Eclogite, Garnet Peridotite, Garnet Pyroxenite and HP Granulite in the Gföhl Unit

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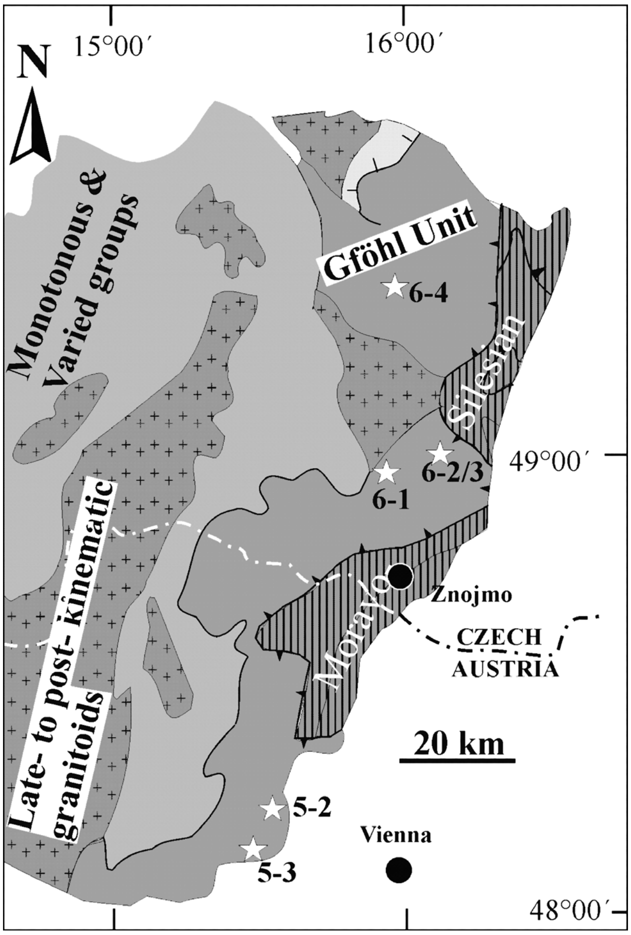
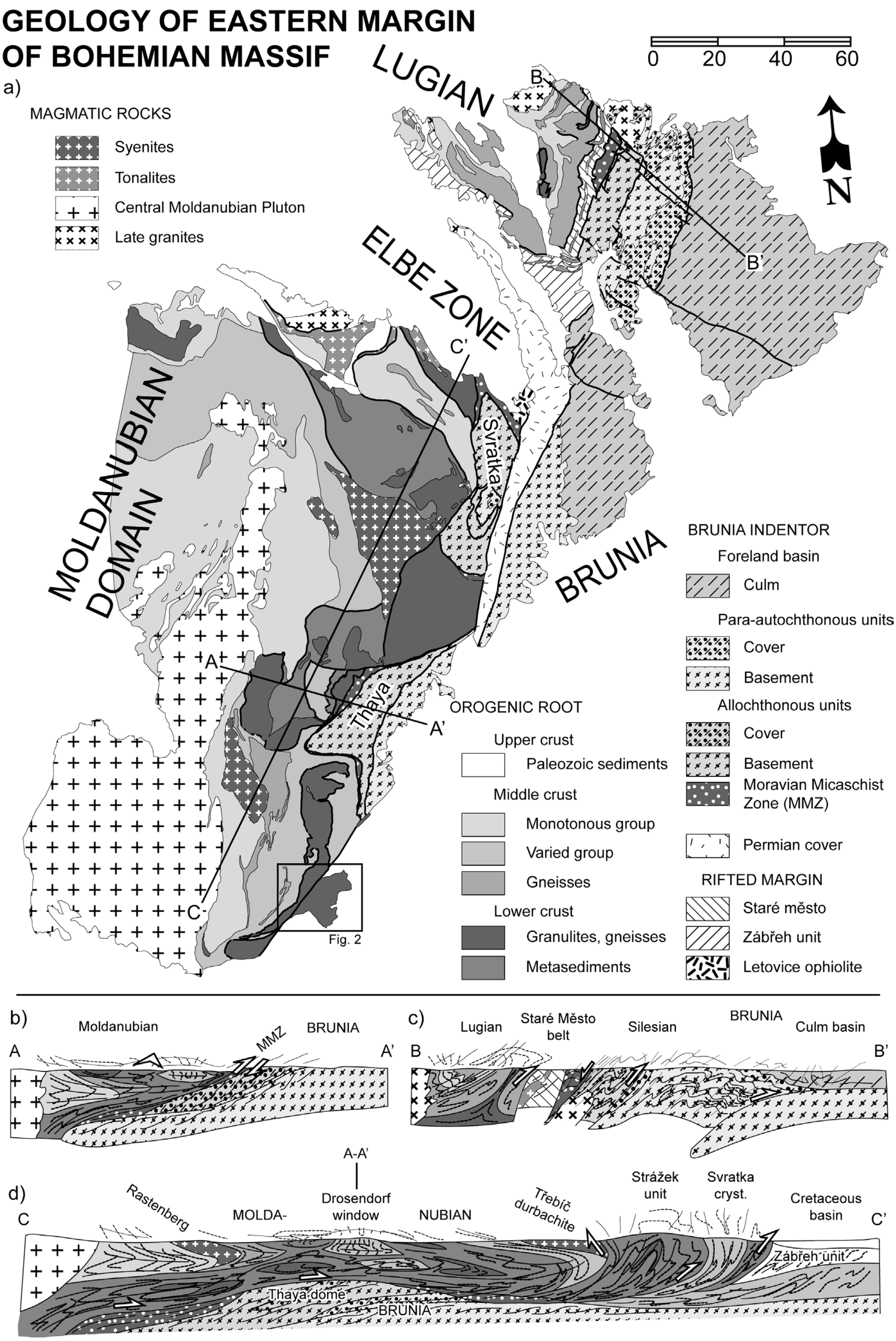


■ **Fig. 1.** Localities of field trip stops in garnet peridotites, garnet pyroxenites and eclogites in the Gföhl unit (area B in Fig. 1 of the Introduction to post-conference excursion) Stops 5-2–6-4 in the Gföhl unit with HP/UHP granulite and granulitic gneiss, garnet peridotite, garnet pyroxenite and eclogite.

The excursion to the *Gföhl unit* will start in HP granulite and associated garnet peridotite and garnet pyroxenite (stops 5-2 and 5-3) in Dunkelstein Wald (Lower Austria) about 30 km NW of Vienna (Fig. 1). We will continue to the north into the Czech Republic, where we will visit eclogite and garnet peridotite at Nové Dvory (stop 6-1), spinel peridotite and garnet peridotite at Mohelno (stops 6-2 and 6-3), and HP granulite, peridotite, and pyroxenite at Horní Bory (stop 6-4).

High-grade rocks in the eastern margin of the Bohemian massif are exposed along the contact between the Moldanubian and Brunovistulian or Moravo-Silesian domains (Fig. 2a). The Brunovistulian domain consists mostly of undeformed Late Proterozoic granitoids that are overlain by Cambrian to Carboniferous sediments with volcanic rocks (e.g., Dudek, 1960; Hartley and Otava, 2001; Kalvoda et al,. 2003). Variscan deformation caused northeastward thrusting of Moldanubian high-grade rocks over the Brunovistulian domain (Fritz and Neubauer, 1993; Schulmann et al., 1994), which are exposed in three tectonic windows in a 300-km-long and 30- to 50-km-wide belt along the eastern margin of the Bohemian Massif. Metamorphism of the Moravian Zone is tectonically inverted within imbricated orthogneiss-metasedimentary nappes from the kyanite zone in the west to the chlorite zone in the east (Štípská and Schulmann, 1995; Fritz et al., 1996; Štípská et al., 2000).

The Moldanubian domain consists of high-grade rocks of the Gföhl unit structurally overlying generally lower-grade rocks of the Varied and Monotonous groups (Fig. 2b,c), all intruded by plutonic rocks of Carboniferous age (Fuchs, 1976; Thiele, 1976). *The Gföhl unit* is dominated by migmatitic orthogneisses (the Gföhl gneisses) that are commonly associated with felsic kyanite-garnet-K-feldspar granulite and subordinate intermediate and mafic granulites, which enclose serpentinized garnet peridotites, garnet pyroxenites and retrogressed eclogites. Structurally, the lower part of the Gföhl unit, which is characterized by amphibolites interlayered with felsic metavolcanics and paragneisses, is called the Raabs group (Thiele, 1984; Fritz and Neubauer, 1993; Finger and Steyer, 1995). U-Pb zircon dating of the Gföhl orthogneiss and granulites shows an age range of 500–390 Ma for magmatic protolith of the Gföhl unit (Finger and von Quadt, 1995; Friedl et al., 2004; Schulmann et al., 2005). The Gföhl gneiss, granulite, and migmatites record HT/HP peak metamorphic conditions of 18–20 kbar and 800–1000 °C (e.g., Carswell and O'Brien, 1993; Cooke and O'Brien, 2001; Štípská and Powell, 2005a,b; Racek et al., 2006; Racek et al., 2008). According to numerous geochronological studies, the age of high-grade metamorphism in the Moldanubian domain is Carboniferous (Kröner et al., 2000; Friedl et al,. 2003, and references therein). U-Pb zircon ages ranging from ~350 to 340 Ma (van Breemen et al., 1982; Schulmann et al., 2005, and references therein) are interpreted as the age of peak metamorphic conditions, whereas Ar-Ar ages of ~330 to 325 Ma (Dallmeyer et al., 1992; Fritz et al., 1996) correspond to the cooling of the Moldanubian and Moravian zones.



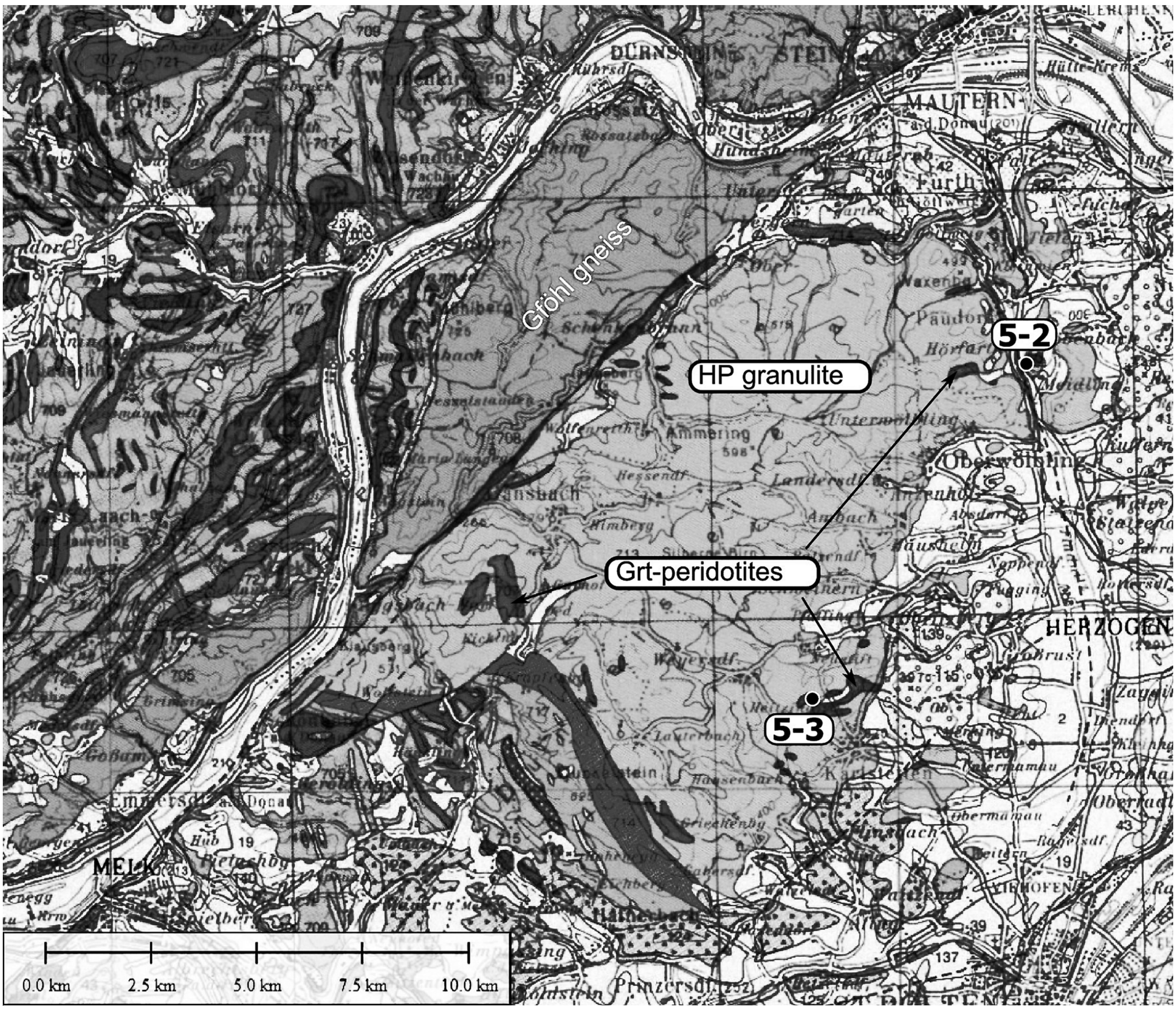
■ **Fig. 2** (a) Simplified geological map of the eastern margin of the Bohemian Massif, with three interpretative cross-sections along the marked profiles showing the inferred orogenic crustal architecture.(b) E–W cross-section of the southern Moldanubian Domain, showing flat-lying fabrics in the lower crust *vs.* steep fabrics in mid-crustal units. Dismembered orogenic middle crust forms large-scale boudins surrounded by rocks of the Gföhl unit. (c) Cross-section of the Lugian–Silesian domain. (d) North–south cross-section of the Moldanubian domain, showing strong deformation in the southern part of the system with important mixing of orogenic lower crust and orogenic middle crust due to "channel flow" processes and weak deformation in the northern part of the section.

The Varied group is composed of paragneiss with layers of quartzite, marble, graphite schist, amphibolite, and bodies of granitic gneiss. The granitic gneisses are Late Proterozoic in age and/or display a Late Proterozoic anatectic overprint. An age of 358 Ma for a felsic metavolcanite within the amphibolites (Friedl et al., 1993) suggests that sedimentation of the Varied unit is Devonian in age (Gebauer and Friedl, 1993; Friedl et al., 2004). *The Monotonous unit* is dominated by paragneisses and contains minor quartzite, calcsilicate, and mafic rocks with a presumed Late Proterozoic age of sedimentation (Kröner et al., 1988). The Varied and Monotonous groups record a prograde metamorphic evolution at P-T conditions up to 700–800 °C and 10 kbar (e.g., Petrakakis, 1997; Racek et al., 2006; Linner, 1996; Büttner and Kruhl, 1997).

The structural position of the Gföhl unit is widely interpreted as resulting from low-angle, long-distance thrusting over mid-crustal rocks of the Varied and Monotonous groups (e.g., Suess, 1918; 1976; Thiele, 1976; Tollmann, 1982; Matte, 1986; Franke, 1989). Recent models of Štípská et al., (2004), Schulmann et al. (2005; 2008), and Racek et al. (2006), however, suggest that the juxtaposition of the mid- and lower-crustal rocks in the same present-day crustal level was achieved by vertical mass transfer caused by E-W compression. This compressive phase was then followed by thrusting of the whole sequence over the Brunovistulian basement in the form of channel flow in a partially molten milieu that resulted in pervasive flat reworking and disintegration of all of units, now preserved as boudins.

Dunkelsteinwald HP granulites and garnet peridotites

The Dunkelsteinwald granulites are exposed south of the Danube River near Krems am der Donau (Fig. 3). A striking feature of the granulites is the presence of interfolded lensoidal bodies of dark-coloured garnet peridotite (Carswell, 1991).



■ **Fig. 3.** Geological map of the Moldanubian Zone in Lower Austria (largely after Fuchs, 1971), showing the locations of garnet peridotites within the Dunkelsteinwald granulite and Field Trip Stops 5-2 and 5-3.

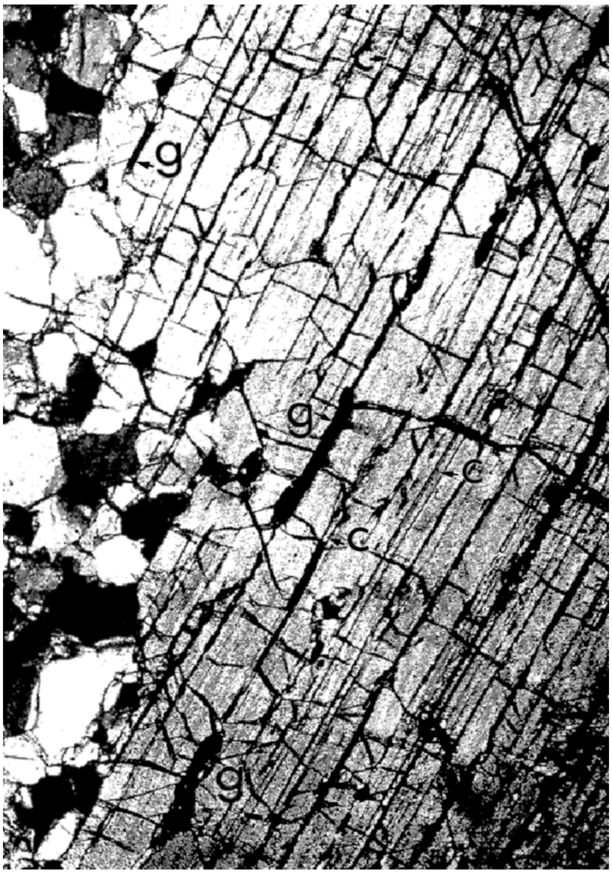
The garnet peridotites are highly deformed, with a platy fabric accentuated by late-stage serpentinisation. Boudinaged layers or lenses of pyroxenites within the peridotites are relatively unaltered and preserve high-pressure (HP) garnet-clinopyroxene assemblages.

The felsic granulites are predominant and contain almandine-rich garnet + kyanite + mesoperthite + quartz. Subordinate, intermediate granulite contains orthopyroxene and rare clinopyroxene (Scharbert and Kurat, 1974). More mafic granulites directly enclosed in felsic granulites are rare. These rocks contain garnet + sodic clinopyroxene + plagioclase, (and abundant late replacement amphibole). Granulites usually have a protomylonitic or blastomylonitic fabric, which is especially pronounced in extremely platy and lineated variants (Plattenstein) developed towards the base of the granulite unit. Granulite is extensively retrograded, with kyanite replaced by sillimanite, garnet by biotite, mesoperthite by microcline and oligoclase, and pyroxenes by amphiboles.

Garnet peridotites include lherzolite, harzburgite, and more rarely dunite (Becker, 1997). Dunite and harzburgite locally contain layers of garnet pyroxenite. Both the garnet peridotites and the spatially associated garnet pyroxenites typically display complex reaction textures that reflect a prolonged, polyphase, tectono-metamorphic history (Carswell, 1991; Carswell et al,, 1989). Garnet pyroxenites occur as millimetre- to decimetre-thick layers within the garnet peridotites. Most of them show relatively sharp contacts with the host garnet peridotite. Garnetite lenses with more than 90 vol% of garnet are also present within peridotites (Becker, 1997).

Textural and compositional relations of minerals

Garnet peridotites and garnet pyroxenites contain several textural and compositional varieties of olivine, orthopyroxene, clinopyroxene garnet, spinel, and amphibole. In addition to deep purple garnets with high Cr content (2.5 ± 7.6 wt% Cr_2O_3) in lherzolite and harzburgite, orange-brown garnets with low Cr_2O_3 contents (<1 wt% Cr_2O_3) occur in pyroxenite. Garnet shows zoning with Fe and Mn increasing and Mg decreasing from grain cores to rims. Some orthopyroxene megacrysts show exsolution lamellae of garnet and clinopyroxene and marginal recrystallisation to an assemblage of orthopyroxene + clinopyroxene + olivine (± later amphibole and spinel). Pyroxene porphyroclasts within the peridotites from Meidling-im-Tal contain garnet exsolution lamellae, and they are often recrystallized near the rims (Fig. 4). The orthopyroxene megacrysts contain 4.55 wt% Al_2O_3 and 2.19 wt% CaO. This high-Al, high-Ca orthopyroxene composition suggests an early high-temperature igneous protolith stage. Clinopyroxene I porphyroclasts recrystallized to a neoblast assemblage of clinopyroxene II ± orthopyroxene ± plagioclase. Rare clinopyroxene megacrysts (3 × 2 cm in size) in harzburgite contain millimetre-thick orthopyroxene exsolution lamellae that appear to have exsolved together with intergrown garnet lamellae.



■ **Fig. 4.** Photomicrograph (crossed polarizers) of an orthopyroxene megacryst with lamellae of garnet (isotropic blebs, g) and clinopyroxene (c) from clinopyroxenite in Meidling-im-Tal, Dunkelsteinerwald (Carswell, 1991). Note marginal recrystallization along the left side of the photomicrograph. Width of field of view is approximately 5 mm. Note uneven extinction in orthopyroxene due to strain.

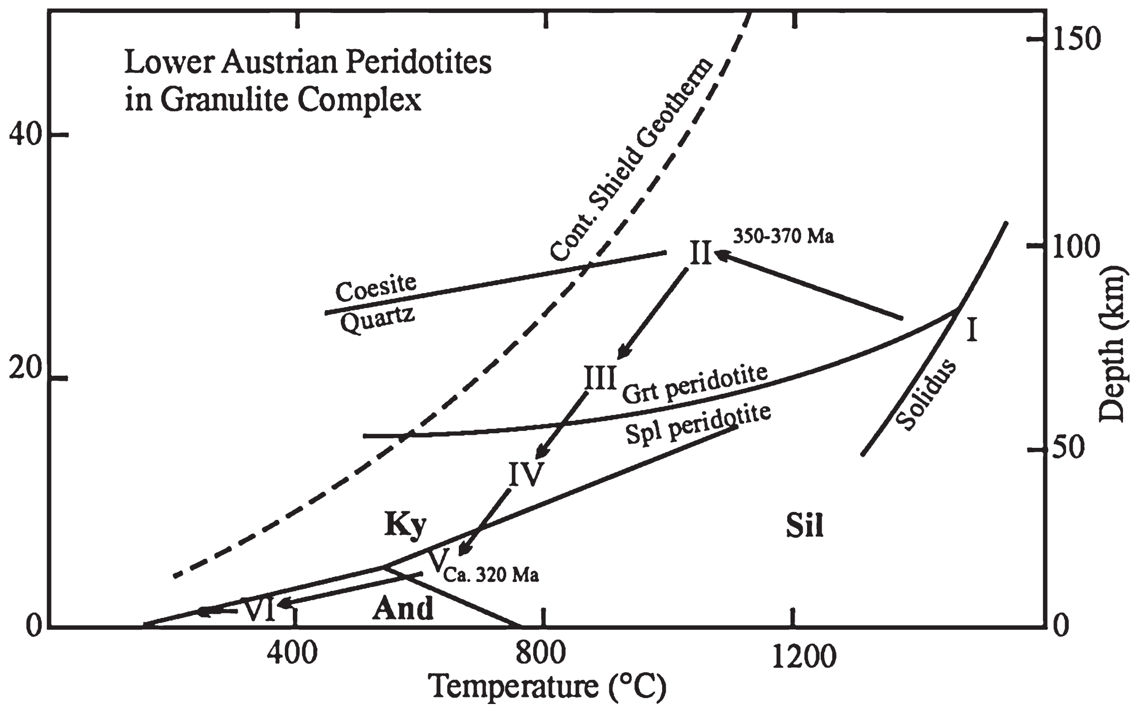
One sample from a pyroxenitic layer in peridotite contains garnet, with a continuous range in composition from $Py_{64\text{-}56}Alm_{23\text{-}27}Grs_{13\text{-}17}Uv_0$ to $Py_{42}Alm_{21}Grs_{33}Uv_0$, in which the low-Prp, high-Grs composition garnet occurs locally as rims on high-Prp, low-Grs garnet and as separate grains. Garnet is accompanied by omphacite, which contains 25 mol % jadeite. The high-Prp, low-Grs garnet is interesting for the presence of numerous monomineralic or multiphase inclusions, consisting of some combination of Na-Ca amphibole, alkali feldspar, phlogopite, chlorite and carbonate. The inclusions have negative crystallographic forms in garnet, suggesting the presence of former fluid-bearing phase(s). The presence of alkali with chlorine, as well as the negative forms of inclusions, suggests recrystallization of this mantle rock in a subduction zone environment with attendant fluid circulation.

Metamorphic evolution of the ultramafic rocks

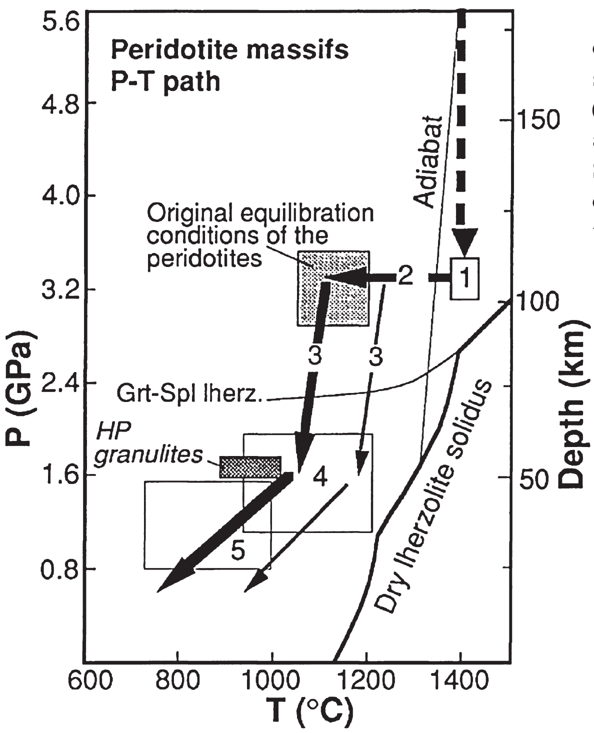
Based on textural relations observed in a large number of samples, six mineralogical stages have been established in the metamorphic evolution of the Lower Austrian peridotites (Carswell, 1991). Stage 1 is representedby the assemblage, Ol_1 + Opx_1 + Cpx_1 ± Spl_1, which reflects near-solidus upper-mantle conditions (Fig. 5). Stage II is represented by the garnet-bearing assemblage, Ol_2 + Opx_2 + Cpx_2 + Grt_1, where orthopyroxene porphyroclasts invariably show a marked decrease in Ca and an increase in Al from core to rim. PT conditions for the Stage II assemblage in garnet peridotite, using the thermobarometry of Carswell et al. (1989) and Nickel and Green (1985), are 32.2 kbar/1052 °C and 31.5 kbar/1035 °C, respectively (Carswell, 1991).

The Stage III assemblage, includes a second generation of low-Cr garnet coexisting with Cr-spinel (Ol_3 + Opx_3 + Cpx_3 + Grt_2 + Spl_2), although this complete assemblage cannot be explicitly demonstrated due to extensive overprinting by the later granulite facies assemblages of Stage IV, Ol_4 + Opx_4 + Cpx_4 + Spl_3, and amphibolite facies Stage V, Ol_5 + Opx_5 + Amp_1 + Spl_4. Development of the Stage IV granulite-facies assemblage is essentially restricted to the growth of fine-grained filamental kelyphites around garnets, presumably under strain-free conditions. Subsequent high-strain deformation promoted the development of the Stage V amphibolite-facies assemblage with aggregates of orthopyroxene + amphibole + spinel replacing the earlier pyroxene + spinel kelyphites.

A different PT evolution for garnet peridotite in the Dunkelsteinwald was proposed by Becker (1997). He obtained temperatures of 1400 ± 1420 °C (Stage 1 in Fig. 6) using Ca-in-orthopyroxene and two-pyroxene thermometry (Brey and Kohler, 1990). Based on such high crystallization temperatures of pyroxene megacrysts and the bulk composition of the pyroxenites, Becker (1996) suggested that the pyroxenite and megacryst cumulates crystallized in the lithosphere from hot low-degree melts, which were derived from the asthenospheric mantle from minimum depths of 180 to 200 km (ca. 5.5 to 6.0 GPa). Pressures of 3 to 3.5 GPa at 1100 °C were estimated for the assemblage garnet-orthopyroxene-clinopyroxene-olivine in garnet peridotite for stage 2. The garnet exsolution textures and growth of garnet II, interpreted to be at the expense of clinopyroxene I, are apparently restricted to pyroxenite layers and their surroundings. According to this interpretation, the exsolution textures reflect subsequent subsolidus cooling of the cumulates to the ambient lithospheric geotherm.



■ **Fig. 5.** Deduced pressure-temperature-time path for the six recognised stages in the metamorphic evolution of the Lower Austrian peridotits (Carswell, 1991). Spinel peridotite/Garnet peridotite reaction from O'Hara et al. (1971); Quartz/Coesite reaction from Mirwald and Massonne (1980); Al-sihcate stability fields – Ky/Sil/And from Salje (1986); "Dry" pyrolite solidus from Green and Ringwood (1967); Precambrian shield geotherm from Clark and Ringwood (1964).



Sm/Nd garnet-clinopyroxene-whole rock isochron ages of 344 ± 10 Ma and 370 ± 15 Ma for two garnet pyroxenite samples within Dunkelsteinerwald peridotite bodies (Carswell and Jamtveit, 1990) indicate an early Variscan age for the formation of the Pmax (Stage II) assemblages. Similar U-Pb zircon ages (347 ± 9 and 367 ± 18 Ma) were obtained by Kroner et al. (1988) from granulite massifs in the southern and eastern parts of the Moldanubian Zone.

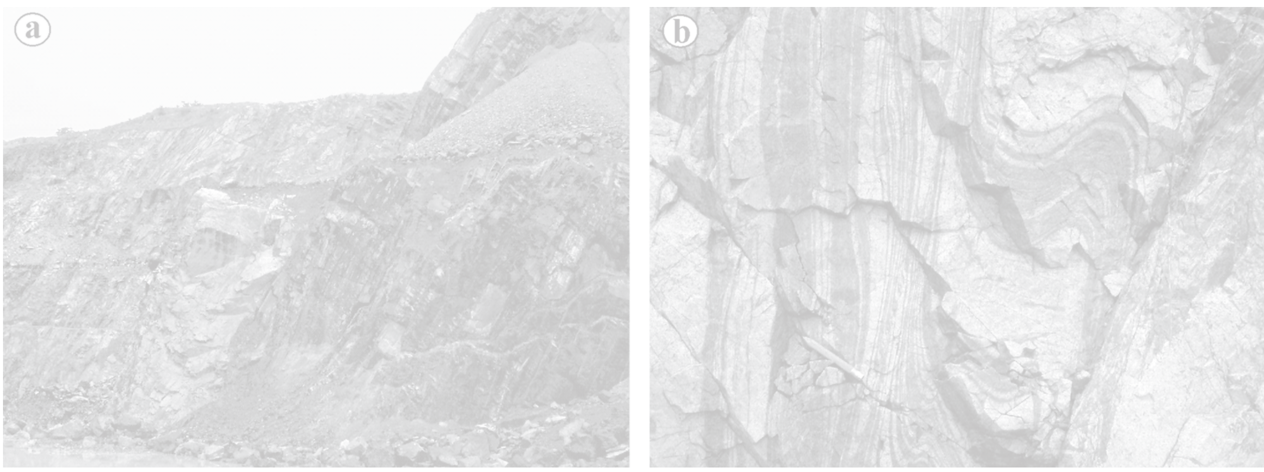
■ **Fig. 6.** P-T diagram showing the P-T paths of peridotite massifs from lower Austria (Becker, 1997). Stage 1, formation of pyroxenites and pyroxene megacrysts as high-pressure igneous cumulates; Stage 2, isobaric cooling; Stage 3, near-isothermal decompression; Stage 4, exsolution of spinel in pyroxenes and growth of coarse-grained symplectites; and Stage 5, formation of kelyphites. The dashed arrow represents isothermal interpolation to the intersection with an upper-mantle adiabat and implies fast ascent of superheated magma in the sublithospheric mantle. Thick and thin arrows indicate different paths for peridotites that followed somewhat different cooling histories. Equilibration conditions of high-pressure granulites are also shown (Carswell and O'Brien, 1993).

Stop 5-2 (Day 5). Garnet Peridotite and Garnet Pyroxenite, Granulite Quarry in Meidling-im-Tal, 6 km South from Krems am der Donau

Coordinates: N48°20′40.0″ E15°37′32.3″

The high-pressure granulite with elongated boudins of garnet peridotite exhibits a highly sheared fabric, which is homogeneously developed across the quarry and originated during the early stages of exhumation of the rocks. Felsic granulites are dominant in the quarry, consisting of feldspar, quartz, garnet, kyanite ± sillimanite, rutile, and variable amounts of biotite. Ternary feldspar (+ mesoperthite) is well preserved in garnet and occurs locally in the matrix. Some mafic varieties of granulite may contain clinopyroxene and orthopyroxene. Garnet contains oriented needles of rutile.

A large body of strongly serpentinized garnet peridotite, including lherzolite, harzburgite, and rare dunite, is exposed in the



■ **Fig. 7.** Meidling-im-Tal granulites and peridotites. (a) large deformed body of peridotite within strongly foliated HP granulite; Meidling quarry. (b) relicts of early compositional layering transposed to a dominant Grt-Ky bearing granulitic fabric; Meidling quarry