Whole-rock geochemical and mineralogical constraints on the genesis of the metaigneous Variscan lower crust in Central Europe – case study of the Lišov granulite Massif, Southern Bohemia

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The Gföhl Unit of the Moldanubian Zone, Bohemian Massif, has become a classic and much investigated terrain, as many of the Variscan granulite occurrences, associated with mantle-derived peridotite and pyroxenite, are concentrated here. The Lišov granulite Massif (LGM) E of České Budějovice (S Bohemia) shows major differences from the neighbouring granulite bodies (e.g., the Blanský les Massif) (Vajner 1964; Vrána – Jakeš 1982; Vrána 1990; Kotková 1998; Janoušek – Vrána 1999):

(i) Much greater relative proportion of intermediate and mafic granulites;

(ii) Abundance of Opx-bearing types (gabbroic and quartz dioritic granulites to relatively felsic charnockites);

(iii) Limited evidence for the high-pressure metamorphism but prolonged MP–HT (pyroxene granulite-facies) equilibration;

(iv) Absence of alumosilicates in the felsic Grt-bearing granulites;

(v) Association with spinel peridotites and pyroxenites devoid of garnet;

(vi) Complete absence of eclogites.

The timing of the MP–HT metamorphism is given by the U–Pb zircon age for the mafic two-pyroxene granulite (340 ± 3 Ma: van Breemen *et al.* 1982) that is in line with the established age of the granulite-facies crystallization in the region (Kröner *et al.* 2000).

The Lišov granulites define a calc–alkaline trend spanning a range of compositions from basic (gabbroic/quartz dioritic) to leucogranitic (total SiO_2 range 46.7–79.6 wt. %). The Harker diagrams display strong negative correlations of SiO_2 with TiO_2, Al_2O_3, FeOt, MgO and CaO, while K_2O and A/CNK form rather poorly defined positive trends. Finally, the plots with Na_2O, P_2O_5 and *mg* are characterized by inflections or discontinuities at $SiO_2 \sim 55$–60 % and, or, $SiO_2 \sim 70$ % indicative of either a complex evolution or, more likely, presence of several petrogenetic suites, each with a relatively independent history.

Concerning the trace elements, silica is strongly negatively correlated with Cr and Sr (for SiO_2 >50 %, i.e. except for mafic Grt granulites of Kotková 1998). Thorium generally decreases, and Y (for SiO_2 >50 %) increases with SiO_2. The SiO_2–Rb plot displays a poorly defined positive trend but the concentrations of Rb are low in all rock types. The diagrams of SiO_2 vs. Ba, La and Zr show scattered convex upward patterns, with an inflection at $SiO_2 \sim 60$–65 %. On the basis of petrology, mineral compositions and whole-rock geochemistry, four main rock groups were distinguished:

(1) **Mafic two-pyroxene granulites of quartz dioritic–gabbroic composition *(LM qtzD)***, constitute two larger (*c.* 4 km^2) bodies near Zvíkov, in the E of the Lišov mass. These are finer-grained, foliated rocks with mineral assemblage Opx–Cpx–Bt–Pl–Qtz (± Kfs, Amf, Grt); Ilm, Ap and Zrn are common accessories. Pyroxenes together with Bt and Pl occur in an equilibrated granular mosaic texture. High-Ca pyroxene is light grey-green, nearly non-pleochroic, with some fine Opx lamellae. Hypersthene shows a strong pleochroism, X: light red-brown, Y: beige, Z: light grey-green.

The metaluminous (A/CNK = 0.73–0.89) granulites *LM qtzD* are characterized by $K_2O/Na_2O << 1$ (0.2–0.8), within the data set the highest Sr (median = 533 ppm) and Cr (71 ppm) accompanied by the lowest Rb (27 ppm) and Y (25 ppm). They have moderately LREE-enriched REE patterns (Ce_N/Yb_N = 5.8–6.4) with slight negative Eu anomalies (Eu/Eu* = 0.80–0.86). The analysed two samples are isotopically the most primitive ($^{87}Sr/^{86}Sr_{340}$ = 0.7063 and 0.7067, e^{340}_{Nd} = –1.6 and –2.4).

The modally layered sequences (e.g., Rudolfov) document the role for fractional crystallization in the genesis of the presumed gabbroic–quartz dioritic magmatic protolith to the granulites *LM qtzD*. The trends in the Harker plots are consistent with a fractionation of mainly Amf–Pl assemblage, ± pyroxene.

The rare Grt-bearing modally layered granulites described from the borehole LV-1 (Kotková 1998) have significantly flatter, in respect to the rest of the group LREE-depleted patterns (Ce_N/Yb_N = 2.0–2.9) with variable Eu anomalies. Some geochemical trends (increase in SiO_2, MgO and mg# accompanied by drop in Sr, Y, TiO_2, Al_2O_3, FeOt, SREE, diminishing Eu anomaly swapping to a positive one), often oblique to those defined by the *LM qtzD* granulites, are compatible with progressive accumulation of an assemblage dominated by Mg-rich, Fe–Ca-poor pyroxene.

Pyroxenites (± phlogopite) with alternative predominance of high-Ca Cpx or enstatite occur as small (<0.5 m across) enclaves. They seem to represent magmatic cumulates crystallized from, and later captured by, a basic magma parental to the granulites *LM qtzD*.

(2) **Two-pyroxene tonalitic granulites *(LM to)*** are foliated finer-grained pyroxene–biotite rocks with min-

eral assemblage Opx–Cpx–Bt–Pl–Qtz (± Kfs, Amf); Ilm, Ap and Zrn are common accessories. High-Ca pyroxene contains fine lamellae of orthopyroxene; primary Opx is often absent. The tonalitic granulites form no larger coherent unit but occur sporadically throughout the LGM, in particular in layered sequences.

The granulites *LM to* are metaluminous (A/CNK = 0.78–0.98) with K_2O/Na_2O ratios normally lower than unity (mean = 0.67). They contain in general the highest SREE with moderately LREE-enriched patterns (Ce_N/Yb_N = 3.7–7.9) and pronounced negative Eu anomalies (Eu/Eu* = 0.50–0.62). The isotopic signature is significantly more evolved both in neodymium (ε^{340}_{Nd} = –5.2 to –5.3) as well as strontium ($^{87}Sr/^{86}Sr_{340}$ = 0.70854 and 0.71027) than in the case of the group *LM qtzD*. The considerably more radiogenic Sr of the latter sample seems to reflect its retrogression to foliated Amf–Bt tonalitic gneiss.

(3) **Opx–Grt charnockites *(LF ch)*** of granitic–granodioritic composition, including fine-grained, unfoliated rock types, form not only tabular to podiform bodies, up to 300 m long, but also thin layers in layered sequences (Rudolfov). Estimated modal composition of the sample Li-5 is Qtz 35 vol. %, Pl ($An_{25–27}$) 34 %, mesoperthite 25 %, Opx 5 %, Alm-rich Grt 1 %; Ilm, Ap and Zrn are the main accessories. Granular mosaic of the rock-forming minerals indicates equilibrated assemblage. The Fe-rich Opx (Fs ~70 mol. %) is strongly pleochroic, X: red brown, Y: beige, Z: bluish green.

The rather siliceous (SiO_2 = 72.2–75.2 %) charnockites are saturated in alumina (A/CNK = 0.96–1.10, mean 1.05). The sample Li-5 has a relatively flat REE pattern (Ce_N/Yb_N = 2.9) with a deep negative Eu anomaly (Eu/Eu* = 0.39). Its strontium isotopic composition is intermediate between the groups *LM to* and *LF gr* ($^{87}Sr/^{86}Sr_{340}$ = 0.71614), while its Nd isotopic signature is practically undistinguishable from the tonalitic granulites (ε^{340}_{Nd} = –5.4). Grt–Opx–Pl barometry indicates crystallization at moderate pressures (*c.* 5 kbar).

(4) **Felsic Grt** (± Bt) **granulites *(LF gr)*** predominate within the LGM (>70 vol. %). Apart from rare relict domains preserving massive texture and primary HT mineralogy, most of them were mylonitized and recrystallized to foliated varieties with platy quartz and fine-grained feldspar mosaic. Modal composition (Li-6): mesoperthite 50 %, Qtz 39 %, Pl 5 %, Alm-rich Grt 4 %. Accessories are Mt, Ap, Zrn and acicular Rtl. Mesoperthite is made of about equal proportions of Kfs and Na-oligoclase.

The granulites *LF gr* are silica- and K-rich (SiO_2 = 75.0–79.6 %, K_2O/Na_2O = 1.0–2.4), mainly slightly peraluminous rocks (A/CNK = 0.95–1.20). The only limited excess of alumina accounts for the absence of alumosilicates (Vrána – Jakeš 1982). The sample Li-6 has a REE pattern with the lowest LREE enrichment (Ce_N/Yb_N = 2.1) and a huge negative Eu anomaly (Eu/Eu* <0.16). As shown by Valbracht *et al.* (1994) and our results, the granulites *LF gr* contain a highly radiogenic strontium ($^{87}Sr/^{86}Sr_{340}$ = 0.73042 and 0.72990) and their Nd isotopic composition overlaps with the previous groups (ε^{340}_{Nd} = –4.2 to –5.4).

The granulites *LF gr* are thought to have crystallized at moderate pressures (*c.* 5 kbar) as an anhydrous assemblage of quartz and ternary feldspar ($Or_{51.5}Ab_{42}An_{6.5}$) with garnet (X_{Ca} ~ 0.04), minor plagioclase, and Fe–Ti oxide. The Fe–Ti oxide is characterizded by Mt–Ilm intergrowths indicating unmixing accompanied by oxidation of former ulvöspinel (implying high T and low water activity during the primary crystallization of acid Lišov granulites).