to equant or subequant grains (up to 0.8mm size; Photo 5) pyroxene forms intergrowths with plagioclase, occurring in the matrix and in inclusion in garnet in pyroxene-bearing granulites (sample from Stráž nad Ohří).

All pyroxenes analysed are Ca-rich pyroxenes, having rather constant Mg/Mg+Fe ratios (0.79-0.87) (Fig. 5.4). Pyroxenes from T38 borehole have composition X_{Di}=0.45-0.51, X_{Hed}=0.01-0.05, X_{Jd}=0.2-0.24, X_{Tsch}=0.13-0.16. Pyroxenes from Stráž upon Ohře quarry are characterized by following values: X_{Di}=0.56-0.68, X_{Hed}=0.09-0.12, X_{Jd}=0.07-0.11, X_{Tsch}=0.04-0.09. Pyroxene from intergrowths with plagioclase - especially in the inclusion in garnet - has a higher Mg/Mg+Fe ratio (at the upper limit of Di interval) and lower Jd (lower limit) than equant grains from the matrix of the same sample.

Kyanite

Kyanite reaches up to 3mm in size (esp. in felsic rocks). Large grains of KyI are frequently intensively internally deformed (even kink band substructures, Photo 7). KyII is smaller, prismatic, concentrated in trails together with GrtII. Garnet and quartz inclusions occur in kyanite grains. Frequently, larger plagioclase grains concentrate around kyanite, and biotite is in contact with kyanite.

Zoisite/Clinozoisite

These minerals occur in subacid and intermedite to basic rocks. In subacid composition, zoisite occurs in two forms. Large (up to 1.5mm) grains concentrating in Bt-rich zones are equant to subequant, prismatic, and they contain abundant quartz inclusions especially in their cores. Another type are elongated grains developing at the expense of garnet, or associated with fine-grained muscovite and quartz in oval aggregates. The former type contains inclusions of quartz and biotite. Zoisite is quite abundant in basic rocks, where it occurs in form of aggregates of needle-like grains, and in symplectites with quartz, commonly associated with biotite

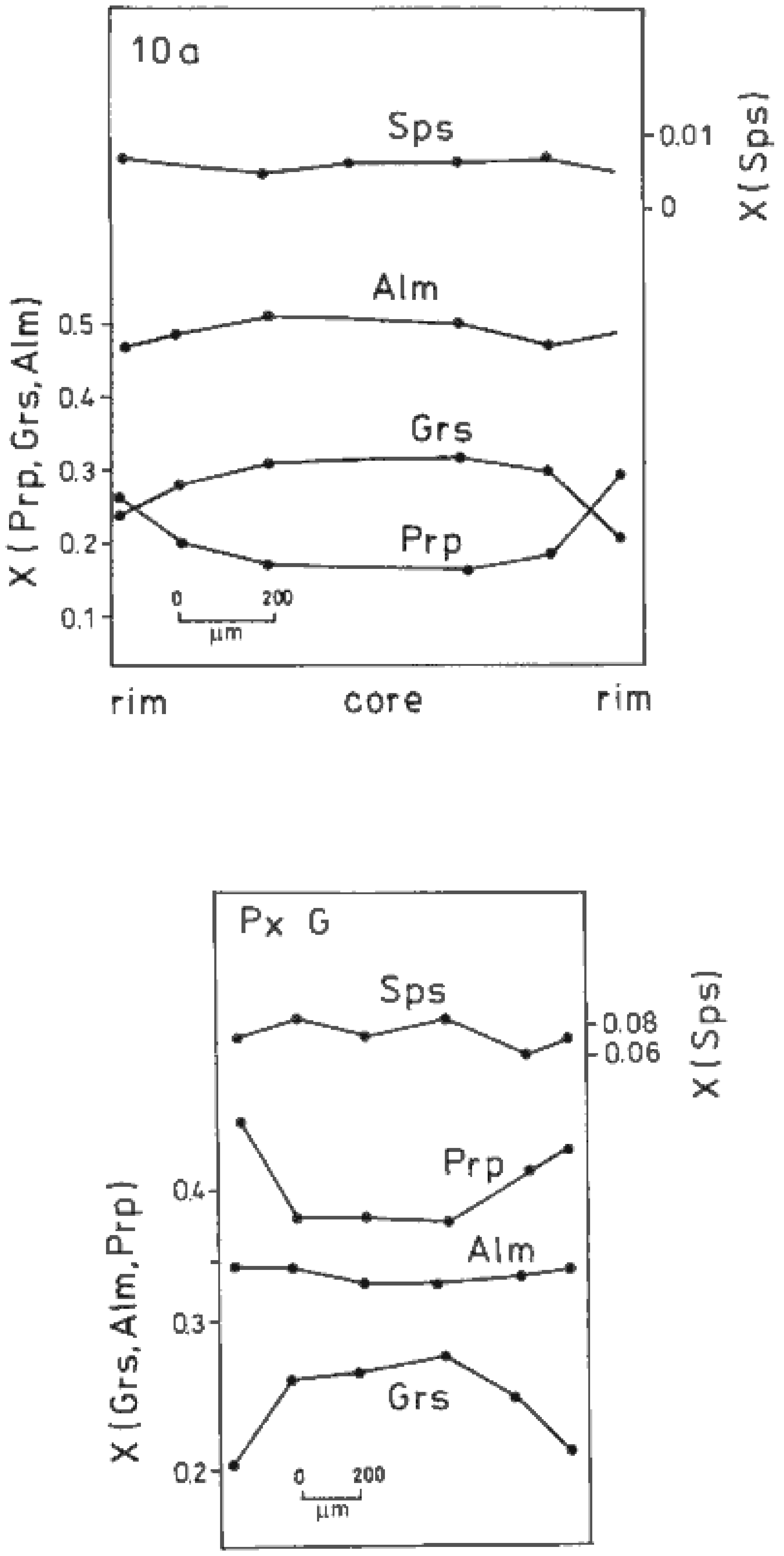

Fig. 5.2 Zonation of garnets. Subacid granulite Stráž nad Ohří (10a), pyroxene-bearing granulite (borehole T38).

and amphibole. The former type contains inclusions of quartz and biotite.

Amphibole

Amphibole occurs in form of equant or subequant grains, or as irregular fine-grained patches clouded with opaque and brownish dust in basic amphibole-biotite-rich rocks. All analysed grains are Ca-amphiboles, with composition corresponding to Mg-horn-

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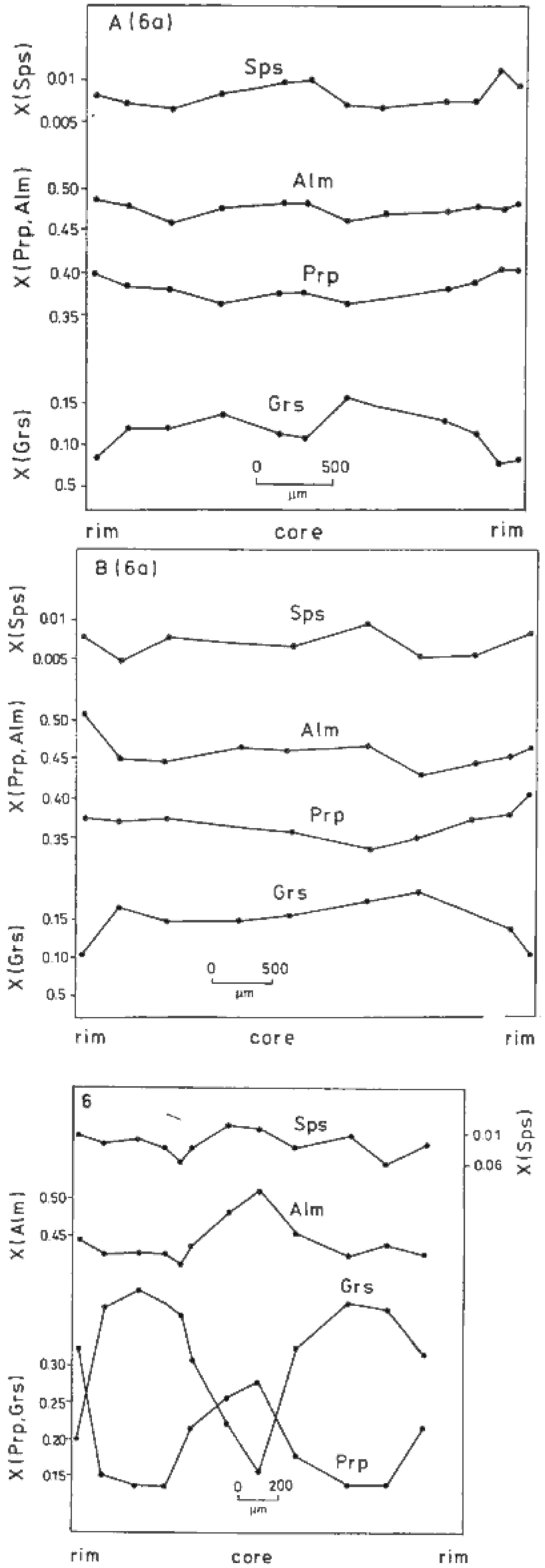

Fig. 5.3 Zonation of garnets. Subacid granulite, Stráž nad Ohří (6a); basic amphibole-biotite-rich rock, Stráž nad Ohří (6).

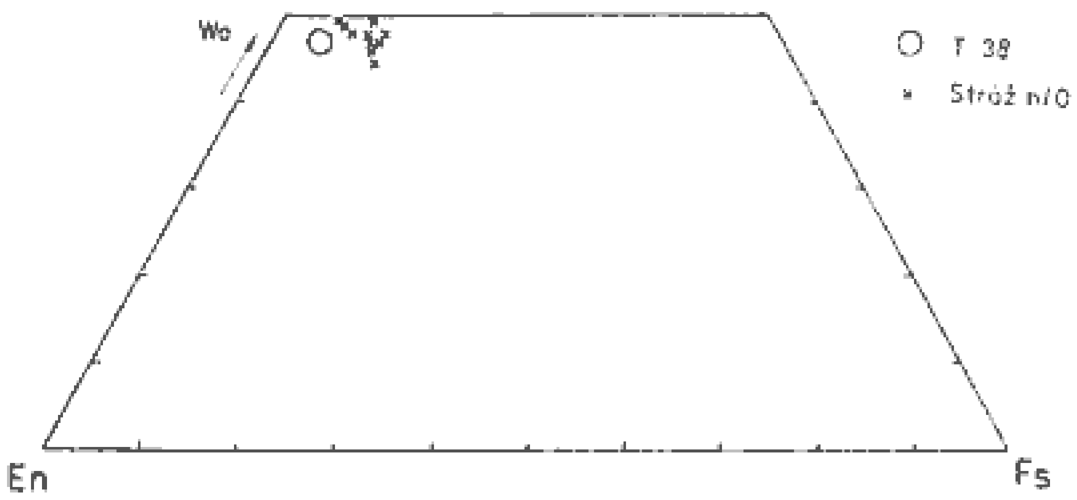

Fig. 5.4 Chemical composition of pyroxenes, pyroxene-bearing granulites. Circle - field of the T38 borehole sample, cross - Stráž nad Ohří sample.

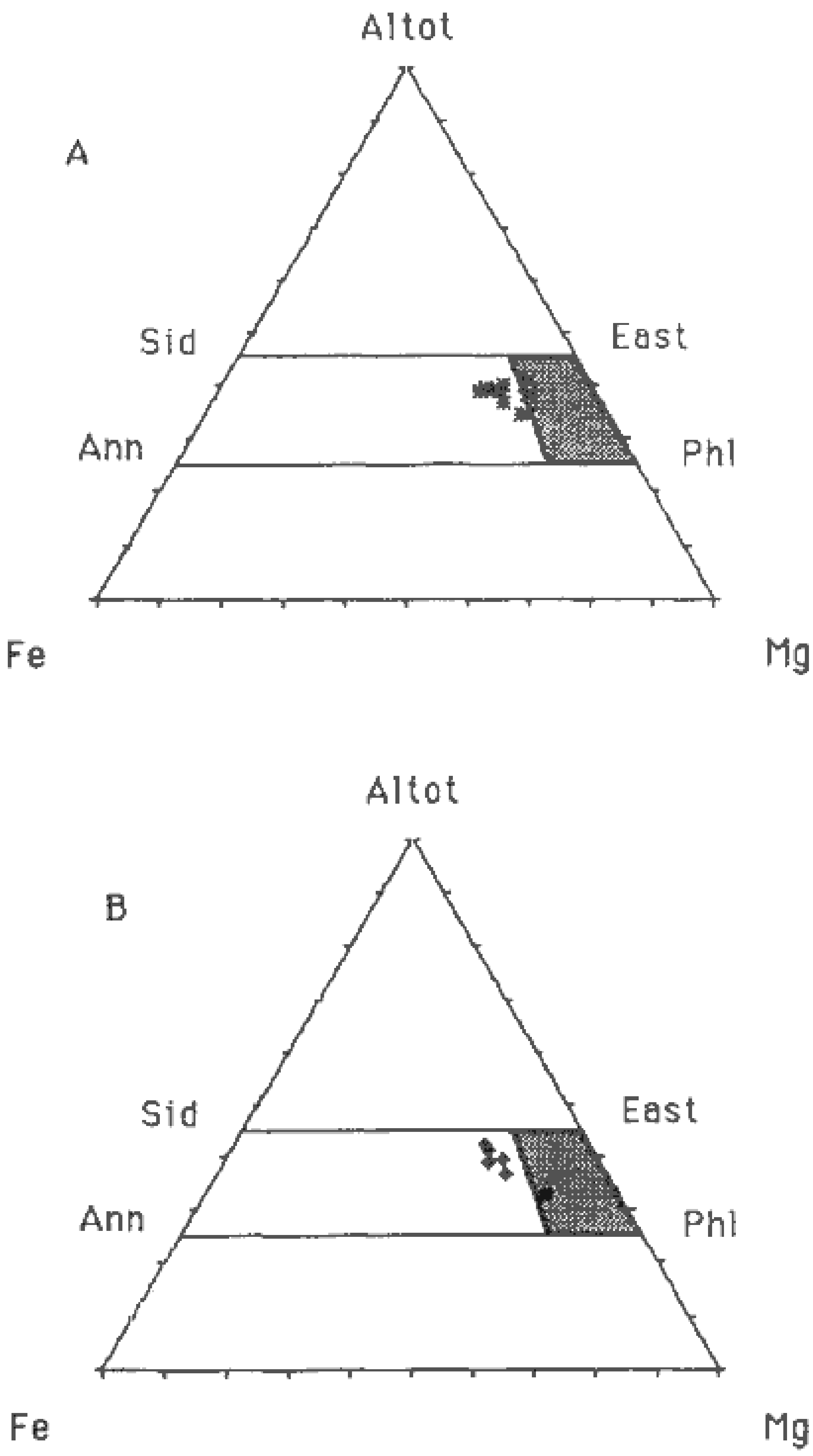

Fig. 5.5 Chemical composition of biotites. Borehole T7, 133m. A - biotites at garnet rim, B - biotite inclusions in garnet.

blende, actinolite, ferroan pargasitic hornblende, or edenite (after classification of Leake 1978).

Biotite

Biotites are generally strongly pleochroic, commonly with reddish tint reflecting high Ti content; many samples contain high amount of eastonite component, too.

Biotites in the foliation and static flakes in the matrix of metapelitic assemblages have high Mg/Mg+Fe ratios (0.63-0.83) and high TiO_2 contents (3.3-5wt%). Biotites adjacent to garnets and kyanites differ in lower TiO_2 contents (2.5-2.8wt%), and higher Al contents. Biotite inclusions in garnets are of two types: Ti-rich and Al-rich, respectively. Biotites from basic amphibole-bearing rocks have Mg# = 0.65-0.7, but low Ti contents (below 2wt%).

Muscovite

Muscovite in the rock foliation is phengitic, containing up to 3.34 Si p.f.u.. In the RPZ borehole felsic rocks, Si contents varies even within one muscovite grain (total range 3.13-3.21 p.f.u.). Muscovite grains associated with Ky have max. 3.15 p.f.u. Si. Fine-grained products of Ky breakdown contain as much as 3.1 p.f.u. Si. Muscovite forms even complete fine-grained pseudomorphoses esp. in felsic rocks, in some cases it recrystallizes in larger flakes.

6. Mantle assemblages

Investigated samples (courtesy dr. Fiala and own sampling) come from a 228m continuous ultrabasic rock sequence crossed by T7 borehole. Mineralogy, mineral chemistry and whole-rock chemistry of these rocks, described as wehrlites, dunites and eclogites, were studied by Fiala (1965), Rost & Grigel (1969), Kopecký & Paděra (1974) and Fiala & Paděra (1977, 1984).

The ultrabasic body from the T7 borehole is stratified, with predominant garnet lherzolites interlayered with dunites with or without garnet. The boundaries between lherzolites and dunites are sharp, the layer thickness ranges from a few centimeters to several tenths of meters (Kopecký & Paděra 1974). The least abundant rock type is garnet pyroxenite, that occurs in the lherzolites as small lenses, inclusions and layers of cm, and rarely dm size. The exception is a thicker body at a depth of 408-415 m.

6.1 Mineralogy and petrology

a) Lherzolites and dunites

Rock textures are characterized by generally completely recrystallized, rather homogeneous fine-grained (0.1-0.4mm) matrix, surrounding large garnet porphyroclasts. Large Opx, resp. Cpx and Ol porphyroclasts occur exceptionally, associated with garnets, resp. as inclusions in garnets in dunitic compositions. Deformation is concentrated in narrow zones with mylonitic texture (elongation of Sp grains) and pronounced serpentinization. Coronitic textures have been preserved in domains of low strain.

The mineral assemblage of the lherzolites is olivine, clinopyroxene, orthopyroxene, garnet, and serpentine, with minor