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ORIGINAL PAPER

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Magmatic stoping as an important emplacement mechanism of Variscan plutons: evidence from roof pendants in the Central Bohemian Plutonic Complex (Bohemian Massif)

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Abstract The presence of numerous roof pendants, stoped blocks and discordant intrusive contacts suggests that magmatic stoping was a widespread, large-scale process during the final construction of the Central Bohemian Plutonic Complex, Bohemian Massif. The measured total length of the discordant contacts that cut off the regional cleavage and were presumably formed by stoping corresponds to about half of all contacts with the upper-crustal host rocks. In addition, at least some of the straight, cleavage-parallel intrusive contacts may also have recorded complex intrusive histories ending with piecemeal stoping of thin cleavage-bounded host rock blocks into the magma chamber. Based on the above, we argue that the fast strain rates required for emplacement of large plutons of the Central Bohemian Plutonic Complex into brittle upper crustal host rocks over relatively short-time span could not have been accommodated entirely by slow ductile flow or slip along faults. Instead, the emplacement was largely accommodated by much faster thermal cracking and extensive stoping independent of regional tectonic deformation. Finally, we emphasize that magmatic stoping may significantly modify the preserved structural patterns around plutons, may operate as an important mechanism of final construction of upper-crustal plutons and thus may contribute to vertical recycling and downward transport of crustal material within the magma plumbing systems in the crust.

Keywords Bohemian Massif · Emplacement · Magmatic stoping · Pluton · Variscides

Introduction

Although magmatic stoping, i.e., thermal cracking and downward transport of host rock blocks into a magma chamber (Daly 1903; Furlong and Myers 1985; Marsh 1982; Pignotta 1999; Pignotta and Paterson 2001, 2006; Pignotta et al. 2001a, b), was recognized long ago (Daly 1903) and stoped blocks have been described in many plutons worldwide, the extent and the importance of stoping with respect to other processes in magma chambers has been a matter of longstanding controversy and vigorous scientific discussion. For example, Coleman et al. (2004), Glazner and Bartley (2005), and Glazner et al. (2004) recently claimed that magmatic stoping does not exist or is highly unlikely to occur in granitoid plutons supposed to be constructed through incremental diking, i.e., by accumulation of multiple dikes that cool below their solidi between injections.

In contrast, other studies of the three-dimensionally well-exposed plutons in the North American Cordillera and the Andes suggest that extensive magmatic stoping may play an important role during final construction of plutons in magmatic arcs and orogenic belts. For instance, the following examples of extensive magmatic stoping indicate that large volumes of host rock have been detached from the pluton roofs and transported downward into magma chambers: La Gloria pluton, Chile (Mahood and Cornejo 1992), Chita pluton, Argentina (Yoshinobu et al. 2003a), Coastal Batholith, Peru (Myers 1975), Cerro Aspero batholith, Argentina (Pinotti et al. 2002), Mitchell Intrusive Suite (Pignotta et al. 2001b; Pignotta and Paterson 2006) and Tuolumne Batholith, Sierra Nevada (Žák and Paterson 2005), the Searchlight pluton, southern Nevada (Bachl et al. 2001;

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Perrault et al. 2005) and the Mount Stuart Batholith, Cascades, Washington (Paterson and Miller 1998a). These studies also show that the importance of magmatic stoping increases in the upper crust above the brittle-ductile transition, predominantly due to large thermal gradients between the magma and brittle host rocks prone to thermal fracturing.

Magmatic stoping is an important process from several points of view, since it may: (a) operate as a significant vertical (magma up—host rock down) material transfer process during final emplacement of plutons (i.e. MTP of Paterson and Fowler 1993); (b) remove large sections of host rock and thus also evidence of earlier emplacement processes (e.g., ductile strain, diking) and thus significantly reduce the information on emplacement processes (Paterson and Fowler 1993; Paterson and Vernon 1995; Paterson et al. 1991; Yoshinobu et al. 2003a, b); (c) be used to test magma chamber construction models and indicate the presence of ancient large magma chambers in the crust—extensive stoping requires large molten regions in the crust (magma chambers) and thus should not occur in plutons assembled via the incremental diking mechanism (Clemens 1998, 2005; Clemens and Mawer 1992; Glazner et al. 2004; Petford et al. 1994, 2000); (d) contribute to vertical exchange of mass and heat within the crust in vertically extensive magma-plumbing systems (Paterson et al. 1996); (e) contribute to chemical contamination of magmas during their ascent and emplacement (Barnes et al. 2004; Clarke et al. 1998); (f) stoped blocks are useful for interpreting the formation and timing of magmatic fabrics, establishing possible paleo-plumb lines, and may also be used as ''chronometers'' and ''viscometers'' in magmatic bodies (Fowler and Paterson 1997; Paterson and Miller 1998b); and, in addition, (g) discrete stoping events and collapses of magma chamber roofs may trigger volcanic eruptions (Hawkins and Wiebe 2004).

Field evidence for magmatic stoping in plutons typically includes the presence of stoped blocks, i.e., pieces of host rocks, which were detached from pluton roofs and sank into a magma chamber. However, the preservation of stoped blocks, in fact, is fortunate, since the rate at which blocks sink is much greater than the rate at which magmas crystallize (Pignotta et al. 2001b) and stoped blocks may be also rapidly disintegrated within a granitic magma (Clarke et al. 1998). Therefore, only blocks formed during final crystallization will be trapped within a chamber (Pignotta et al. 2001b). Other important evidence for stoping is represented by (a) stepped intrusive contacts formed by opening-mode fractures (mode I, i.e., extension fractures where the relative displacement across the fracture surface occurred in the direction perpendicular to the fracture walls during its formation; Twiss and Moores 1992), sharply truncating host rock markers, with no evidence for emplacement-related faulting or ductile strain (Buddington 1959; Paterson et al. 1991; Yoshinobu et al. 2003a, b), and (b) abruptly missing lithological units along pluton/host rock contacts, or missing large sections of intrusive units along contacts between separate magma pulses (Žák and Paterson 2005).

Magmatic stoping has been recognized as a widespread and important process during construction of Cordilleran and Andean plutons; however, its importance seems to be commonly overlooked in many studies of plutons in the European Variscides. In this study, based on the examination of stoped blocks, host rock rafts, and roof pendants from the Central Bohemian Plutonic Complex, Bohemian Massif, we evaluate the extent of stoping at the present-day erosion level and we show that highly extensive magmatic stoping played an important role during final construction of the plutonic complex in the upper crust. Finally, we discuss the significance of magmatic stoping during construction of plutons in the European Variscides and elsewhere.

Geological setting

The Central Bohemian Plutonic Complex

The ~3,200 km^2 Central Bohemian Plutonic Complex crops out between two contrasting crustal units (see below) in the central part of the Bohemian Massif (Czech Republic; Figs. 1, 2): low-grade, upper-crustal Neoproterozoic and Lower Paleozoic sequences of Teplá-Barrandian Unit to the NW and exhumed lower to mid-crustal orogenic root domain (Moldanubian Unit) to the SE. The plutonic complex is made up of multiple individual plutons and smaller magmatic bodies that vary in age, petrographic and geochemical characteristics, shape, size, internal fabrics and relationships to the host rock structures (Holub et al. 1997a; Žák et al. 2005a).

Available geochronological data indicate that the entire plutonic complex was assembled episodically over a timescale of less than ~20 Ma during the early Carboniferous, precisely bracketed by the age of the oldest (Sázava pluton, 354.1 ± 3.5 Ma, U–Pb on zircons; Janoušek and Gerdes 2003) and the youngest plutons (Tábor pluton, 336.6 ± 1.0 Ma, the same method and source). Recent geochemical and isotopic studies suggest that geochemical evolution from older calc–alkaline to potassium-rich calc–alkaline and ultrapotassic plutons is compatible with subduction zone-related magmatism in a magmatic arc with significant involvement of mantle-derived magmas (Holub et al. 1997b; Janoušek et al. 1995, 2000, 2004a). Field cross-cutting relationships, geochemical zoning, and radiometric data indicate overall growth direction of the Central Bohemian Plutonic Complex from the NW to the SE, i.e., toward the Moldanubian Unit (Holub et al. 1997a, b; Janoušek and Gerdes 2003; Žák et al. 2005a and references therein). The emplacement level of plutons of the Central Bohemian Plutonic Complex was upper-crustal (Žák et al. 2005a), since the plutons display sharp intrusive contacts accompanied with

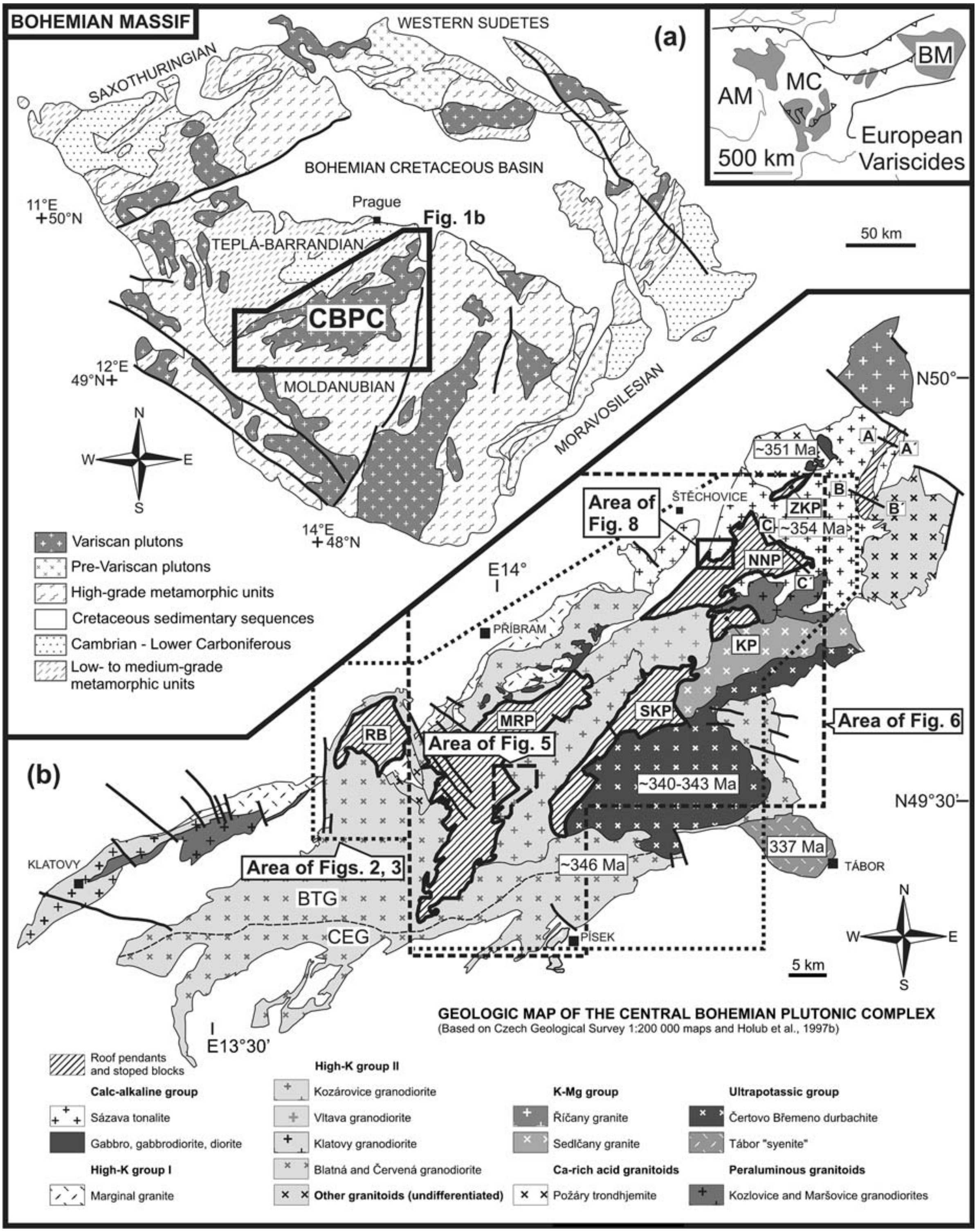

Fig. 1 Schematic geological map of the Central Bohemian Plutonic Complex (**b**) and its position in the Bohemian Massif (**a**). The map is based on Czech Geological Survey 1:200,000 maps and Holub et al. (1997b) and shows the main intrusive units (or "types") with some recently published radiometric ages (Holub et al. 1997a; Janoušek and Gerdes 2003). The areas outlined by *bold dashed lines* refer to detailed maps. *AM* Armorican Massif, *BM* Bohemian Massif, *BTG* Blatná granodiorite, *CBPC* Central Bohemian Plutonic Complex, *CEG* Červená granodiorite, *KP* Křečovice pendant, *MC* Massif Central, *MRP* Mirovice pendant, *NNP* Netvořice–Neveklov pendant, *RB* Rožmitál Block, *SKP* Sedlčany–Krásná Hora pendant, *ZKP* Zbořený Kostelec pendant

distinct thermal aureoles in the upper-crustal host rocks of Teplá-Barrandian Unit that were previously almost unmetamorphosed to low-grade. The upper-crustal emplacement level is also indicated by Al-in-hornblende geobarometry (Janoušek et al. 2004a; Scheuvens and Zulauf 2000).

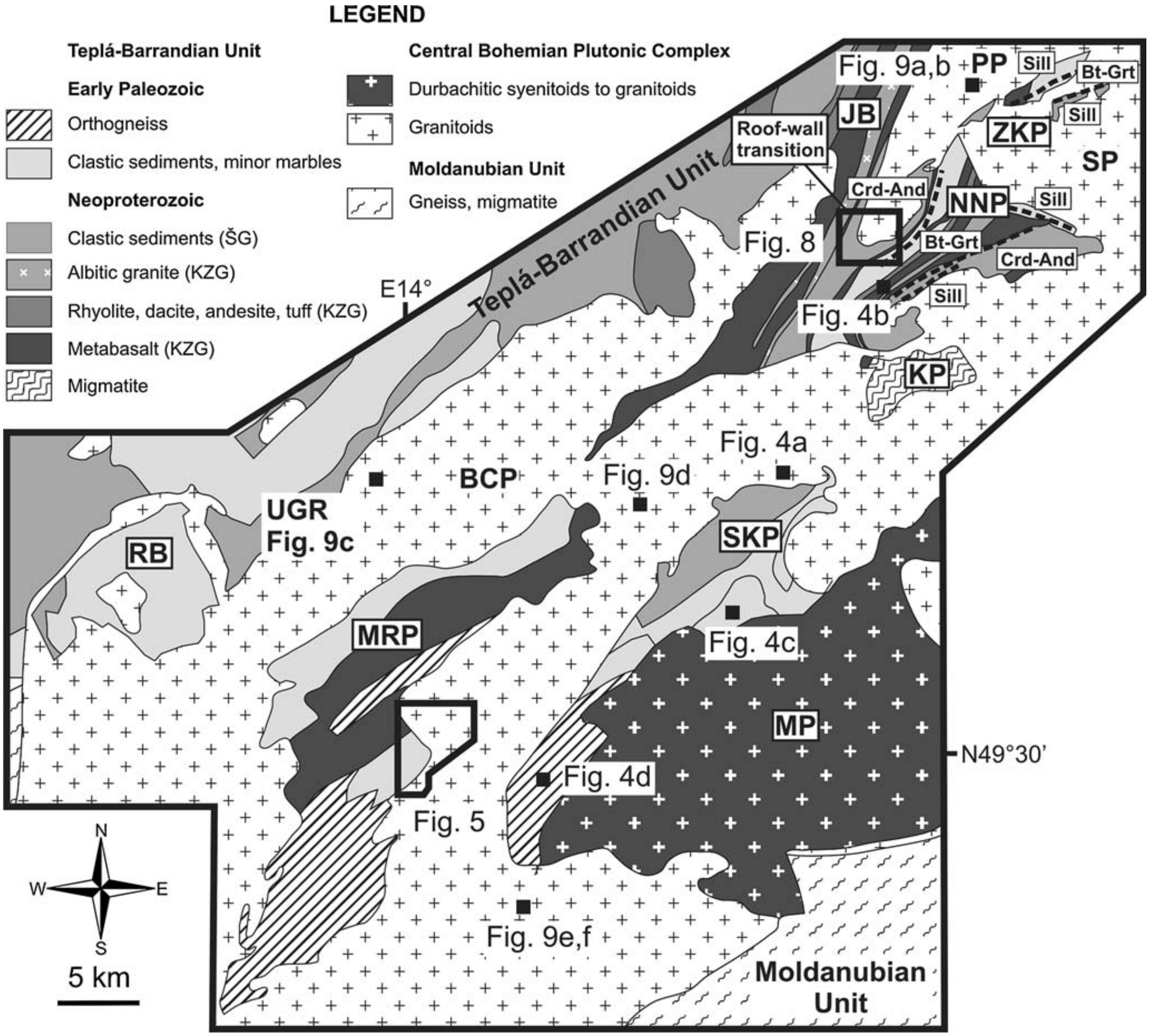

Fig. 2 Map of stoped blocks and roof pendants in the study area. Metamorphic isogrades from Kachlík (1992). Geology based on Czech Geological Survey 1:200,000 maps. *BCP* Blatná composite pluton, *KZG* Kralupy-Zbraslav Group, *KP* Křečovice pendant, *MP* Milevsko pluton, *MRP* Mirovice pendant, *NNP* Netvořice–Neveklov pendant, *PP* Požáry pluton, *RB* Rožmitál Block, *SKP* Sedlčany–Krásná Hora pendant, *SP* Sázava pluton, *ŠG* Štěchovice Group, *UGR* Underground Gas Storage, *ZKP* Zbořený Kostelec pendant

In this study, we focused on the roof pendants and stoped blocks in the northern half of the Central Bohemian Plutonic Complex (Figs. 1, 2) where the following large plutons intruded the Barrandian host rock (from the NE to SE; for overview of radiometric ages see Table 1 in Žák et al. 2005a): (a) the 351 ± 11 Ma (Holub et al. 1997a) Ca-rich biotite granodiorites to trondhjemites of the Požáry pluton; (b) the 354.1 ± 3.5 Ma (Janoušek and Gerdes 2003) calc–alkaline biotite–hornblende tonalite to hornblende–biotite granodiorites with quartz dioritic to gabbroid rocks of the Sázava pluton; (c) high-K calc–alkaline biotite granites (Marginal granite; not dated as yet) forming a sheet-like body along the NW margin of the Central Bohemian Plutonic Complex; (d) the most widespread, 346 ± 10 Ma (Holub et al. 1997a) high-K calc–alkaline amphibole–biotite to biotite granodiorites (Blatná, Červená, Kozárovice, Těchnice, and Vltava granodiorites) and associated shoshonitic rocks (quartz monzonites, monzonites, and monzogabbros; Holub et al. 1997b; Janoušek et al. 2000 and references therein) altogether referred to as Blatná composite pluton (Žák et al. 2005a); (e) the 343 ± 6 Ma (Holub et al. 1997a) amphibole-biotite melagranites to quartz melasyenites (durbachites) of the Milevsko pluton.

Host rocks of the Central Bohemian Plutonic Complex

Teplá-Barrandian Unit

The Neoproterozoic basement of the Teplá-Barrandian Unit adjacent to the Central Bohemian Plutonic Complex (Figs. 1, 2) is made up of volcanosedimentary sequences overlain by clastic turbidites (Kralupy-Zbraslav and Štěchovice Groups, respectively; see Kříbek et al. 2000 for review). The lower part of the Kralupy-Zbraslav Group represents sediments of a back-arc or inter-arc basin with active sea floor spreading centers producing MORB and P-MORB basalts, while its upper part reflects a change of tectonic regime to destructive tectonic setting and island-arc calc–alkaline volcanism (Kříbek et al. 2000; Vítková and Kachlík 2001; Waldhausrová 1984). U–Pb zircon dating on pebbles of acid volcanics and trondhjemites redeposited in the younger Štěchovice Group showed that island arc volcanism was active at least in the period of ~617–564 Ma (Dörr et al. 2002; Drost et al. 2004; Sláma et al. 2003). Clastic turbidites of the overlying Štěchovice Group represent the onset of Cadomian deformation of Peri-Gondwanan active continental margin. The degree of Cadomian MP-MT regional metamorphism of the Neoproterozoic sequences is low in general but increases from anchizone (in the study area along the NW margin of the Central Bohemian Plutonic Complex) up to amphibolite facies further to the NW and SE.

The Neoproterozoic basement is unconformably overlain by Early Paleozoic sedimentary sequences accompanied by submarine basaltic volcanism of within-plate signature (Kachlík and Patočka 1998). Early Paleozoic sequences comprise (see Chlupáč et al. 1998 for review; Patočka and Štorch 2004; Patočka et al. 2003): (a) Lower Cambrian continental siliciclastic sediments, Middle Cambrian marine deposits and Upper Cambrian subaerial volcanics; (b) Ordovician siliciclastic sequence (shales, sandstones, graywackes); (c) Lower Silurian black shales and Upper Silurian to Lower Devonian limestones overlain by Middle Devonian flysch clastic sediments reflecting the onset of Variscan orogeny.

In the study area, low-grade or unmetamorphosed Lower Paleozoic sedimentary sequences along the NW margin of the Central Bohemian Plutonic Complex were not pervasively affected by regional Variscan greenschist to amphibolite facies metamorphism, which has been recorded elsewhere in Teplá-Barrandian Unit (Dallmeyer and Urban 1998; Kreuzer et al. 1989) and also in the roof pendants in the Central Bohemian Plutonic Complex (Kachlík 1992; Košler et al. 1993, 1995). Variscan regional metamorphism was closely followed by HT-LP contact metamorphism during the emplacement of the Central Bohemian Plutonic Complex. The contact metamorphism is recorded in an up to 2 km wide aureole around the NW margin of the plutonic complex and in roof pendants and stoped blocks. The extent and intensity of contact metamorphism vary with host-rock lithologies, contact geometry, distance from the pluton margin and local structural position.

Moldanubian Unit

In contrast to the low-grade Teplá-Barrandian Unit, high-grade rocks of Moldanubian Unit (paragneisses, orthogneisses, and migmatites) crop out along the SE margin of the Central Bohemian Plutonic Complex (Figs. 1, 2). The high-grade Moldanubian rocks are characterized by strong Variscan polyphase metamorphism and complex deformational history (see Vrána 1988; Vrána et al. 1995 for reviews). The HP-HT metamorphic event in the Moldanubian Unit is recorded in granulites and rarely also in pelitic lithologies; most U–Pb zircon and monazite ages fall into the range 355–337 Ma (Friedl et al. 1993; Janoušek et al. 2004b, 2006 and references therein; Kröner et al. 1988, 2000; Wendt et al. 1994) and were followed by LP-HT metamorphism and migmatization at ~337–333 Ma (Friedl et al. 1993, 1994; Gerdes et al. 2000 and references therein). Estimations of PT conditions of metamorphism from domains adjacent to the SW part of the Central Bohemian Plutonic Complex, Pitra et al. (1999) suggested that the differences in peak metamorphic conditions of metamorphism of the units exposed on either side of the plutonic complex are up to 300–400°C and 5–7 kbar.

Regional structural pattern

A wide, ~NE–SW trending zone of regional transpression accompanied by ~NW–SE contraction and ~NE–SW stretching defines the structural pattern of both the NW margin of the Central Bohemian Plutonic Complex and its roof pendants (Žák et al. 2005a, b). Steep ~NNE–SSW trending regional foliation (Fig. 3), parallel to axial planes of major folds, is developed throughout the pluton host rock and almost entirely overprints older pre-existing structures along the NW margin of the Central Bohemian Plutonic Complex. This regional foliation is mostly developed as penetrative low-temperature spaced cleavage, the intensity of which, as well as the temperature conditions of deformation, significantly increase toward the NW margin of the plutonic complex (Žák et al. 2005b). In domains adjacent to the pluton-host rock contact and in the Neoproterozoic and Early Paleozoic metasedimentary rocks in the roof pendants, low-temperature spaced cleavage grades into high-temperature foliation defined as compositional banding of domains rich in biotite and domains formed by recrystallized quartz (Žák et al. 2005b). Recrystallization textures of quartz ribbons indicate temperatures exceeding 500°C. More pelitic (mostly Early Paleozoic) lithologies in the roof pendants are also commonly recrystallized to unfoliated coarse-grained hornfelsic rocks (Kachlík 1992).

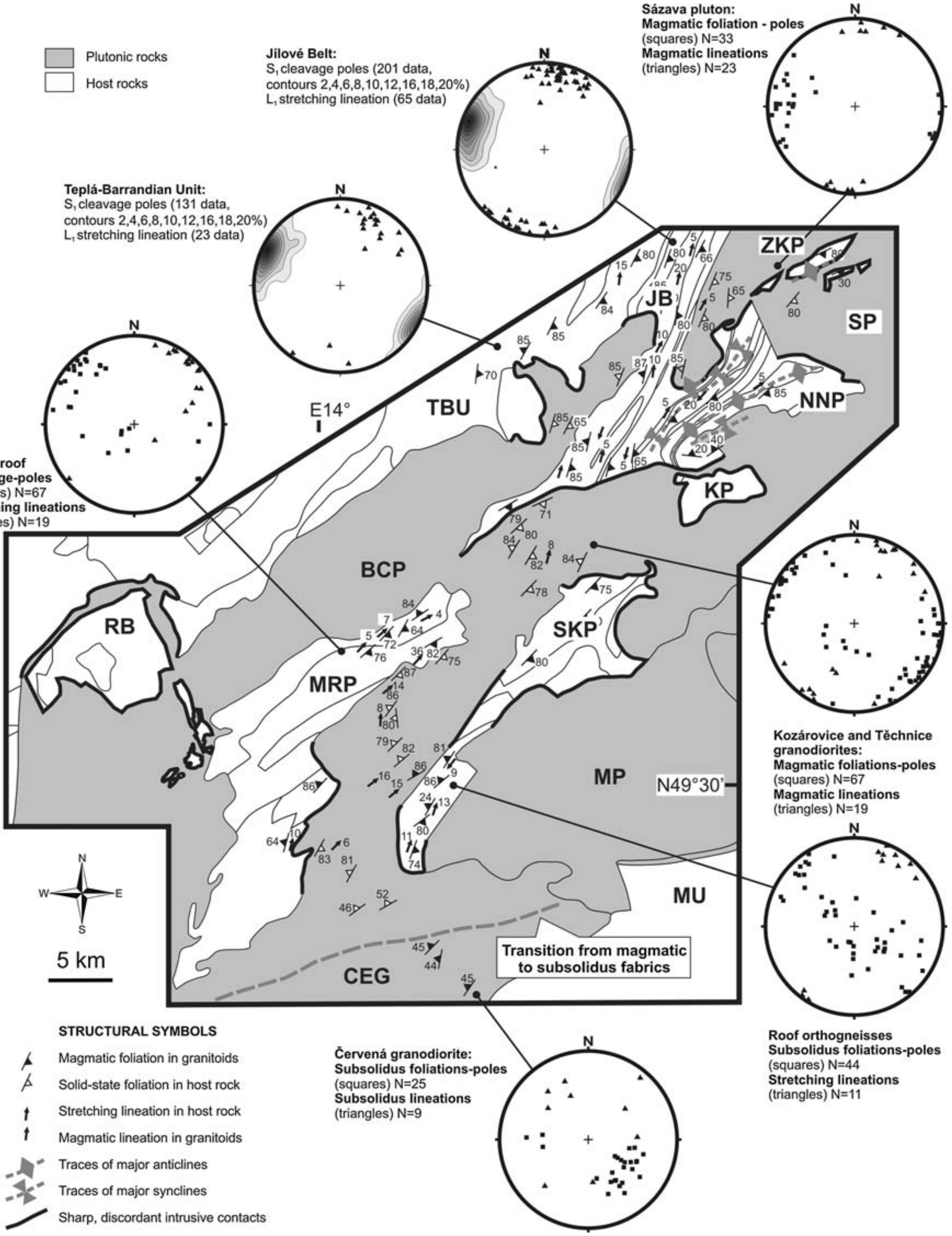

Fig. 3 Structural map of roof pendants and stoped blocks in the Central Bohemian Plutonic Complex; stereograms show the orientations of regional structures (foliations and lineations). Regional structures are pre-dominantly represented by steep ~NNE–SSW to ~NE–SW foliation associated with ~NNE–SSW to ~NE–SW stretching lineation in the roof pendants, and magmatic foliations and lineation of similar orientation in the granitoids of the Central Bohemian Plutonic Complex. *BCP* Blatná composite pluton, *CEG* Červená granodiorite, *JB* Jílové Belt, *KP* Křečovice pendant, *MP* Milevsko pluton, *MRP* Mirovice pendant, *MU* Moldanubian Unit, *NNP* Netvořice–Neveklov pendant, *RB* Rožmitál Block, *SKP* Sedlčany–Krásná Hora pendant, *SP* Sázava pluton, *TBU* Teplá-Barrandian Unit, *ZKP* Zbořený Kostelec pendant

Both the cleavage and high-temperature foliations in the pluton wall-rocks and roof pendants are typically associated with shallowly plunging to sub-horizontal ~NNE–SSW lineation (Figs. 3, 4b) sub-parallel to minor fold axes. This is developed either as mineral stretching lineations in the metavolcanics or by intersection lineations (intersections of bedding and cleavage planes) in the overlying flysch sequence. We have concluded elsewhere that this fabric and finite strain pattern is a result of Variscan regional transpression which operated along the SE flank of the Teplá-Barrandian Unit prior to and during emplacement of the earlier magma pulses of the Central Bohemian Plutonic Complex (370 Ma—Košler et al. 1993, 1995; ~354–346 Ma; Žák et al. 2005a, b) and was significantly enhanced in overlapping aureoles of individual plutons and in the roof pendants (Žák et al. 2005a). The orientation and distribution of the lithostratigraphic units in the roof pendants was also affected by both pre-Variscan and Variscan (broadly synchronous with the early stages of emplacement of the Central Bohemian Plutonic Complex) folding and faulting.

A major part of the contact between the SE margin of the Central Bohemian Plutonic Complex and Moldanubian Unit is characterized by coupled sub-solidus foliations in granitoids and metamorphic foliations in Moldanubian gneisses, both shallowly to moderately dipping to the NW and bearing down-dip stretching lineations (Fig. 3) associated with SE-side-up kinematics. These fabrics were interpreted as being a result of exhumation of the Moldanubian Unit along the SE margin of the Central Bohemian Plutonic Complex (Žák et al. 2005a).

Large roof pendants and stoped blocks in the Central Bohemian Plutonic Complex

Numerous roof pendants, thin inter-pluton wall-rock screens, and kilometer- to submeter-scale stoped blocks of host rocks (Figs. 2, 4a) are preserved in most plutons of the Central Bohemian Plutonic Complex; some of them are examined in detail below. However, due to generally poor exposure in the area and limited vertical topography (maximum ~300 m), it is difficult in some cases to exactly establish whether these units remained in their original pre-emplacement position (i.e. are roof pendants or rafts) or had been detached from the pluton roof and sank into a chamber (i.e. are stoped blocks).

Stratigraphic correlation revealed that these units correspond to Neoproterozoic-Middle Devonian of Teplá-Barrandian Unit (Kachlík 1988, 1992). Lithologically, roof pendants and stoped blocks comprise Neoproterozoic metavolcanics overlain by a flysch sequence at least partially corresponding to the Štěchovice Group. Lower Paleozoic sequences encompass metamorphosed Cambrian psammitic and psammo-pelitic rocks and acid calc–alkaline volcanics.

Neoproterozoic metasedimentary units in the roof pendants were affected by only weak Cadomian deformation and metamorphism; the major metamorphic event here was Variscan low-pressure high-temperature (< 4 kbar) metamorphism, which was broadly synchronous with transpressional deformation (Fig. 4b, c, d) and pluton emplacement (Žák et al. 2005b).

At the present-day erosion level, several large (> 1 km longest dimension) segments of pluton roof are preserved within plutons in the study area covering much of the Central Bohemian Plutonic Complex (Fig. 2). From the NE to the SW, the major roof pendants in the study area are:

(1) The Zbořený Kostelec pendant crops out along the contact of the Sázava pluton to the SE and younger

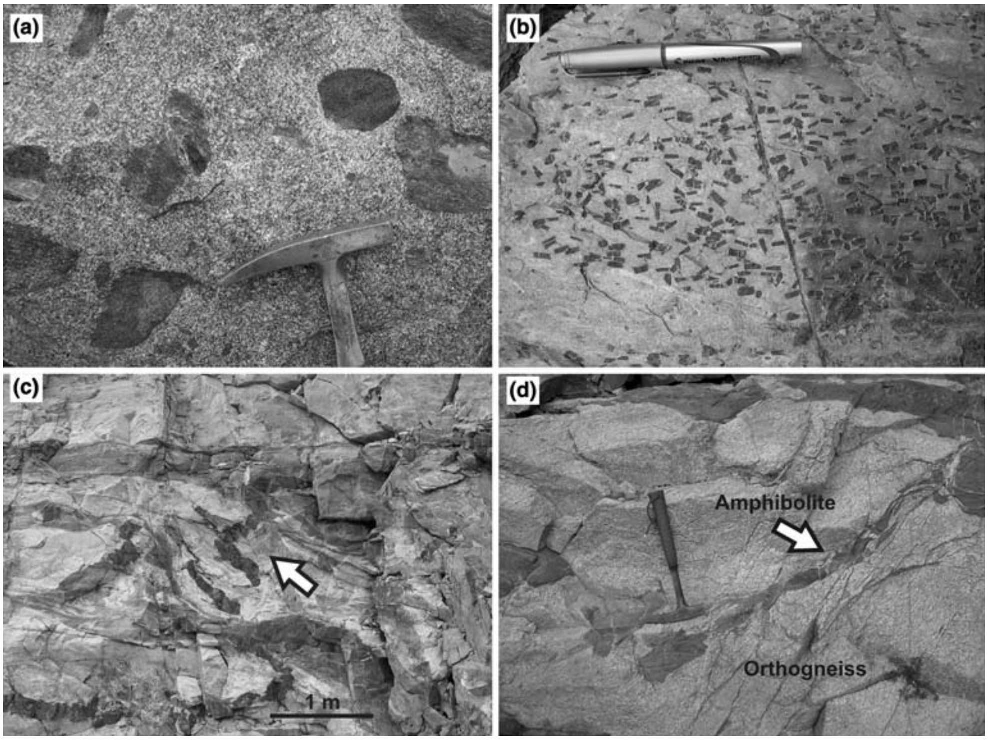

Fig. 4 Photos of structures from the roof pendants of the Central Bohemian Plutonic Complex (see Fig. 2 for locations). **a** Accumulation of small xenoliths in the Sedlčany granite close to the northern margin of the Sedlčany–Krásná hora pendant, Solopysky quarry, hammer for scale; **b** Sub-horizontal mineral lineation in roof metapelites as a result of synkinematic growth of andalusite during contact metamorphism, Bělice quarry, Netvořice–Neveklov pendant, pencil for scale; **c** Folded and boudinaged minette dike in Devonian marbles, Skoupý quarry, Sedlčany–Krásná hora pendant; **d** Pervasively deformed Upper Devonian orthogneisses with boudinaged gabbrodioritic sheets, Sedlčany–Krásná hora pendant, hammer for scale

Požáry trondhjemite to the NW and comprises two larger segments separated by granitoids. Several smaller host rock blocks are also scattered around the two segments. The pendant is made up of ~1 km wide belt of Neoproterozoic basaltic tuffs recrystallized to amphibole hornfelses, overlain by Neoproterozoic flysch metasedimentary rocks of the Štěchovice Group. The Neoproterozoic rocks are overlain by Cambrian to Ordovician (meta) psammo-pelitic sequence. The degree of contact metamorphism varies from the sillimanite zone (pendant margins) to the garnet–biotite zone (central part).

(2) The Netvořice–Neveklov pendant is one of the largest roof pendants in the Central Bohemian Plutonic Complex. The north-western, eastern and south-eastern margins of the pendant form an irregular, discordant intrusive or faulted contact with the Sázava pluton and Vltava granodiorite of the Blatná composite pluton (southernmost part), whereas to the SW the roof pendant passes continuously to the steep pluton wall (the roof-wall transition is described in detail below). The pendant comprises the Neoproterozoic volcano-sedimentary complex in its south-eastern and eastern part, unconformably overlain by Cambrian basal conglomeratic sandstones passing into psammitic to aleuritic sediments and acid calc–alkaline metavolcanics. Ordovician clastic sediments (metagraywackes, minor conglomerates and quartzites) are preserved only along the northern margin of the pendant and in a smaller block to the N. Clastic metasedimentary rocks are commonly metamorphosed to muscovite–biotite hornfelses. The degree of contact metamorphism in the pendant varies from the garnet–biotite zone in its inner part, through cordierite–andalusite zone in the outer parts, to a narrow sillimanite zone rimming the contact with the nearby granitoids.

(3) The Křečovice pendant is irregular, as viewed in the map and is entirely surrounded by three distinct intrusive units of the Central Bohemian Plutonic Complex (Maršovice granite to the N, Sedlčany granodiorite to the S, and Vltava granodiorite to the W; Fig. 1). The pendant is made up of highly migmatized metasedimentary rocks, probably of Neoproterozoic age, dominated by partially melted biotitic horfelses that grade into stromatitic and nebulitic migmatites.

(4) The Sedlčany–Krásná Hora pendant crops out between the Kozárovice and Těchnice granodiorites of Blatná composite pluton to the west and the Čertovo Břemeno durbachite to the east. Contacts with both the granitoids and the durbachite are pre-dominantly intrusive, with large sections of discordant contacts, which sharply truncate both lithological contacts and structures in the roof pendant. The pendant comprises three distinct lithostratigraphic units: Neoproterozoic metabasalts and clastic metasedimentary rocks that are unconformably overlain by Lower Paleozoic clastic sequence starting with Ordovician conglomeratic sandstones, passing to psammo-pelitic shales with quartzite intercalations. The Silurian begins with graptolithic shales and calc–silicate rocks passing to hornfelses interbedded with marbles of Silurian to Lower Devonian age. Devonian sequence is finished by siliciclastic sediments (hornfelses, quartzites, and conglomerates). The southern and south-western parts of the pendant are made up of Upper Devonian (Košler et al. 1993, 1995) orthogneisses with minor gabbrodioritic bodies (Fig. 4d).

(5) The Mirovice pendant is structurally rather complex, entirely enclosed within several varieties of granitoids of Blatná composite pluton. The oldest exposed rocks comprise Neoproterozoic metapelites (metamorphosed to hornfelses) with dikes or sills of boninitic metavolcanics, unconformably overlain by Ordovician psammo-pelitic sediments and Silurian black shales with marble intercalations. The sedimentary complexes were intruded by granitoids during Late Devonian (380–365 Ma; Košler et al. 1993, 1995), preserved as several large bodies of orthogneisses along the NW and SE margins of the pendant.

A particularly intriguing example of arrested mechanical disintegration of a roof pendant is exposed along the eastern margin of the Mirovice pendant. Here, granitoids (Kozárovice and Těchnice granodiorites) of Blatná composite pluton intrude Ordovician to Silurian metasedimentary rocks and Middle Devonian orthogneisses and metabasites (Fig. 5). Lithological contacts and foliation (cleavage) in the roof pendant are steeply oriented ~NE–SW. The roof pendant/pluton contact is intrusive. In the ~NW–SE sections, nearly perpendicular to the host rock foliation, the contact is highly irregular and sharply truncates pre-existing host rock markers, whereas the foliation-parallel (roughly oriented ~NE–SW) sections are straight or less irregular (Fig. 5). A ~7 km long and ~2 km wide zone of abundant, highly elongated, up to kilometer-scale host rock blocks or rafts bounded by regional cleavage is preserved within the granitoids to the east of the roof pendant (Fig. 5).

This zone probably represents an initial stage of stoping, where granitoids intruded along the cleavage planes, presumably by a magma wedging mechanism and mechanically disintegrated the margin of the roof pendant into thin cleavage-bounded blocks. The blocks were then arrested in the highly crystallized cooling magma, which prevented them from further disintegration and sinking down into the chamber (see Discussion section). By contrast, the host rock markers truncated by the NW–SE, highly irregular, intrusive contacts indicate that abruptly missing large parts of the roof pendant were removed out of the present-day exposure level, i.e., stoped into the magma chamber.

(6) The Rožmitál block is surrounded on all sides by the granitoids of the Blatná composite pluton (for a detailed map of the block and further information, see Zachariáš et al. 2001). To the NW and NE of the block, the granitoids form only ~1 km thin steeply dipping sheets that separate the block from the host Teplá-Barrandian wall-rock. The block is bounded by irregular intrusive contacts that sharply truncate the host rock markers from all sides. The Rožmitál block is made up of Cambrian clastic sediments with minor volcanics

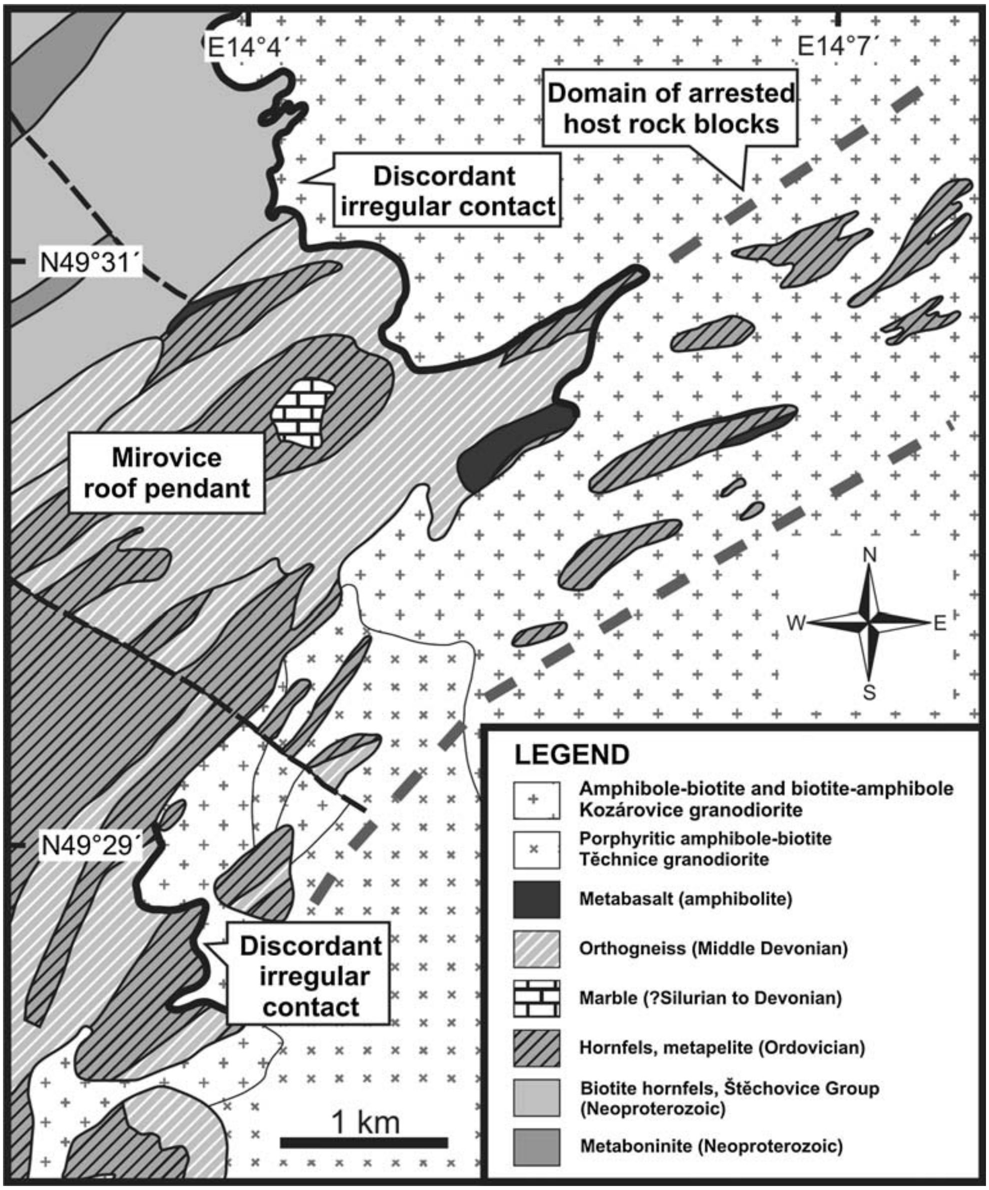

Fig. 5 Map of the eastern part of Mirovice pendant showing arrested mechanical disintegration of the roof pendant margin in a domain of abundant, highly elongated host rock blocks or rafts bounded by regional cleavage within the granitoids. The ~NW–SE pluton/host rock contacts are highly irregular and sharply truncate host rock markers, indicating that abruptly missing large parts of the roof pendant were stoped into the magma chamber

uncorfomably overlain by Ordovician to Devonian metasedimentary rocks. The Paleozoic rocks were intruded by small bodies of Variscan granodiorites and affected by polyphase deformation, the intensity of which increases toward the southern margin of the block (Zachariáš et al. 2001). The ~NNW–SSE to ~NW–SE orientation of cleavage and trends of large-scale folds in the Rožmitál block lie at high angles to the regional orientations elsewhere in the area of the Central Bohemian Plutonic Complex.

Image analysis of roof pendants and stoped blocks

The aim of the analysis

The critical parameter when evaluating the importance of magmatic stoping during pluton emplacement is quantitative estimation of the scale of the preserved field evidence for stoping with respect to other emplacement-related structures. Unfortunately, in areas with limited three-dimensional exposure and vertical relief, such as the European Variscides, we cannot simply establish either the exact volumetric proportions of stoped blocks and surrounding plutonic rocks or the vertical displacement paths of stoped blocks within a pluton. It is also important to emphasize several points: (a) magmatic stoping is a vertical material transfer process (magma up—host rock down) and, as such, results in the removal and downward displacement of host rocks out of a horizontal section through a pluton (Paterson and Fowler 1993; Paterson et al. 1991); (b) evidence for the most efficient stoping is thus not the presence and high-volumetric proportion of stoped blocks in a pluton, but rather the absence of large volumes of host rock in areas characterized by discordant pluton/host rock contacts (Pignotta et al. 2001b; Yoshinobu et al. 2003b).

Therefore, we suggest that a possible tool for the approximate estimation of the extent of stoping in two-dimensional horizontal sections through plutons (i.e. maps) may be a search for abruptly missing lithological units along pluton/host rock contacts and geometrical analysis of intrusive discordant contacts, presumably formed by magmatic stoping.

Several further important considerations should be taken into account prior to the geometrical analysis. First, only discordant contacts, where plutonic rocks truncate pre-existing host rock markers with no evidence for syn-emplacement faulting or ductile strain, provide unambiguous evidence for magmatic stoping. Second, dikes may also result in the formation of discordant contacts, for example if they propagate upward from a magma chamber and start to break up its roof. Importantly, the absence of dikes along discordant intrusive contacts does not preclude that the contacts initially developed from a dike network, since the evidence for diking or for other processes may have been destroyed by later stoping. In such a case, however, stoping should be anyway considered as the final material transfer process during emplacement, regardless of whether or not diking (or other processes) were initially involved in the intrusive history. Last but not least, concordant contacts may also correspond to stoping, because the pre-existing foliation of host rocks may represent a plane of weakness making opening fractures and thus stoping easier. However, as concordant contacts may also result from other emplacement processes (e.g., ductile flow), or record complex intrusive histories (see below), their actual significance is ambiguous and not easy to interpret.

In summary, the length (measured in the map-space) of only discordant intrusive contacts with no evidence for diking, faulting, or syn-emplacement ductile strain may provide unambiguous constraints about the *minimum* importance of stoping during final emplacement at a given exposure level. This means that, if some concordant contacts have also been formed by stoping, its real extent in a given pluton during final emplacement would be higher.

The method of the analysis

In this study, image map analysis was carried out to provide some quantitative constraints on scales, size and spatial distribution of the roof pendants and stoped blocks in the Central Bohemian Plutonic Complex. The area for this analysis was selected to cover much of the Central Bohemian Plutonic Complex and to involve the great majority of roof pendants and stoped blocks. We also measured the length of discordant intrusive contacts to obtain information on the *minimum* extent of magmatic stoping at the present-day exposure level. The discordant intrusive contacts interpreted as a result of stoping were selected on the basis of both their map characteristics and our field observations. The selected contacts delineated in Fig. 6 thus represent the minimum lengths of possible contacts associated with magmatic stoping in the study area. The outcome of the analysis, summarized in Fig. 6, is presented as a map of digitized outlines of large stoped blocks, roof pendants, and discordant intrusive contacts with insets showing the measured and rounded-off geometrical characteristics of the blocks and contacts. The figure was constructed using Czech Geological Survey 1:25,000 and 1:50,000 maps and the outlines were then analyzed using the freeware UTHSCSA ImageTool program (ftp://maxrad6.uthscsa.edu). Despite errors in contact line lengths of approximately hundred meters to kilometers that may have arisen from digitizing contact lines and map generalization, we argue that this method still provides reasonable estimations, given the overall major role of stoping in the Central Bohemian Plutonic Complex (Fig. 6; see below).

Results—supporting evidence for large-scale stoping

The total area of roof pendants and stoped blocks represents 18% of all exposed plutonic rocks in the analyzed domain (Fig. 6). The size (i.e. their longest and shortest perpendicular dimension in the map) of the analyzed roof pendants and stoped blocks varies from tens of kilometers to several hundred meters (the smallest mappable blocks), with an area of up to 220 km^2 (the largest Mirovice roof pendant). The shapes of the analyzed pendants and blocks may be rather irregular in the map view, but their long axes are usually oriented parallel to the trend of regional host rock structures (NNE–SSW) in the Teplá-Barrandian Unit (Fig. 6).

The extent of the discordant, unfaulted intrusive contacts selected using the criteria defined above are highlighted in Figs. 3 and 6. The southeastern margin of the plutonic complex is excluded from this analysis, since this contact is a large shear zone resulting from the exhumation of the mid-crustal Moldanubian Unit (Žák et al. 2005a).

The measured total length of the contact of plutonic rocks with the wall-rock of the Teplá-Barrandian Unit along the NW margin of the Central Bohemian Plutonic Complex is ~183 km with up to ~80 km of the discordant sections (Fig. 6). Within the plutonic complex, smaller roof pendants and stoped blocks are entirely bounded from mostly all sides by irregular, intrusive discordant contacts; thus discordant contact length equals the perimeter of the pendants and blocks. The two largest roof pendants have variably long discordant sections, ranging from 13% (Mirovice pendant) of the block perimeter to 74% (Sedlčany–Krásná Hora pendant). The measured total length of contacts of plutons with upper-crustal Teplá-Barrandian host rocks (i.e. NW margin of the Central Bohemian Plutonic Complex + roof pendants + stoped blocks) in the

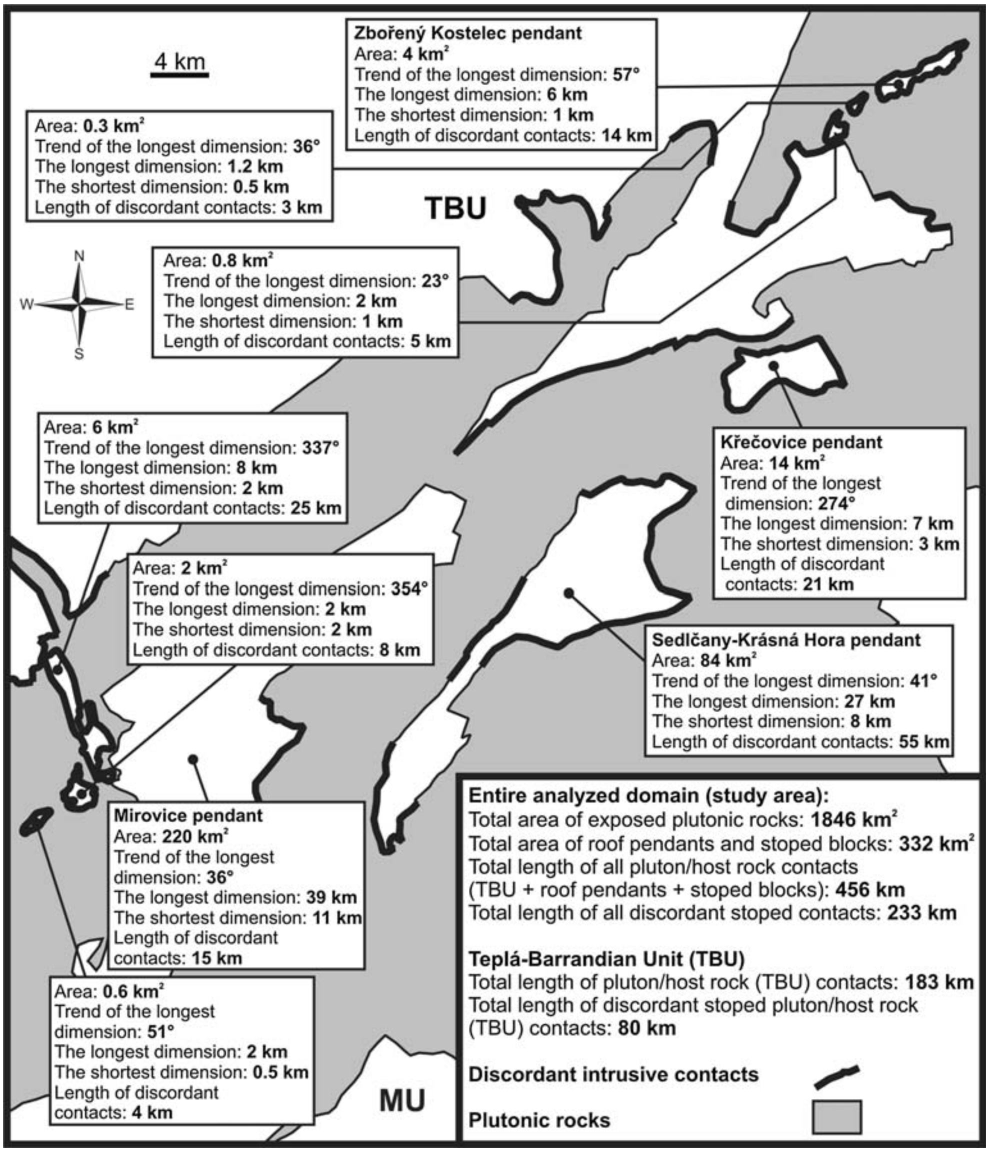

Fig. 6 Map of host rock/pluton contacts, roof pendants and stoped blocks within the Central Bohemian Plutonic Complex used for image analysis, constructed from Czech Geological Survey 1:50,000 and 1:25,000 maps. *Bold lines* delineate discordant contacts with no evidence for faulting, emplacement-related strain or diking and interpreted as being a result of magmatic stoping. The insets show the main geometrical and spatial characteristics of the analyzed blocks and pendants (the results are rounded off). The measured total length of the discordant intrusive contacts is 233 km (about a half of all contacts with upper-crustal host rocks). Small unmappable blocks are omitted. *MU* Moldanubian Unit, *TBU* Teplá-Barrandian Unit

study area is $\sim$456 km; the measured total length of discordant sections is $\sim$233 km.

Roof-wall transition in the Sázava pluton

Transitions from steep walls to flat-lying roofs have been recognized as critical regions for interpreting emplacement mechanisms in upper parts of plutonic systems, since any given material transfer process (e.g., fault-accommodated translation, ductile flow, diking, or magmatic stoping) would result in rather different characteristics of the roof/wall transition in a pluton (Fowler 1996; Yoshinobu et al. 2003a; see also Žák and Paterson 2006 for further details). It is in these regions that information is best preserved on how host rock is displaced during rise/growth of magma chambers, as the nature of contacts and aureoles near tops of plutons may differ remarkably from the sides. Structures near the roofs and at roof-wall transitions better reflect the dominant material transfer processes during emplacement, whereas the pluton sides reflect the more complex effects of continued heating, complex strain patterns, and later post-emplacement elastic rebound around plutons. Therefore, many ambiguities in interpreting pluton emplacement are eliminated in cases where the pluton roof and particularly roof-wall transitions are examined. To date, several studies documented roofs and roof-wall transitions in well-exposed Cordilleran and Andean plutons (e.g., Bussell et al. 1976; Myers 1975; Paterson and Miller 1998a; Yoshinobu et al. 2003a; Žák and Paterson 2006); however, no such examples have been described as yet in plutons in the European Variscides.

In the Central Bohemian Plutonic Complex, several flat-lying thin pluton roof segments that are discordant to generally steeply dipping host rock markers (Fig. 7) were documented by Kachlík (1992). In addition, we examined a roof-wall transition in the Sázava pluton (Fig. 8), intruding Neoproterozoic metavolcanics (the Jílové Belt) overlain by a flysch (meta) sedimentary sequence along its western margin. In the south-western part of the pluton, the pluton wall is preserved as an up to ~3–4 km wide, steep ~NNE–SSW trending inter-pluton screen which separates the main part of the pluton from the smaller tonalite body to the west (Figs. 2, 8). The inter-pluton screen (Jílové Belt and its Neoproterozoic metavolcanic and metasedimentary cover) continuously passes into the large Netvořice–Neveklov roof pendant (lying structurally above the Sázava tonalite) to the east. Here, the Neoproterozoic acid tuffs of the Kralupy-Zbraslav Group and overlying black shales and flysch sediments of the Štěchovice Group have been folded into upright folds of several hundred meters in wavelength. The folds are associated with pervasive cleavage parallel to the axial planes of the folds and shallowly plunging, stretching lineation parallel to the fold axes. While the general orientation of host rock markers (cleavage, lithological contacts, folds) in the pluton wall is ~NNE–SSW, they continuously reorient to ~NE–SW orientation in the pluton roof. No syn-intrusive faults or shear zones were observed at the roof-wall transition. The pluton/host rock contacts, where not affected by post-emplacement brittle faults, are intrusive and sharply truncate all the structures (foliation, lithological contacts) in both the wall and the roof of the pluton, to form rectangular steps with no evidence for off-sets of host rock markers. Such roofs, not detached from the pluton walls by faults, and which have stepped geometry and sharply truncate host rock markers, provide direct evidence for magmatic stoping (Paterson and Miller 1998a; Yoshinobu et al. 2003a; Žák and Paterson 2006).

Examples of stoping of older intrusive units within younger magma pulses

Numerous stoped blocks of older intrusive units within younger magma pulses are preserved throughout the Central Bohemian Plutonic Complex, in particular along internal contacts between separate magma pulses. The best examples of intra-chamber stoping (see Fig. 2 for locations) are described below.

(1) The stoped blocks of the Sázava tonalite in the Požáry trondhjemite. The Požáry trondhjemite forms an elliptical pluton, which intruded the northern part of the Sázava tonalite and its Barrandian host rocks.

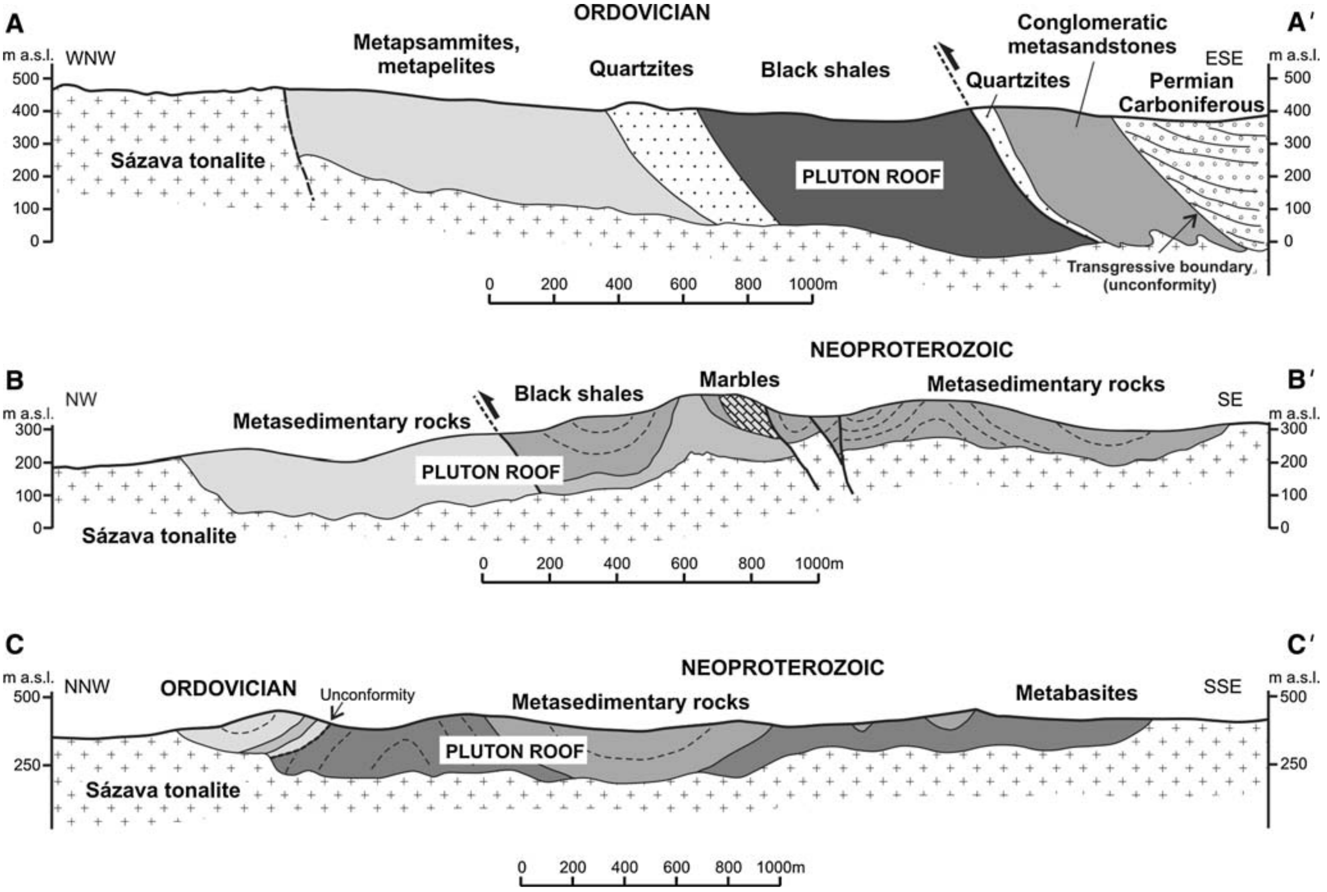

Fig. 7 Schematic cross-sections across some roof pendants of the Central Bohemian Plutonic Complex showing flat-lying, thin segments of pluton roofs that are discordant to generally steeply dipping host rock markers (see Fig. 1 for locations of cross-sections)

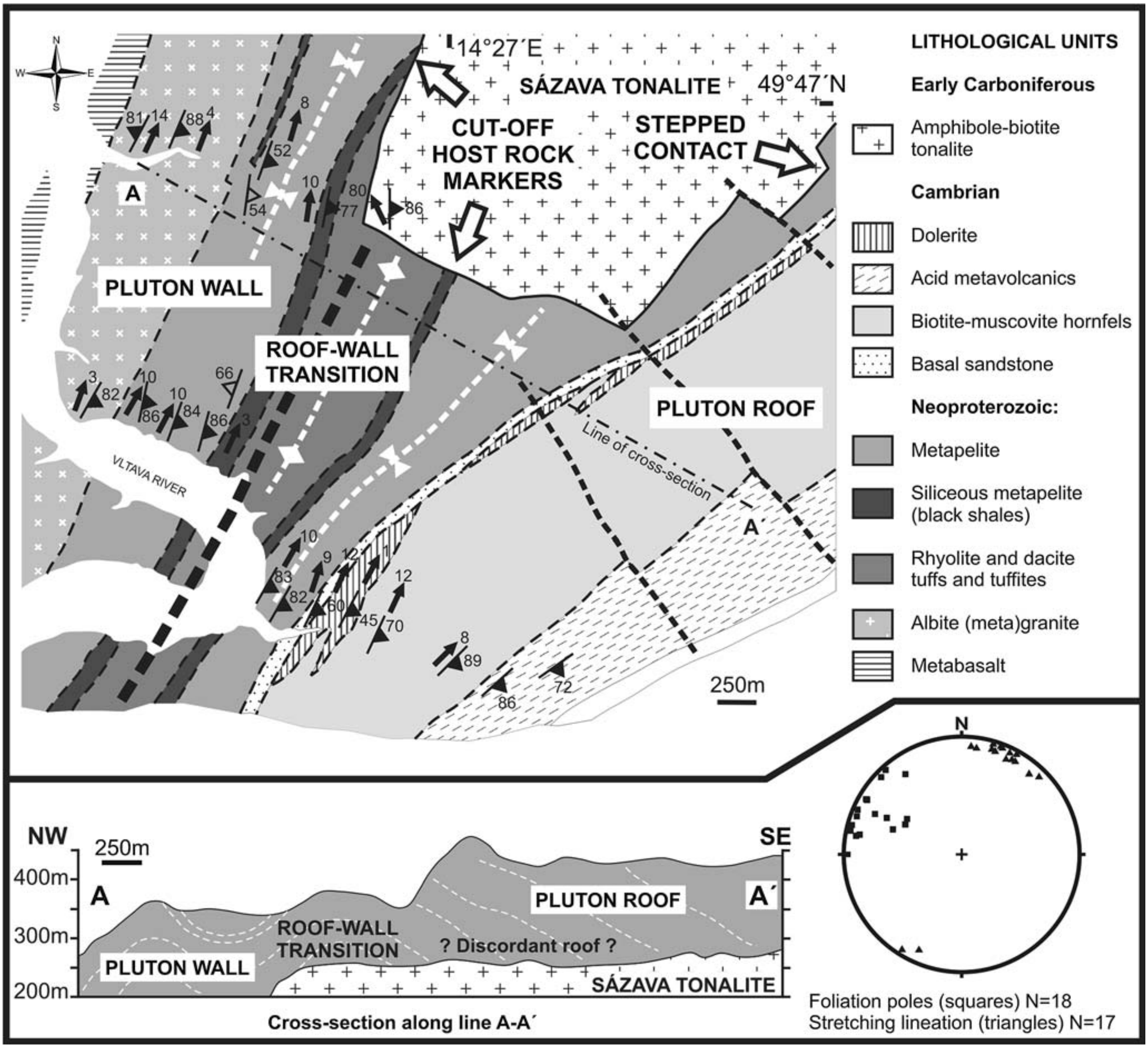

Fig. 8 Map of the roof-wall transition at the western margin of the Sázava pluton. The general orientation of host rock markers in the pluton wall is ~NNE–SSW, but they continuously reorient to ~NE–SW orientation in the pluton roof. No faults or shear zones were observed at the roof-wall transition and the lithological units are continuous (with no offsets) across the transition. The pluton/host rock contacts are mostly intrusive and sharply truncate all structures to form rectangular steps with no evidence for off-sets of host rock markers

Abundant stoped blocks of the Sázava tonalite within the trondhjemite are well-exposed in the Požáry quarry (Fig. 9a, b), ~300 m from the southern margin of the Požáry pluton. Here, the tonalite blocks range from ~1 up to ~15 m in size, have typically rectangular shapes, and their margins are formed by knife-sharp fractures. The fractures commonly cut off both magmatic fabrics and microgranular enclaves inside the tonalitic blocks at centimeter-scale (Fig. 9b). Mafic schlieren or several centimeter thick felsic rims commonly develop in the trondhjemite around the blocks. Locally, weak magmatic foliations defined by biotite alignment in the trondhjemite are deflected or form complex patterns around the tonalitic blocks. All these features as well as spatial distribution and relative orientation of the blocks in the quarry indicate that they were variably rotated and displaced in the surrounding trondhjemitic magma.

(2) The "stoping graveyard" close to the floor of the Sázava pluton. In the deep-seated Underground Gas Storage near Příbram (UGR in Fig. 2) that exposes a section close to the floor of the western part of the Sázava pluton (Janoušek et al. 2004a; Sokol et al. 2000), 1 km below the present-day surface, we

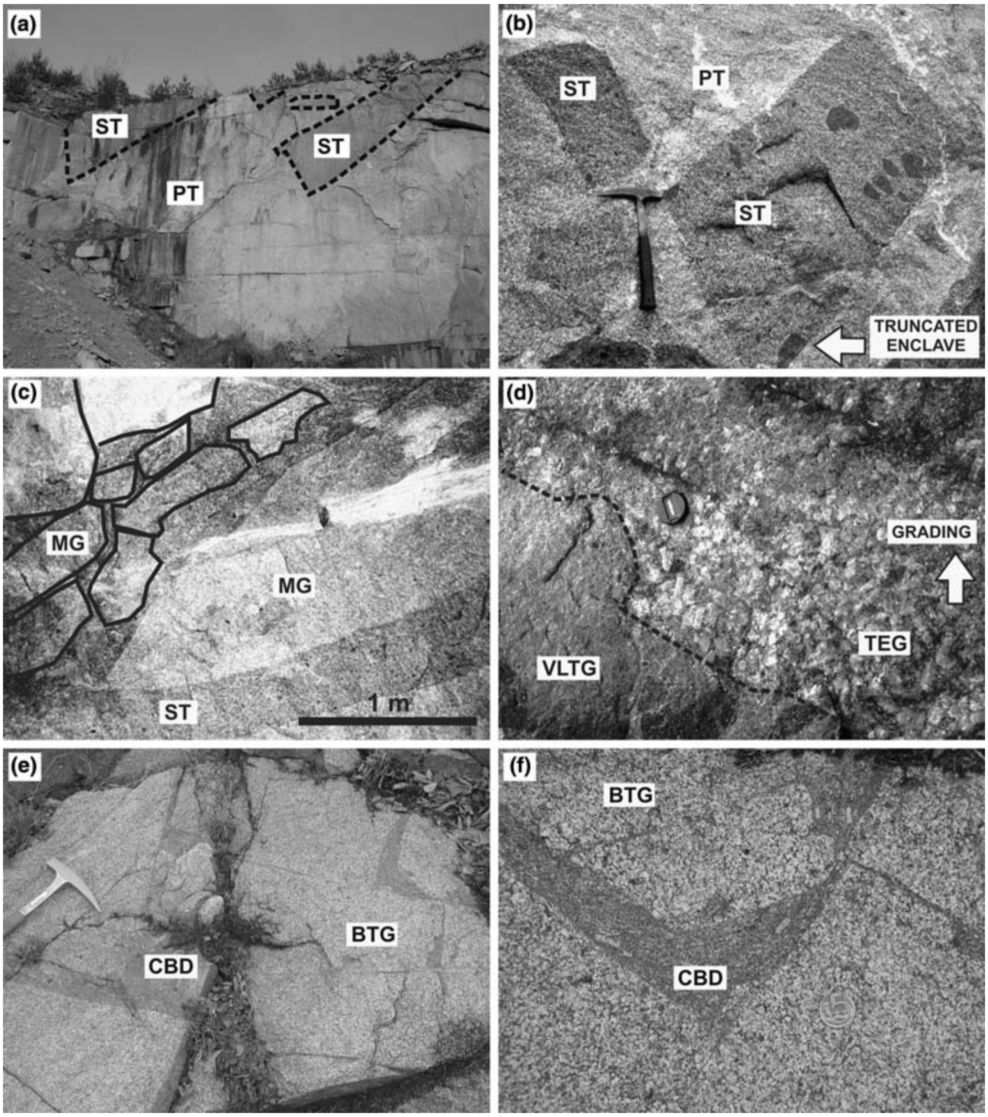

Fig. 9 Photos of stoped plutonic blocks within younger plutonic units in the Central Bohemian Plutonic Complex (see Fig. 2 for locations). **a** Up to several-meter-large stoped blocks of the Sázava tonalite (*ST*) within the Požáry trondhjemite (*PT*). Požáry quarry. The quarry face is 15 m high. **b** Detail of two rectangular stoped blocks of the Sázava tonalite (*ST*) within the Požáry trondhjemite (*PT*). Blocks are bounded by knife-sharp, mode I fractures that sharply truncate both the magmatic fabric and enclaves in the tonalite. Požáry quarry, hammer for scale. **c** Accumulation of stoped blocks (“stoping graveyard”) close to the pluton floor. The closely-packed blocks with touching edges are formed by the Marginal granite (*MG*) and are enclosed within Sázava tonalite (*ST*). Underground Gas Reservoir near Příbram, 1 km below the present-day surface. **d** Detail of the margin of rectangular stoped blocks of the Vltava granodiorite (*VLTG*) within the porphyritic Těchnice granodiorite (*TEG*). Note upward-grading accumulations of K-feldspar phenocrysts at the block margins. Kamýk nad Vltavou, lens cap for scale. **e** and **f** Example of arrested initial stage of formation of stoped blocks through cracking of the Blatná granodiorite (*BTG*) by the younger Čertovo Břemeno durbachite (*CBD*). The durbachite intrudes into thin cracks that are oriented nearly perpendicular to each other and form blocks of rectangular shape in the horizontal section. Note K-feldspar phenocrysts in the durbachite aligned parallel to the block margins. Zvíkov, hammer (**e**) and coin (**f**) for scale

documented numerous examples of accumulation of stoped blocks of Marginal granite enclosed within a tonalite corresponding in composition to the Sázava type (Fig. 9c). The meter-scale stoped blocks are rectangular, bounded by knife-sharp fractures and are typically closely packed with touching edges. We suppose that these accumulated stoped blocks may represent a rarely-seen example of a “stoping graveyard” where stoped blocks of older plutonic rocks have sunk into a magma chamber and accumulated close to its floor.

(3) The stoped blocks of the Vltava granodiorite in the Těchnice granodiorite. Along the contact between the equigranular Vltava and porphyritic Těchnice granodiorites of the Blatná composite pluton, we found numerous stoped blocks of the former within the latter (Fig. 9d). The blocks are rectangular to irregular in shape, up to several meters in size, and

have knife-sharp margins sharply truncating the magmatic fabric inside the blocks. In the surrounding porphyritic Těchnice granodiorite, K-feldspar phenocrysts, up to ~2–4 cm in size, commonly form upward-grading accumulations or clusters at flat-lying sections of block margins, suggesting that, after stoping of the Vltava granodiorite into the Těchnice granodiorite, some phenocrysts settled down due to gravitational sorting. In some places between subparallel block margins, alignment of phenocrysts defines the flow pattern, indicating magma flow between the blocks similar to flow in dikes.

(4) The stoped blocks of the Blatná granodiorite in the porphyritic durbachite. Several stoped blocks of the Blatná granodiorite with associated dikes are enclosed in the Čertovo Břemeno porphyritic durbachite to the SE of Zvíkov in the central part of the Central Bohemian Plutonic Complex. Here, Holub and Žežulková (1978) mapped a large (~30×50 m) block of granodiorite surrounded by the porphyritic durbachite (for geologic map of the block see Fig. 2 in Holub 1997). The block has rectangular shape in the map view and is bounded from all exposed sides by sharp, straight fractures. The northern half of the block is made up of the equigranular, medium-grained biotite-hornblende granodiorite which has been intruded by several ~E–W minette dikes. The southern part of the block is fine-grained granite porphyry, which intruded and was cooled against the granodiorite along an ~E–W contact with chilled margin developed in the granite porphyry. All these intrusive contacts, as well as the internal magmatic fabrics in the block, are sharply truncated by the durbachite. The fabrics in the surrounding durbachites are commonly parallel to block margins. In the same area, we also documented an initial stage of formation of stoped blocks through cracking of the Blatná granodiorite and intrusion of the durbachite along thin perpendicular cracks (Fig. 9e, f).

Discussion

A recent lively debate on the principal mechanisms of pluton growth and evolution of large magma chambers has also brought to the foreground the issue of the importance of magmatic stoping during emplacement. A central aspect of the discussion is whether plutons represent ancient magma chambers that were largely molten at once, or whether they were constructed incrementally through addition of multiple small magma batches (e.g., Bachl et al. 2001; Bartley et al. 2005; Clemens 2005; Coleman et al. 2004; Glazner et al. 2003, 2004; Žák and Paterson 2005). In this context, large-scale stoping requires the presence of large regions of interconnected melt in the crust (magma chambers) to allow removal and sinking of host rock blocks into the magma. Magmatic stoping should thus not be a volumetrically significant process in plutons thought to accumulate via the diking mechanism. Hence, field evidence for extensive stoping may testify some pluton construction models and imply the presence of large ancient magma chambers in the crust.

In the Central Bohemian Plutonic Complex, numerous roof pendants, stoped blocks, and discordant, unfaulted pluton/host rock contacts in all the major intrusive units (plutons) suggest that magmatic stoping was a widespread, important process during its final construction, in particular during the emplacement of calc–alkaline and high-K calc–alkaline plutons between ~354–346 Ma. In addition, we also have documented the roof of the Sázava pluton with stepped geometry and not detached from the pluton wall. In some cases, lithological contacts in the large roof pendants in the Central Bohemian Plutonic Complex can be traced between pendants across the intrusive units, suggesting that at least some of the roof pendants may be in their pre-emplacement position. However, discordant intrusive contacts sharply truncating host rock-markers with no evidence for syn-emplacement ductile strain or diking indicate that large sections of these roof pendants or rafts now occupied by plutonic rocks are missing and were sunk into a chamber. The roof characteristics, steep pluton walls, no evidence for roof-wall detachment, and missing large sections of host rock all indicate that at least the upper parts of upper-crustal plutons of the Central Bohemian Plutonic Complex may have been largely emplaced by magmatic stoping. These plutons are thus very similar to "bell-jar" plutons with steep sides and flat stepped roofs described in the Andes (Mahood and Cornejo 1992; Myers 1975; Yoshinobu et al. 2003a) and North American Cordillera (Paterson and Miller 1998a).

Moreover, our geometrical image map analysis (Fig. 6) indicates that at least about a half of all the exposed contacts of the Central Bohemian Plutonic Complex with the upper-crustal Teplá-Barrandian host rocks are discordant intrusive contacts presumably associated with magmatic stoping. Estimations of *minimum* length scales of stoped contacts provide supporting evidence that magmatic stoping was an important, large-scale process during the final stages of emplacement of the Central Bohemian Plutonic Complex. In addition, the presence of discordant contacts and stoped blocks throughout the Central Bohemian Plutonic Complex including the oldest (Sázava tonalite) and the youngest (Tábor syenite) pulses indicates batholith-scale spatial extent of stoping, which operated over a long period of time, i.e., during the entire (~17 My) time span of the plutonic complex assembly.

We have also shown that older plutonic units were commonly broken off and reincorporated into younger magma pulses during emplacement (i.e. intra-chamber stoping; Fig. 9). Such evidence is preserved most commonly along internal contacts between intrusive units of the Central Bohemian Plutonic Complex (e.g., contact between Sázava tonalite and Požáry trondhjemite, contact between Vltava and Těchnice granodiorites). The characteristics of the plutonic stoped blocks described above suggest that they were formed by fracturing of solidified plutonic rocks (as they are typically bounded by straight, sharp fractures, Fig. 9e) by thermal stresses of younger magma. After cracking, they sank into a magma chamber (e.g., Požáry quarry, Fig. 9a, b). We also documented an example of touching plutonic stoped blocks that accumulated close to a pluton floor (Fig. 9c) to form a "stoping graveyard"—a situation that is rarely seen in plutons. Our study thus provides field examples of various arrested stages in the "lifetime" of stoped blocks in a magma chamber from the initial formation (Fig. 9e, f), through sinking into a chamber (Fig. 9a), to final accumulation on a pluton floor (Fig. 9c).

A particularly intriguing aspect is the interplay of regional tectonic deformation and magmatic stoping during the emplacement of the Central Bohemian Plutonic Complex. We concluded elsewhere that the emplacement of the ~354–346 Ma calc–alkaline and high-K calc–alkaline plutons into Teplá-Barrandian Unit was broadly synchronous with the regional transpresion in the upper crust characterized by arc-normal WNW–ESE contraction and arc-parallel ~NNE–SSW stretching (Žák et al. 2005a, b). Regional transpression resulted in the development of two principal mechanical anisotropies in the pluton host rocks: the ~NNE–SSW regional foliation (cleavage) and ~WNW–ESE to E–W extensional brittle fractures often utilized by regional dike swarms.

Although some of the contractional strain recorded in overlapping pluton aureoles along the NW margin of the Central Bohemian Plutonic Complex may have accommodated emplacement of individual plutons (Žák et al. 2005a, b), we commonly see sheeting along the ~NNE–SSW trending intrusive contacts where magmatic sheets intruded parallel to regional cleavage, presumably through a magma wedging mechanism. Large sections of knife-sharp, straight ~NNE–SSW contacts of granitoids with wall-rock and roof pendants parallel to regional cleavage as well as examples of disintegration of margins of large roof pendants (Fig. 5) suggest that the magmatic sheets which intruded along pre-existing cleavage planes effectively disintegrate strongly foliated host rock into thin cleavage-bounded blocks. Some of these blocks may also have sunk or may have been rapidly disintegrated in the surrounding magma (Clarke et al. 1998; McLeod and Sparks 1998).

Thus, we propose that at least some of these ~NNE–SSW intrusive contacts may have recorded complex intrusive histories. Initially, the enhancement of regional contraction within thermally softened pluton aureoles led to the formation of pervasive high-temperature cleavage (Žák et al. 2005b). This was followed by the formation of sheeted zones by magma wedging along cleavage planes and piecemeal stoping of thin host rock blocks into the magma chamber. If this actually occurred, such a scenario would further increase the extent and importance of stoping, which was estimated in this study solely from discordant, cleavage-perpendicular intrusive contacts (Fig. 6).

We believe that our present study significantly elucidates the emplacement of the calc–alkaline and high-K calc–alkaline plutons of the Central Bohemian Plutonic Complex and provides constraints on the relative importance of a variety of emplacement processes in the upper crust. We have shown elsewhere (Žák et al. 2005a) that no field evidence from large plutons of the Central Bohemian Plutonic Complex supports the role of regional faulting (i.e. host rock translation along faults) or shearing as near-field material transfer processes during final stages of their emplacement. Instead, we concluded that ductile shortening in pluton aureoles may have partly accommodated emplacement of some plutons during regional transpression (Žák et al. 2005b). In addition, the field evidence presented in this paper clearly indicates that magmatic stoping during collapse of pluton roofs was a very important, highly efficient large-scale material transfer process during final emplacement of the Central Bohemian Plutonic Complex. This implies that the emplacement of the ~354–346 Ma calc–alkaline and high-K calc–alkaline plutons of the Central Bohemian Plutonic Complex was much less controlled by regional tectonic deformation than previously assumed (e.g., Košler et al. 1995; Rajlich 1993).

Indeed, recent numerical models of fault-assisted emplacement and strain rates in pluton aureoles (Albertz et al. 2005; Gerbi et al. 2004; Johnson et al. 2001; Paterson and Schmidt 1999; Yoshinobu et al. 1998) point out that neither fault-slip rates nor ductile flow on their own could accommodate fast strain rates during emplacement of large magma batches. Instead, additional mechanisms, such as brittle cracking and stoping, which are several-orders-of-magnitude faster, are necessary (Albertz et al. 2005). Our study thus may provide an excellent field example for predictions made by these numerical models, since large calc–alkaline and high-K calc–alkaline plutons of the Central Bohemian Plutonic Complex (e.g., ~346 Ma Blatná pluton) were emplaced into the upper crust over a relatively short-time span and therefore fast strain rates in the host rocks were required to accommodate emplacement of the Central Bohemian Plutonic Complex. Hence, we may assume that limited slower ductile flow in the narrow structural aureoles of individual plutons was largely overtaken by much faster thermal cracking and stoping of the Barrandian host rocks.

Finally, based on our study from the Central Bohemian Plutonic Complex, we propose that extensive magmatic stoping, recently called into question by Glazner et al. (2004) and Glazner and Bartley (2005) and commonly neglected in most emplacement studies of Variscan plutons, may indeed be an important mechanism of final construction of plutons in the upper crust. We have also shown that magmatic stoping may significantly modify preserved structural patterns around plutons and reduce evidence for earlier emplacement processes (e.g., ductile strain) by removal of many of the structural aureoles. Generally speaking, magmatic stoping may be a highly efficient emplacement process that can significantly contribute to vertical recycling (magma up—host rock down) and downward transport of crustal material within magma plumbing systems in the crust. Thus, it may operate as a large-scale exchange process during crustal thickening (Paterson and Miller 1998a; Paterson et al. 1996). From this point of view, we see many similarities between the Variscan Central Bohemian Plutonic Complex and the large Andean and Cordilleran plutonic systems.

Conclusions

In brief, the main conclusions following from the present study are as follows:

(1) The presence of numerous roof pendants, stoped blocks and discordant intrusive contacts in the Central Bohemian Plutonic Complex suggests that magmatic stoping was a widespread process during its final construction. The measured minimum total length of the irregular discordant contacts perpendicular to the regional cleavage comprises about half of all contacts with the upper-crustal Teplá-Barrandian Unit, indicating that magmatic stoping was a large-scale process at the present-day exposure level. Moreover, older plutonic units were commonly broken off and reincorporated into younger magma pulses (intra-chamber stoping).

(2) At least some of the straight, cleavage-parallel intrusive contacts may have recorded complex intrusive histories. Initially, an enhancement of regional contraction within thermally softened pluton aureoles led to the formation of pervasive cleavage. Then sheeted zones formed by magma wedging and consequently thin cleavage-bounded host rock blocks were stoped into the magma chamber. These processes would increase the extent and further importance of magmatic stoping in the Central Bohemian Plutonic Complex estimated solely from discordant contacts.

(3) No field evidence indicates that regional faulting or shearing acted as near-field material transfer processes during emplacement of the large ~354–346 Ma calc–alkaline and high-K calc–alkaline plutons of the Central Bohemian Plutonic Complex in the upper crust. Ductile shortening may have partly accommodated emplacement of some plutons during regional transpression, however, preserved field evidence clearly indicates that at the exposed upper-crustal level extensive magmatic stoping during collapse of the pluton roofs was an important, highly efficient large-scale material transfer process. If this actually occurred, then the emplacement of the Central Bohemian Plutonic Complex was controlled far less by regional tectonic deformation than previously thought.

(4) We suggest that the fast strain rates required for emplacement of large plutons of the Central Bohemian Plutonic Complex into brittle upper crustal host rocks over a relatively short-time span could not have been accommodated entirely by slow ductile flow within the narrow structural aureoles of individual plutons. A dominant role was played by much faster thermal cracking and stoping of the host rocks as predicted by recent numerical models of pluton emplacement.

(5) We argue that extensive magmatic stoping may, in general, be an important mechanism of final construction of upper-crustal plutons. Magmatic stoping is also likely to significantly modify preserved structural patterns around plutons and obscure the evidence for earlier emplacement processes due to removal of large parts of structural aureoles. In summary, stoping may have significantly contributed as a large-scale exchange process to vertical recycling and downward transport of crustal material within magma plumbing systems in the crust during Variscan orogeny, similarly to Mesozoic Andean and Cordilleran plutonic systems.

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