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Discussion on: "Structural evolution of the central part of the Krušné Hory (Erzgebirge) Mountains in the Czech Republic—evidence for changing stress regime during the Variscan" by J. Konopásek, K. Schulmann and O. Lexa [J. Struct. Geol. 23 (2001), 1373–1392]☆

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1. Introduction

During the last 2.5 decades our understanding of mass movements within the deep lithosphere improved substantially. The introduction of concepts from material science into geology in combination with a better understanding of phase petrology and isotope systems fundamentally changed the views on the tectonic evolution of many regions. Yet many uncertainties exist how experimental and theoretical studies translate into tectonic models for metamorphic regions exposing rocks deformed in the deep lithosphere. Thus, for quite a few metamorphic regions tectonic models continue living that are inconsistent with P–T- and geochronological data and that apply inadequate mechanical concepts to observed deformation structures. This was discussed in detail for the Variscan Bohemian Massif by Krohe (1998). Many mutually excluding models exist here making it difficult for geoscientists from the 'outside' to get an insight into the actual processes portrayed by structures and P–T–t–d histories in this particular region.

Konopásek et al. suggest a tectonic evolution model for the Erzgebirge (ultra)-high-pressure metamorphic region (Northern Variscan Bohemian Massif) essentially based on strain and fold analyses from the SW-part of the Erzgebirge. The structural observations presented in their paper are mostly consistent with the observations from the German part of the Erzgebirge. However, we strongly disagree with Konopásek et al. in (i) how they translate observed structures into tectonic mechanisms, (ii) how they correlate the structures of the separate tectonic units in the Erzgebirge complex with the respective P–T–t evolutions, and (iii) how they interpret the structures of Erzgebirge complex within the regional framework of the N-Bohemian Massif (cf. Willner et al., 1994, 2000, 2002; Krohe, 1996, 1998).

2. The 'Saxothuringian enigma'

Traditionally, based on observations in the western Saxothuringian zone, the northern Bohemian Massif has been described as originated during a Late Devonian to Early Carboniferous collision: there, allochtonous units metamorphosed between 420–400 Ma to medium and high-P ('Münchberg nappe') overly (par-)autochtonous low grade (pre-)Palaeozoic rocks interpreted as a foreland.

For a reason not explained in the paper (and based on the investigation of only a very small part of the Erzgebirge >10 km in diameter) Konopásek et al. presuppose (i) that the eastern Saxothuringian zone (Erzgebirge complex) would consist of equivalents to the allochtonous medium-P/high-P nappe units and the (par-)autochtonous, (pre-) Palaeozoic rocks of the western Saxothuringian, and (ii) that both were simply metamorphosed to a higher grade during the Early Carboniferous. Therefore, it would be 'difficult if not impossible' to separate these two from each other in the field (p. 1373, introduction). However, the following facts

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are inconsistent with this idea and suggest a more complex structural evolution of the entire ‘Saxothuringian’.

As has been known for a long time, the high-*P* and ultra-high-*P* units of the Erzgebirge complex (eastern Saxothuringian zone) actually *underlie* the low grade rocks, which are predominant in the western Saxothuringian zone. On a large scale, the main foliation (D2) of all Erzgebirge units (including the high-*P* and ultra-high-*P* units) forms a W-plunging (more or less corrugated) antiform structure (‘dome’) with a steep southern limb and a flat SW- and NW-dipping northern part. This means that the Erzgebirge units emerge within a window *beneath* the low grade rocks of the Saxothuringian (Krohe, 1998; Willner et al., 2000)—a setting, which is somewhat similar to the Tauern-window in the eastern Alps.

Also U–Pb zircon data on high-*P* granulite and Sm–Nd garnet-whole rock data on eclogites show that the Erzgebirge complex underwent high-*P* and ultra-high-*P* metamorphism between 340 and 360 Ma (Schmädicke et al., 1995; Kröner and Willner, 1998). That is much later than the Münchberg nappe. Also, Ar–Ar and Rb–Sr white mica ages of the gneisses (Tichomirova et al., 1996; Werner et al., 1997; Werner and Lippolt, 2000) suggest exhumation of these (ultra)-high-*P* units between 340 and 330 Ma, i.e. *30–40 Ma after denudation of the Münchberg nappe.*Therefore, the Erzgebirge complex reflects tectonic processes that occurred at a totally different time (and that are unrelated to) those of the Münchberg nappe and of the low grade rocks of the western ‘Saxothuringian’.

3. Deformation concepts

It is a general observation in the studied area that the Erzgebirge complex was pervasively strained in its entire volume after the high-*P* stage, but locally still at fairly high pressure. This deformation represented by a dominant foliation occurred at temperatures from about 550 to 800 °C (depending on the tectonic unit; cf. Willner et al., 2000 and references cited therein). In the structural concept of Konopásek et al. this deformation reflects two successive deformation episodes (D2 and D3) supposed to be characterised by multiple short term switches of the principal stress axes.

In the northern Erzgebirge flat WNW–WSW dipping foliation planes are attributed to D2 with a flat W-dipping lineation and tight to isoclinal intrafolial folds with axes oriented at low angle to the lineation; shearing is generally top-to-the-W (cf. Willner et al., 2000). Konopásek et al. attributed this to compression and westward nappe transport. W–E-trending steep kink-band boundaries and large-scale open folds doming the D2 foliation are referred to as D3 and interpreted to reflect N–S-contraction.

In the southern Erzgebirge, steep E–W-trending foliations are also referred to as D3. The orientation of the foliation is parallel to the kink-band boundaries in the north and thus also interpreted as to result from flexure due to N–S compression. This deformation is typically characterised by flat E–W-dipping lineations, tight folds with axial planes oriented sub-parallel to the steep foliation and axes oriented at low angle to lineation. We think that this D2/D3-distinction is artificial:

(i) Kink bands were formed in the brittle and brittle–plastic transition field and hence substantially later in the *P–T* history than steep foliations in the southern Erzgebirge. Microstructures indicate shearing at temperatures that at least allow plastic creep of feldspar during their D3 (Krohe, unpublished data; also obvious from the aggregate shape analysis by Konopásek et al.). Also, no overprinting relationships between their D2 and the *ductile* D3 folds are reported.

(ii) Generally, it is inadequate to determine the principal paleo-stress axes by the orientation of the ductile D3 (southern Erzgebirge) fold axial planes. Similarly to D2, the folding mechanisms in this part are buckling more competent layers into a less competent matrix during shortening along the finite *Z*-strain axis, transposition toward the finite *XY*-plane and then boudinaging during progressive shearing producing the observed stuctures (see below). Orientation and geometry of such folds are dependent from the initial orientation of the competent layer with respect to the instantaneous strain axes, viscosity contrasts, strain magnitude and strain path (or ‘non-coaxiality’), etc. (cf. Ramsay and Huber, 1987). During non-coaxial strain, most fold axes will tend to rotate toward the shear direction. Strictly, only instantaneous strain markers should be used as paleo-stress indicators such as kinkband-boundaries. However, these are clearly developed at the latest stage in the *P–T* evolution of the Erzgebirge *after exhumation of the Erzgebirge complex*. This is not new; late/post-metamorphic N–S compression at the northern edge of the Erzgebirge and resulting brittle structures during foreland deformation have been described many times before; cf. Krohe (1996) and references therein.

In the following interpretation of the structural framework and evolution of the Erzgebirge, the understanding of the *ductile* D3 faults as flexural slip faults results in a row of interpretations that do not apply to the actual structures of the Erzgebirge complex.

4. Structural position of eclogites

The ‘nappe units’ of Konopásek et al. comprise garnet–micaschists, orthogneisses (containing high-pressure assemblages) and eclogites. Nappe units are claimed to be preserved in synform structures of flexural D3 folds. The eclogites are claimed to occur preferentially at the contacts (obviously D2) between 'parautochtonous' and 'nappe' units. The nappe contacts are claimed to separate the nappes from underlying units showing lower maximum $P-T$ conditions.

However, the occurrence of eclogites are not restricted to a discrete horizon. Instead, clusters of eclogite boudins (and boudins of other high-P rocks) are intercalated in many different places *within* (and surrounded by) rocks preserving seemingly lower maximum $P-T$ conditions. Boudins of eclogites occur in different units differing in dP/dT gradients and $P-T$ paths ('gneiss eclogite unit' and 'micaschist eclogite' units of Willner et al. (2000)) including those parts that Konopásek et al. consider as 'parautochtonous').

Such boudins containing eclogites and also coarse grained intrusive rocks represent domains of high viscosity (and deficiency of fluids) during D2. The folded 'allochtonous units' described by Konopásek et al. are actually high-viscosity layers progressively folded and then boudinaged during their D2 (and *ductile* D3). Such (folded) boudins may reach several 100 m in extent. On the map those boudinaged and (tightly) folded layers are more obvious in the south, where both the foliation and fold axial planes are steep, than in the north, where both are flat.

In either case, the internal structures of the boudins were less affected by the D2 (and *ductile* D3) deformation; thus high-P mineral assemblages and microfabrics of older events are best preserved here. Even pre-Variscan magmatic structures are preserved in orthogneisses (Sebastian, 1995), although the surrounding rocks have been totally equilibrated under upper amphibolite facies conditions. In the boudins, the geochronological record from the old stages might also be preserved. This has been well documented in other parts of the northern Bohemian massif (Continental Deep Drilling Site; e.g. Glodny et al., 1998; Krohe and Wawrzenitz, 2000). Only locally, in strongly sheared rocks (D2), high pressure mineral assemblages are preserved; these are generally pre-kinematic relics with respect to D2.

From this it becomes clear that shearing (D2 and ductile D3 according to Konopásek et al.) occurred during juxtaposition of high-P against medium-P rocks and during continuing exhumation (see below; cf. Willner et al., 2000; their D2). This naturally precludes any emplacement of high-P rocks next to medium-P rocks along discrete thrust planes late in the overall metamorphic history, which was anticipated in the model of Konopásek et al.!

5. The Cadomian basement

What Konopásek et al. refer to as '(par-)autochtonous' units consists of metasediments (assumed to be of 'Paleozoic' and 'Proterozoic age') and orthogneisses (cf. their figures 1 and 2, chapter 3) that record lower maximum $P-T$ conditions (15 kbar at 580–630 °C compared with 26 kbar at 650–700 °C for the eclogites and 22 kbar at 640 °C for garnet–micaschists in the 'nappe units') Proterozoic rocks are said to show a 'Cadomian' anatexis reworked by Variscan high dP/dT metamorphism (p. 1377).

This description gives wrong impressions: (i) that the widespread anatectic gneisses of the Erzgebirge would preserve Cadomian anatectic structures, (ii) and that the overprinting Variscan episodes reflect high dP/dT only. This interpretation omits important parts of the Variscan geodyamic history: Large parts of the gneiss–eclogite unit experienced anatexis *after* the high-pressure metamorphism, during near isothermal decompression. During this stage the pre-dominant metamorphic record of these rocks was created. At this stage the rocks were hot and thus had a low viscosity leading to pervasive deformation throughout the rock volume (cf. Willner et al., 2000). Indisputably, the U–Pb zircon data evidence several pulses of 'Cadomian' granitoid intrusions (essentially at 480 and 554 Ma; Kröner et al., 1995), but essentially no in situ Cadomian anatexis. Yet, if at all, structures related to those older events might only be preserved in boudins consisting of material showing higher viscosity than the gneisses deformed in the Variscan.

6. Deformation involving extension tectonics

The reason why westward shearing is taken to result from contraction and westward thrusting is not made clear by the authors (probably, they assume that all deformation events up the D3-steep axial planes are compressive). In fact, all the deformation they describe correlate with decompression and thus *are evidently related to exhumation.* In other words they depict the mass movements associated with exhumation of these rocks! Therefore we disagree with their claim that "... field observation... are not able to provide any information about the mechanism of emplacement of eclogites from a depth corresponding 26 kbar to the base of the non eclogitic orthogneiss nappe" (p. 1391). As mentioned earlier, between 330 and 340 Ma, high-P units were exhumed underneath an upper plate that remained in the upper crust since ~375 Ma (Krohe, 1998). This is what their deformation episodes in fact depict: the emplacement of the Erzgebirge Complex immediately beneath this upper plate.

Actually, D2 is extension tectonics for reasons that we have discussed in context with the $P-T-t-d$ histories of the different units in many papers (Willner et al., 1994, 1997, 2000, 2002; Krohe, 1996, 1998). The most important are: (i) this syn-decompression deformation cuts out several tens of kilometres of the profile between this upper plate and the high/medium pressure assemblages, (ii) clearly the major exhumation mechanism is not erosion due to the preservation of the upper plate, (iii) presupposed thrusting of this higher parts would not result in decompression of the lower plate during deformation, (iv) in the west Erzgebirge, westward shearing points downward with respect to the metamorphic zones.

Konopásek et al. allow extension only to occur in the semi-brittle and brittle regime (horizontal kink-band boundaries). Clearly, this causes only minor vertical shortening magnitudes; hence Konopásek et al. totally missed the point of our papers when they use this small shortening amount as an argument against our extension model (p. 1391).

We think that Konopásek et al.'s D2 (north) and D3 (south) actually are part of one single progressive episode of westward shearing characterised by a high (though locally varying) degree of non-coaxial strain. During shearing, as a result of viscosity contrasts, passive folding, refolding and widespread formation of boudinages occurred on various scales. Importantly, despite the warping of the foliation planes, throughout (northern and southern part) the studied area, the lineation plunge is constantly at a low angle to the WNW, and the shear sense is constantly top-to-the-WNW. The orientation of the fold axes is determined by the orientation of the respective shear zones (Willner et al., 2000). Fold axes are generally oriented at a low angle to the WNW-plunging lineation.

There is no reason to assume that the warping of the foliation was caused by compression and switching stress regimes. Extension was associated with unroofing and differential vertical movements within the hot lower tectonic units driven by buoyancy forces. Such phenomena have been shown in nature and in various numerical models (e.g. Brun and van den Driessche, 1994; Gerya et al., 2001). Substantial vertical movements combined with unroofing are evident from the Ar–Ar- and Rb–Sr mica ages of 340–330 Ma of those parts of the Erzgebirge complex that are said to be (par-)autochtonous: these white micas recrystallised during D2 and their ages are in the same range as the ages of the early sediments that transgressed onto the upper plate. Their ages are a time constraint for the D2 deformation, but also for the exhumation of the deepest parts of the Erzgebirge complex as shearing continued during lower temperatures (D3 according to Willner et al. (2000)). This completely conflicts with the model of Konopásek et al., which would predict burial of the deeper parts (below the nappes) at this time, during D2.

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