Microstructures and Rheological Behaviour of Marbles in Natural Strain Gradient

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Inversion metamorphic zonation is developed in the Eastern margin of the Bohemian Massif where two crustal nappes overlie a paraautochthonous unit of similar protolith origin. Maximum temperature during a prograde Barrovian metamorphism has been estimated at 350°C for the paraautochthone (PA), 450°C for the lower nappe (F_1), 520°C for the upper nappe and 620°C for the base of the orogenic root domain (MO) (Schulmann et al. 1991). Several types of calcite-bearing tectonites has been sampled from each tectonic unit. Mean grain size and crystallographic preferred orientation measurement and complete fabric analysis have been carried out.

Thin sections of marbles have been digitised and used for grain size and quantitative textural analysis. Grain size of coarse grained marbles has been calculated by the intercept area method. In case of grains smaller than 100 microns, long and short axes of each grain have been measured to minimise an error. Digitised images have been used also for estimation of grain shape preferred orientation, grain elongation and analysis of orientation of grain boundaries. This analysis shows at least two groups of different microstructures.

The first type of microstructure belongs to a grain growth process related to a temperature increase during the progressive underthrusting. Equant grains, large single peak grain size distribution and grain boundary migration as a main grain recrystallization mechanism are typical properties of this type of deformation. Strong c-axis fabric with two symmetric maxima is characteristic of these types of textures.

The second type of microstructure is more complex. It was developed during localised deformation and is associated with later nappe stacking. In the paraautochthonous unit, dynamic recrystallization diminished grain size from 200 to 20 μm and crystallographic preferred orientations show weak single peak maxima. Marbles in F_1 have been totally recrystallised reaching similar grain size 300 μm in all samples. The texture is marked by a grain aspect ratio > 3 and cuspate lobbate boundaries indicating that grains grew during dynamic recrystallization via grain boundary migration process. A similar texture has been already explained as a diffusion accommodated dislocation creep (Walker et al. 1990). Crystallographic preferred orientation show transition from two maxima towards a single maximum of c-axes. In the uppermost nappe, F_2, marbles were not activated in a large extent and deformation is localised in narrow zones where coarse grained marble recrystallises showing similar fabric characteristics as marbles in F_1.

The hypothesis of transition from dislocation to diffusion creep (Schmidt 1982) was not confirmed in our case. Our data shows that the ability of calcite to accommodate high strain depends more on dislocation creep than on diffusion creep. In case of PA and F_1, where the temperature did not overcome 500°C during nappe stacking, marbles accommodated the maximum of strain. However, late exhumation deformations are not localised in coarse grained marbles of F_2 that behaved as resistant bodies embedded in weaker rocks. Such a contrasting behaviour is explained in terms of contrasting pre/exhumational grain size of marbles in individual nappes affected by a similar thermomechanical event during the nappe stacking.

Interplay of Intrusion and Transtensional Tectonics: Čistá Granodiorite Stock in the Bohemian Massif

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The Čistá granodiorite intruded the Upper Proterozoic strata in the north-western flank of the Teplá - Barrandian zone in the Bohemian Massif. The central part of the Teplá - Barrandian is composed of two stratigraphic sections which differ from each other in structural style. Unmetamorphosed Lower Palaeozoic sediments (Ordovician to Middle Devonian) are deformed by folds with NE-SW trending hinges and by several NW or SE dipping thrusts, and lie unconformably on the metamorphosed Upper Proterozoic plus Cambrian volcano-sedimentary rocks. The Čistá granodiorite stock is a minor component of the Čistá-Jesenice massif whilst the majority of the pluton is formed by biotitic granite of the Tis type. The granodiorite intruded directly into the Proterozoic rocks apart from the eastern margin which pierced directly the Tis biotitic granite. The contact between these two granitoids coincides partly with a major brittle-ductile shear zone striking NE-SW and the biotite granite rim extends as a narrow tail to the SW.

The Barrandian rocks are characterised by low-grade metamorphism and superposition of several structures. Bedding in the metapelitic and metapsamitic rocks is overprinted by an axial cleavage produced by folding related to the Barrandian - Saxothuringian convergence which occurred at the Middle to Upper Devonian times and was oriented NW-SE in this region. A subsequent deformation phase generated sets kink bands at a scale from centimetres to several metres and dipping at low- to medium-angle to the (W) NW and (E) SE which indicate a lateral extension and vertical shortening.

Macroscopic structures in the igneous rocks are mostly invisible except for margins of the intrusion were magmatic and subsolidus fabrics were measured. The rest of the pluton had to be explored by means anisotropy of magnetic susceptibility (AMS). Magnetic susceptibility of the granodiorite containing magnetite is by two orders higher than in the granite where carriers of magnetisation are presented by ilmenite, haematite, pyrrhotite and biotite. Magnetic foliations along the periphery of the intrusion are fairly concentric, yet the core zone displays only foliations with a regular NE-SW trend and a steep plunge. Magnetic lineations plunge at shallow angles in the periphery whilst in the central zone they are steep. The geometry of AMS fabric implies that the erosion was deep enough to remove the apex of the pluton where conventionally presumed flat-lying magmatic foliations may have been preserved. Moreover, we have found no evidence the magma was indeed flowing subhorizontally in the superficial part of the intrusion.

The strike-slip shear zone at the eastern margin of the pluton cross-cuts both the Tis granite and the Čistá granodiorite and runs parallel to their contact. One deformational event produced different mylonite structures in these rocks, depending on their former mineral composition and igneous fabric. In a profile across the shear zone, the strain intensity increases from magmatic fabrics up to ultramylonite. In the highest-strain zone, the Tis granite shows a development of structures characterised by interconnected weak layers whereas for the Čistá granodiorite a structure composed of ultramylonitic matrix and rounded fragments of plagioclase is typical. We interpret the transition from the magmatic fabric to solid-state mylonitic foliation as a result of the syntectonic granodioritic intrusion combined with continuing activity of the transtensional sinistral shear zone after the emplacement had ceased. Quartz microfabrics determined in samples with a different strain intensity also support syntectonic cooling of the intrusion as is indicated by transition from prism [c] activity to prism [a] glide.

We assume that the transtensional regime in this area was decisive for the emplacement of the Čistá granodiorite. The source of magma could have a linear configuration, as indicated by elongation of the stock parallel to the major shear zone. The width of the stock is supposed to grow as the sinistral transtensional motion of the shear zone went on. The ascent and emplacement of the Čistá granodiorite controlled by this shear zone match with the extension evidenced by kink bands in the Proterozoic rocks west of the intrusion.

Sliding Reaction Sil + Bt + Qtz ⇋ Crd + Kfs + H_2O and Polymetamorphism of Moldanubian Paragneisses Associated with Multiple Shearing Deformations

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The reaction given in the title (Hoffer 1976, Spear and Cheney 1989) tends to be accompanied by several other reactions involving Bt, Sil, Crd, Ms, Kfs, Pl, H_2O and melt, located in neighbouring parts of the amphibolite facies PT field.

Sillimanite-biotite gneisses and cordierite-biotite gneisses represent the most widespread rocks in the Moldanubian Zone. They tend to occur separately in more or less clearly defined regional domains (e.g., Zelenka 1926). In some cases, the two rock types may occur as interlayered bands on scale of metres (Krupička 1968). Elsewhere, in various subareas, either of the two rock types may pass into migmatites which may exhibit a variety of histories: 1) cordierite migmatites around late-Variscan plutons, 2) migmatites with foliated/recrystallised mobilisates, showing a polymetamorphic history.

Major-element analyses indicate that the two types of gneisses tend to show closely similar or comparable composition (Suk 1964, Krupička 1968). With exclusively prograde metamorphic history in mind, Krupička (1968) suggested that examples of intimately interlayered Sil-Bt and Crd-Bt gneisses, such as in the section near Havlíčkův Brod, violate fundamental principles of the phase rule, since both rock types were exposed to the same PT conditions across the small domain of < 100 m. An alternative evolution history, including reactivation of certain structural layers of former Crd-Bt gneiss by shear deformation and minor influx of water-bearing fluid under amphibolite facies conditions (and, possibly, a slight change in PT conditions?) allows interpretation of locally interlayered Sil-Bt gneisses in Crd-Bt gneisses in terms of the reaction Crd + Kfs + H_2O ⇋ Sil + Bt + Qtz. Consequently, the small-scale interlayering of gneisses showing contrasting mineral assemblages poses no problem in context of validity of the phase rule. The example is introduced to visualise the inertia, with which the "prograde-metamorphism-only" concept is ingrained in geological community.

The lecture will present examples of microscopic-scale textures and structural relations and outcrop-scale structural relations pointing to shear deformation repeatedly superimposed on early-stage paragneiss (Vrána 1979).

Pressure solution and fabric reorientation, materialised mainly through efficient recrystallisation of micas and quartz, are important mechanisms. Microscopic-scale structural relations indicate that the reaction Sil + Bt + Qtz ⇋ Crd + Kfs + H_2O (and some related reactions) took place repeatedly as a sliding reaction over certain domains reactivated by deformation and influx of fluids. The structural relations include examples of Sil+Bt+Grt pseudomorphs after Crd. The resulting situation corresponds to population of paragneiss domains with unlike metamorphic evolution histories, including potential differences in the PT (fluid) conditions of the last recrystallization.

As thermobarometry studies of gneisses will proliferate through international efforts (e.g., Owen and Dostál 1996) and activity of local petrologists, it appears as critical that the information should be tied to local (and regional) structural sequence and a possible polymetamorphic history. Without this specific information the PT estimates may be difficult to interpret or may result in artefact PT histories on regional scale.