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Tectonic evolution of the southeastern part of the Pohorje Mountains (Eastern Alps, Slovenia)

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Abstract: Field relations and deformation structures in the southeastern part of the Pohorje Mountains constrain the tectonic evolution of the Austroalpine high-pressure/ultrahigh pressure (HP/UHP) terrane. The Slovenska Bistrica Ultramafic Complex (SBUC) forms a large (ca. 8×1 km size) body of serpentinized harzburgite and dunite including minor garnet peridotite and is associated with partly amphibolitized eclogite bodies. The SBUC occurs in the core of an isoclinal, recumbent, northward closing antiform and is mantled by metasedimentary rocks, mostly gneisses and a few marbles, including isolated eclogite/amphibolite lenses. Before this folding, the SBUC formed the deepest part of the exposed terrane. We interpret the SBUC to be derived from near-MOHO, uppermost mantle which was intruded by gabbros in the subsurface of a Permian rift zone. During Cretaceous intracontinental subduction, the SBUC was most likely part of the footwall plate which experienced HP to UHP metamorphism and was folded during exhumation. In the Miocene, the Pohorje Pluton intruded and, subsequently, the metamorphic rocks together with the pluton were deformed probably due to east-west extension and contemporaneous north-south shortening, thus forming an antiformal metamorphic core complex.

Key words: Eastern Alps, Pohorje, UHP metamorphism, eclogite, garnet peridotite.

Introduction

Eclogite-facies tectonic units in collisional orogens often contain garnet-bearing peridotite lenses and boudins. This is typically, but not exclusively, the case for tectonic units that reached ultrahigh-pressure (UHP) conditions (Coleman & Wang 1995). There are in principle two different ways in which these ultramafic bodies may have been incorporated into the surrounding felsic and mafic rocks. One is that they originated from the mantle wedge above the subducting crust ("mantle" peridotites sensu Brueckner & Medaris 2000) and were incorporated into the downgoing plate either during subduction or exhumation. Alternatively, ultramafic bodies were transferred from the mantle into the crust prior to subduction ("crustal" peridotites sensu Brueckner & Medaris 2000). Understanding these processes yields important constraints for the tectono-metamorphic and geochemical processes in subduction zones.

In this paper we show the field relations between ultramafic mantle rocks, including garnet peridotite, and crustal gneisses in the Pohorje Mountains of the Eastern Alps which experienced HP to UHP metamorphism (Hinterlechner-Ravnik 1987; Hinterlechner-Ravnik et al. 1991; Janák et al. 2004, 2006, 2009; Sassi et al. 2004; Vrabec 2004, 2007; Miller et al. 2005; De Hoog et al. 2009). Janák et al. (2006) documented that garnet peridotites in Pohorje reached UHP metamorphic conditions of up to 900 °C and 4 GPa during Cretaceous intracontinental subduction. They proposed that garnet peridotites were derived from depleted mantle rocks which were subsequently metasomatized in the plagioclase-peridotite or the spinel-peridotite stability field. Subduction of these peridotite protoliths resulted in the development of garnet-bearing assemblages at HP and UHP conditions of metamorphism. As a possible tectonic scenario, Janák et al. (2006) and De Hoog et al. (2009) suggested, based on petrological and geochemical data, that peridotites were incorporated into the subducting crust from the overlying mantle wedge. The field relations reported here, however, show that garnet peridotites and the associated serpentinites and eclogites formed the deepest part of the exposed HP/UHP metamorphic terrane, suggesting an alternative scenario in which the peridotites may have been part of the downgoing plate already from the beginning.

Regional geological setting

The Pohorje Mountains in NE Slovenia are located at the southeastern margin of the Eastern Alps in the vicinity of the Periadriatic Line (Fig. 1). The basement of the area largely consists of Cretaceous-age high-grade metamorphic rocks, mainly gneisses and micaschists, with bodies and lenses of metabasics and a body of ultramafic rocks, the Slovenska Bistrica Ultramafic Complex (SBUC), at the southeastern end. The SBUC extends over 8 km from Modrič in the west to Šentuvec in the east. It has been strongly serpentinized except for a few garnet peridotite remnants in which UHP-assemblages are preserved. The entire metamorphic series is called the Pohorje Nappe after Janák et al. (2006) and belongs to the Lower Central Austroalpine after Janák et al. (2004) or the Koralpe-Wölz nappe system after Schmid et al. (2004). In the

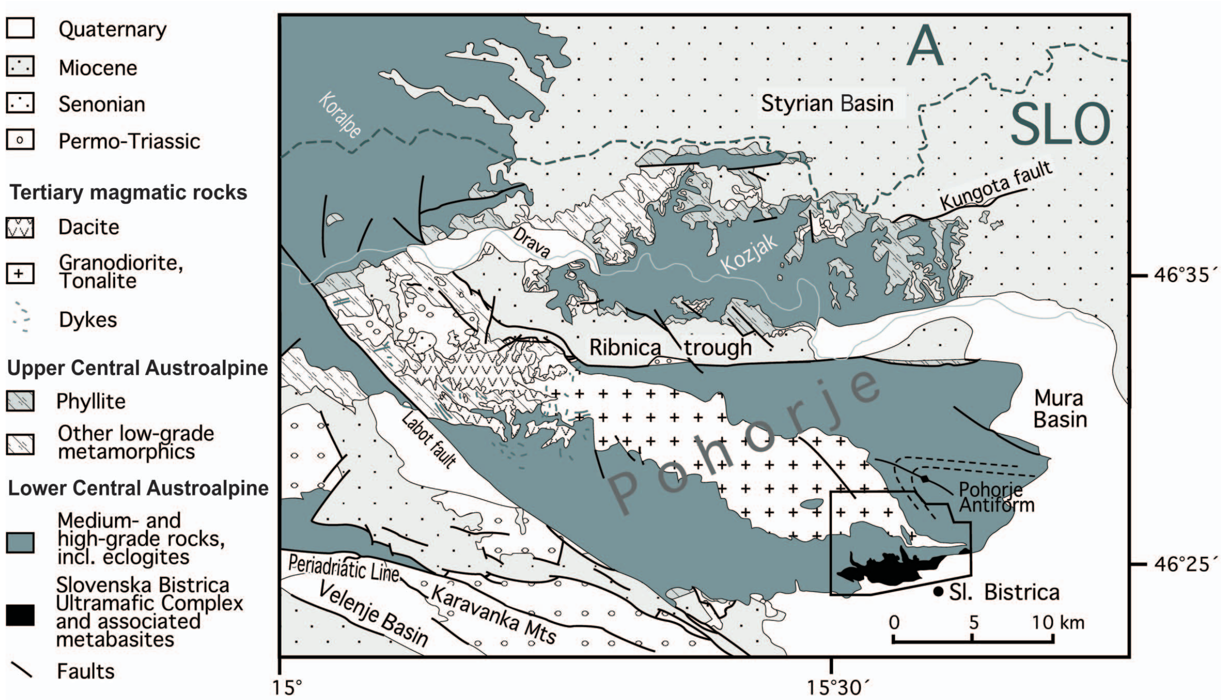

Fig. 1. Geological sketch map of the Pohorje Mountains and adjacent areas with marked location of the map area; modified from Mioč & Žnidarčič 1977.

NW part of the Pohorje Mts, the high-grade metamorphic rocks are overlain by low-grade slates and phyllites of the Upper Central Austroalpine (Drauzug-Gurktal nappe system) along a top-to-the-E low-angle normal fault of Late Cretaceous age. The central part of the Pohorje Mts is built by the Pohorje Pluton, a granodiorite to tonalite intrusion with an Early Miocene crystallization age of ca. 18.6 Ma, followed by rapid cooling (Fodor et al. 2008; Trajanova et al. 2008). The plutonic rocks are associated with subvolcanic dacite bodies to the northwest, representing a shallower crustal level. In this area, the pluton just reaches into the basal part of the Upper Central Austroalpine slates and phyllites. The whole magmatic complex extends over ca. 35 km in a WNW-ESE direction.

Paleogeographically the Austroalpine realm represents the northwestern continental margin of Apulia. From bottom to top, the Austroalpine nappe stack is subdivided into the thrust sheets of the Lower Austroalpine, the Lower Central Austroalpine and the Upper Central Austroalpine (Janák et al. 2004). The Permian to Mesozoic sediment nappes of the Northern Calcareous Alps represent the former sedimentary cover of the Central Austroalpine. The sedimentary rocks are still partly connected with the Upper, partly with the Lower Central Austroalpine (Janák et al. 2004; Nagel 2006). In general, more southeasterly located units of the Austroalpine were thrust over more northwesterly located ones during the Eo-Alpine orogeny in the Cretaceous.

Together with Saualpe, Koralpe and some other areas, the Pohorje Mts belong to the Koralpe-Wölz nappe system which is part of the Lower Central Austroalpine. Before their HP-UHP metamorphism, these units experienced a HT-LP event during Permian rifting (e.g. Schuster et al. 2001; Schuster & Stüwe 2008) causing metamorphism of Paleozoic and older sediments of continental and oceanic affinity. Rifting also led to underplating and emplacement of gabbroic bodies into thinned continental crust (Thöni & Jagoutz 1993; Thöni et al. 2008). During the Cretaceous, these mafic rocks and their host rocks, mainly metasediments with minor orthogneisses, were overprinted under HP to UHP conditions (Janák et al. 2004, 2006, 2009; Sassi et al. 2004; Miller et al. 2005, 2007) in a south- to southeast-dipping, intracontinental subduction zone (Janák et al. 2004). The direction of subduction can be inferred from a general pressure gradient along the Koralpe/Pohorje traverse with lower pressures in the NW and higher pressures in the SE (Tenczer & Stüwe 2003; Janák et al. 2004; Bruand et al. 2010). Subduction and exhumation resulted in strong deformation and nappe stacking of these units. The peak of (U)HP metamorphism in Pohorje was reached at ca. 91 Ma according to garnet Sm-Nd and zircon U-Pb dating of eclogites and gneisses (Thöni 2002; Miller et al. 2005; Thöni et al. 2008; Janák et al. 2009).

Cretaceous subduction and collision were followed by an extensional stage between ~80 and 67 Ma within the Austroalpine units (e.g. Rantitsch et al. 2005). Extension resulted in lithospheric thinning and formation of half-grabens in the upper crust and thus may have contributed to the exhumation of the deeply buried units. The rifting was probably caused by westward rollback of the Penninic subduction zone (Froitzheim et al. 1997). During the Paleocene and Eocene the Austroalpine nappe stack was thrust on top of the Penninic and Helvetic units due to the collision between the Apulian and European continents. In the Miocene, the Eastern Alps underwent orogen-parallel extension and lateral extrusion of crustal blocks to the east (Ratschbacher et al. 1991) as a result of east-directed rollback in the Carpathians

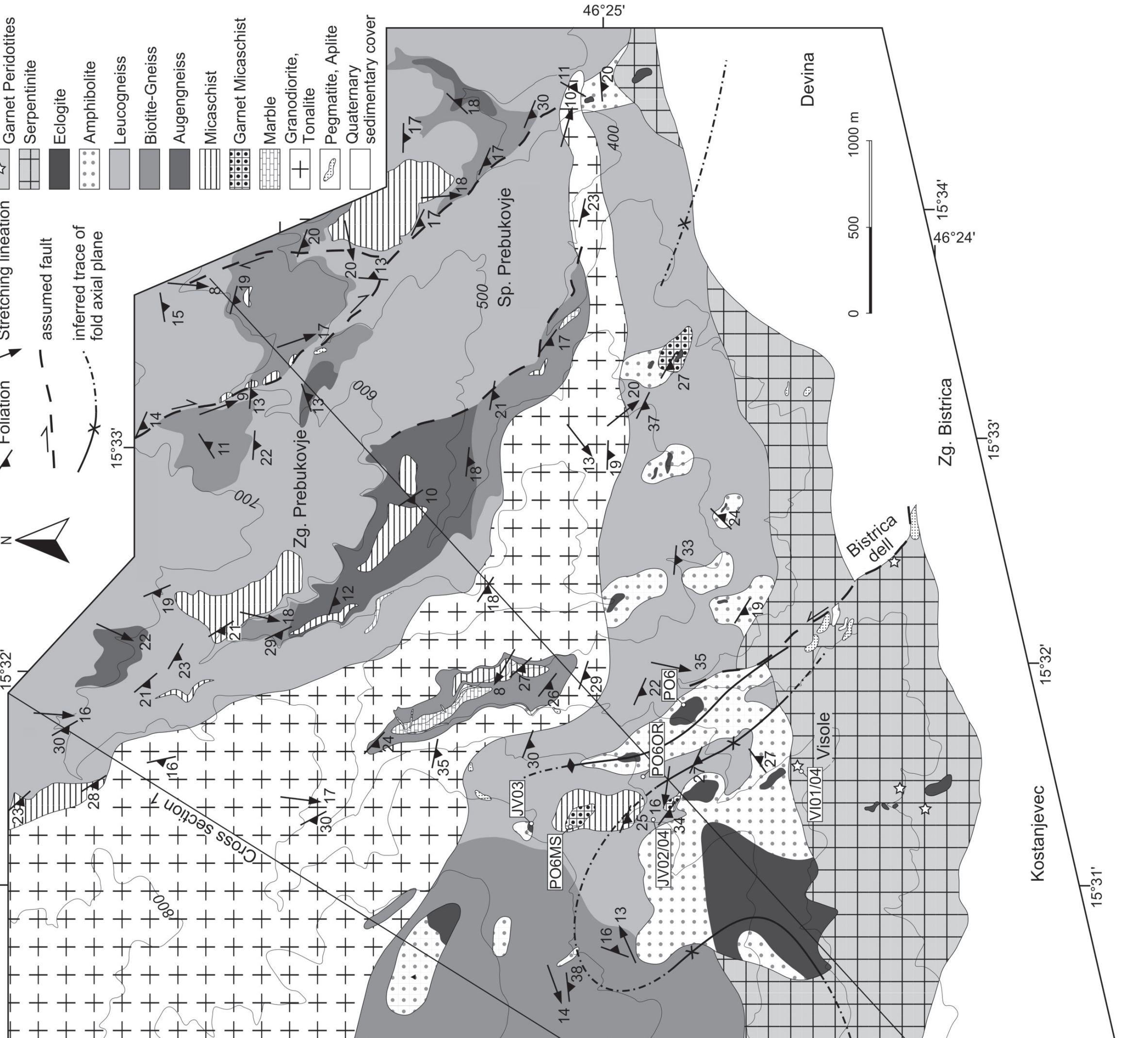

Fig. 2. Geological map of the area NW of Slovenska Bistrica with localities of the samples mentioned in the text and traces of the cross-sections shown in Fig. 3.

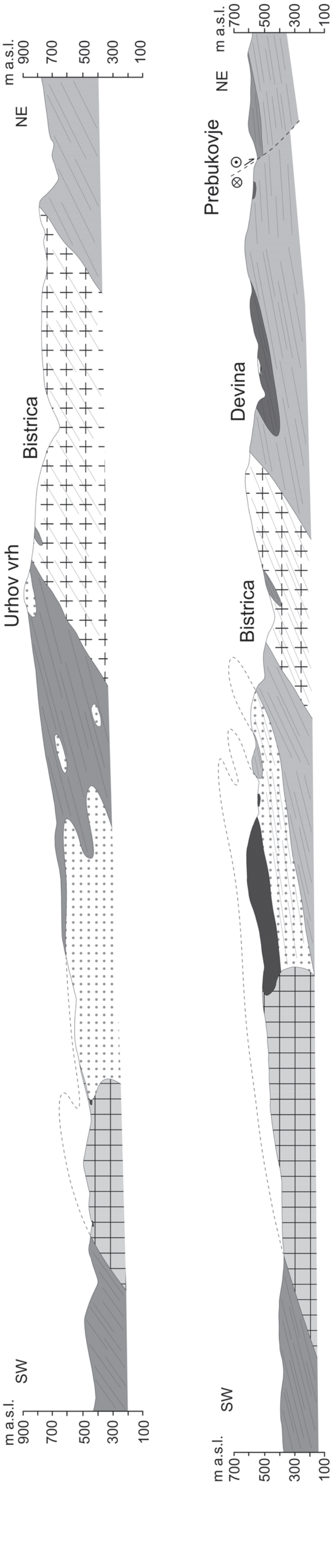

Fig. 3. NE-SW trending cross-sections.

and gravitational collapse. Lithospheric thinning also resulted in magmatism within the Pannonian Basin as well as the adjacent Austroalpine units, including the Early Miocene Pohorje Pluton (Trajanova et al. 2008; Fodor et al. 2008). In the Pohorje Mts, paleostress analysis showed that Neogene E-W extension was temporarily accompanied by N-S shortening (Fodor et al. 2008).

In order to clarify the structural relations between ultramafic rocks, eclogites, and gneisses, we mapped an area of about 35 km^2 in the scale of 1:5,000 northwest of Slovenska Bistrica (Figs. 2 and 3) including the eastern end of the Pohorje Pluton with surrounding gneisses and micaschists as well as metabasics and meta-ultrabasics occurring south of the intrusion. This area includes all the formerly described UHP localities (Hinterlechner-Ravnik 1987; Janák et al. 2004, 2006, 2009).

Field relations and petrography

The Lower Central Austroalpine basement rocks in the study area mostly comprise strongly sheared gneisses and micaschists which have been retrogressed to variable degrees under amphibolite to upper greenschist facies conditions after their Upper Cretaceous HP metamorphism. These rocks host bodies and lenses of metabasics, an ultramafic complex, and the southeastern end of the Miocene Pohorje Pluton.

Metamorphic rocks

Serpentinites vary in colour from black and dark green to very light green. Bastite as a pseudomorph of lizardite after enstatite or bronzite is quite common; its grain-size of up to 1 cm suggests a coarse-grained precursor material. Kernel structures and other mesh-like textures formed during serpentinization. All of the serpentinites have a massive texture without any macroscopically visible preferred orientation of minerals indicating that serpentinization was essentially post-tectonic. According to geochemistry the protolith of the serpentinite was harzburgite and dunite, highly depleted following melting within the spinel stability field and later metasomatized by melts or fluids before serpentinization. It probably originated in the oceanic mantle or in a continental rift zone (De Hoog et al. 2009).

Garnet peridotites occur as small lenses, several meters to tens of meters in size, or as loose boulders. These rocks consist of garnet, olivine, orthopyroxene, clinopyroxene and brown spinel, which are variably replaced by amphibole, green spinel, serpentine, talc and chlorite (see Janák et al. 2006 for more details). All garnet peridotite localities are within the SBUC (Fig. 2) in contrast to the map of Mioč & Žnidarčič (1977) in which one of the localities (119) is away from this body (see also Janák et al. 2006). Two localities of garnet peridotite (119 and VI01/04) show UHP metamorphic conditions of up to 4 GPa and 900 °C (Janák et al. 2006).

Eclogites occur as lenses and bodies several meters to several hundreds of meters in size south of the Pohorje Pluton. They are often associated with or even surrounded by amphibolite but also occur as individual bodies within gneisses and serpentinites. The HP metamorphic assemblage is gar-

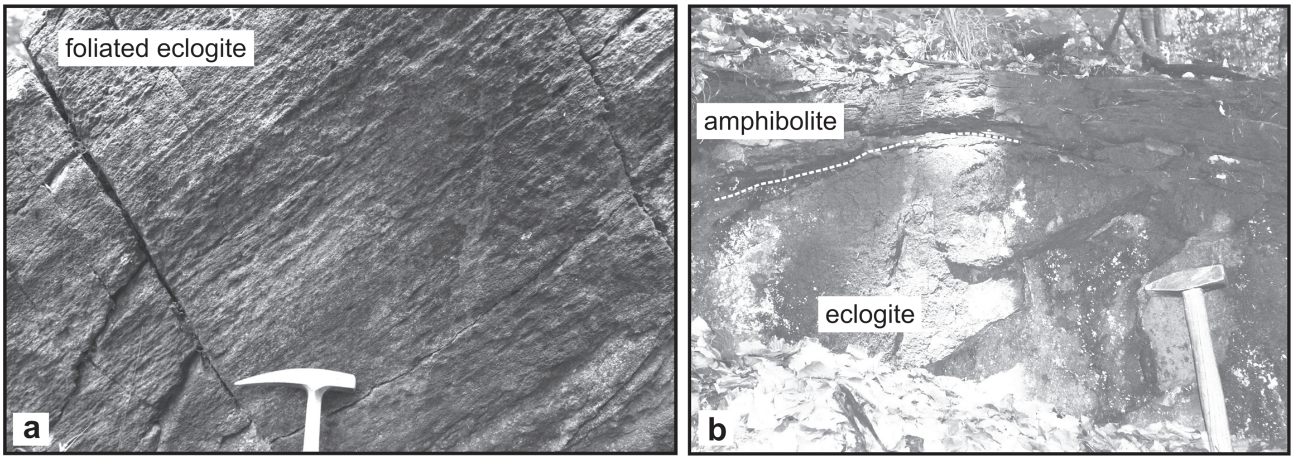

Fig. 4. a — Foliated eclogite. The outcrop surface is perpendicular to the foliation. Outcrop coordinates: 46°24′35″ N, 15°30′58″ E. **b** — Marginal amphibolitization of an eclogite body. Amphibolitization was accompanied by the formation of a new, subhorizontal foliation and a WNW-ESE-trending stretching lineation. The older eclogite-facies foliation in the eclogite is parallel to the surface of the outcrop. Outcrop coordinates: 46°24′59″ N, 15°31′33″ E.

net, omphacite, phengite, kyanite, zoisite and quartz. It is usually retrogressed to some extent so that amphibole, plagioclase and diopsidic clinopyroxene occur as secondary phases (see Janák et al. 2004 and Sassi et al. 2004 for more details). The eclogites differ in their macroscopic appearance, probably reflecting the composition and texture of their protoliths as well as strain partitioning. Some of them show a distinct foliation (Fig. 4a) with alternating garnet-rich layers and layers rich in omphacite and zoisite, while in others garnet is concentrated in patches a few cm in diameter. Janák et al. (2004) reported two UHP localities of kyanite eclogites (JV03, PO6) which are shown on the map (Fig. 2). Metamorphic conditions of these eclogites reached 3.0–3.1 GPa and 760–825 °C (Janák et al. 2004).

Amphibolites consist of hornblende and plagioclase and they are partly foliated. The amphibolites form lenses and bodies from several tens of meters to two kilometers in size. There is a transition between eclogite and amphibolite; typically, the inner part of mafic lenses is preserved as eclogite whereas the outer part is sheared and retrogressed to amphibolite (Fig. 4b).

Gneisses occur as several types. (a) Leucogneiss is dominated by quartz, K-feldspar, and plagioclase, together with white mica and minor biotite. (b) Biotite gneiss consists of

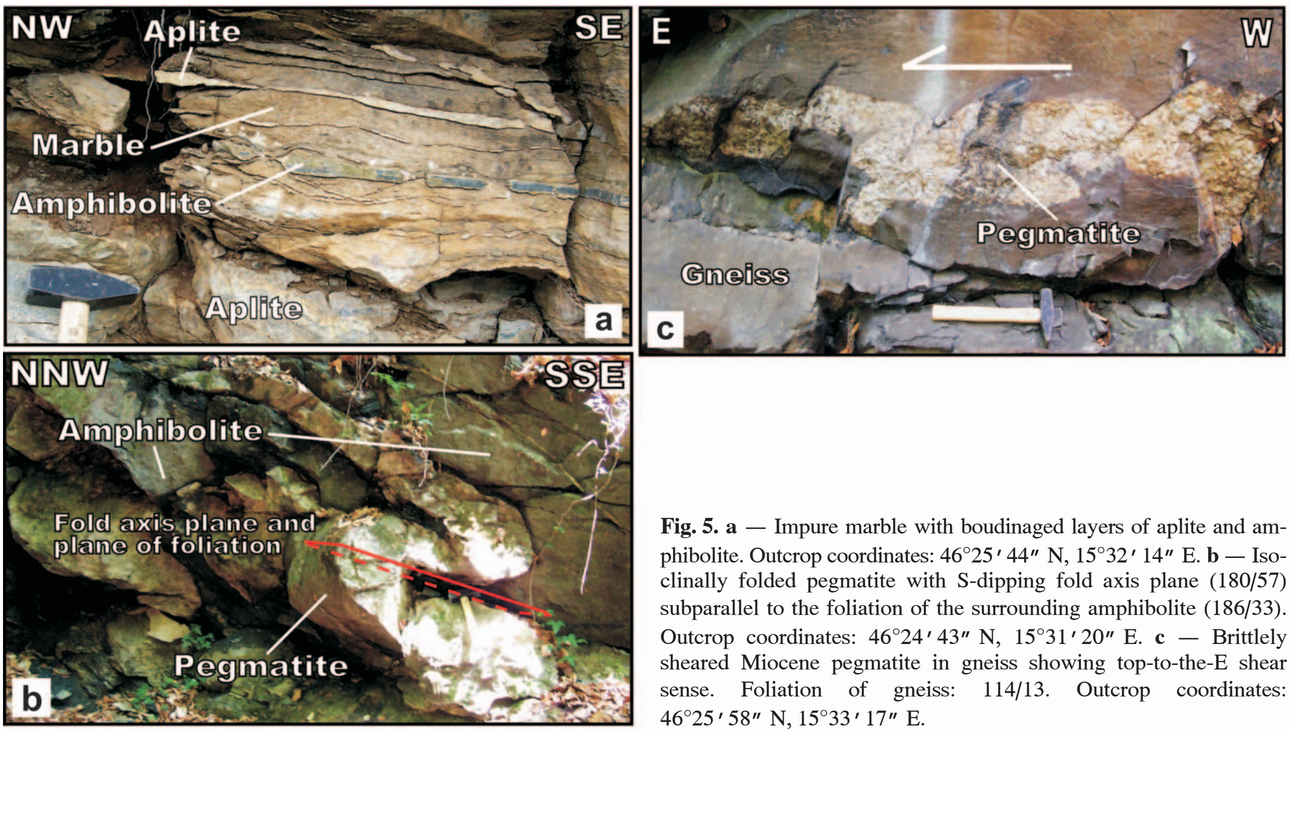

Fig. 5. a — Impure marble with boudinaged layers of aplite and amphibolite. Outcrop coordinates: 46°25′44″ N, 15°32′14″ E. **b** — Isoclinally folded pegmatite with S-dipping fold axis plane (180/57) subparallel to the foliation of the surrounding amphibolite (186/33). Outcrop coordinates: 46°24′43″ N, 15°31′20″ E. **c** — Brittlely sheared Miocene pegmatite in gneiss showing top-to-the-E shear sense. Foliation of gneiss: 114/13. Outcrop coordinates: 46°25′58″ N, 15°33′17″ E.

biotite, K-feldspar, quartz, and plagioclase with minor white mica. (c) Augengneiss contains large K-feldspar porphyroblasts a few cm in diameter, with plagioclase, quartz, biotite and white mica in the matrix. The texture of the augengneiss is inhomogeneous and migmatitic.

Micaschists occur as layers and lenses of different sizes within surrounding gneisses. They consist of variable modal amounts of garnet, white mica and biotite as well as quartz, plagioclase, K-feldspar, kyanite and staurolite. Their Al-rich composition corresponds to metapelites (see Janák et al. 2009 and Hurai et al. 2009 for more details). Janák et al. (2009) determined P-T conditions of 2.2–2.7 GPa at 700–800 °C for these metapelites (JV02/04, PO6MS and PO6OR, Fig. 2) but assumed that they probably experienced the same UHP metamorphism at ~3 GPa as the associated kyanite eclogites. Zircons from the metapelites yielded an age of 92±0.5 Ma using the SIMS ion microprobe (Janák et al. 2009) which is interpreted as the age of HP-UHP metamorphism. Some of the zircon cores record Permian to Triassic events, most probably reflecting HT-LP metamorphism at that time. Chemical Th-U-Pb (EMPA) dating of monazite (Krenn et al. 2009) yielded an age of 100±6 Ma.

Marbles occur within a metamorphic lens surrounded by granodiorite and in two elongate lenses northeast of the intrusion. Marbles are coarse-grained and foliated.

Leucogneisses and biotite gneisses are more abundant than augengneisses and micaschists which form layers and lenses within them. Textures are rather heterogeneous on the outcrop scale as a result of tectonically transposed layering. As an example, Fig. 5a shows an outcrop of impure marble with boudinaged layers of aplite and amphibolite.

Pohorje Pluton

Granodiorites are the most abundant intrusives, composed of quartz, K-feldspar, plagioclase, biotite and hornblende. They are usually slightly foliated, especially at the rims of the intrusion. According to geochemical data the granodiorite originated from a mantle source, was subsequently modified by assimilation of crustal material, and differentiated (Dolenec et al. 1987; Zupančič et al. 1994; Altherr et al. 1995). Fodor et al. (2008) estimated a pressure of 0.6–0.7 GPa which corresponds to magma crystallization at 23–26 km depth (assuming a crustal density of 2.7 g/cm^3) using Al-in-hornblende barometry on a granodiorite from the northwestern part of the map area, which confirms the results of Altherr et al. (1995). Towards the northwest, the pressure decreases to 0.3–0.4 GPa (11–15 km) near the northwestern end of the pluton (Fodor et al. 2008).

Pegmatites and aplites occur within the granodiorite and surrounding metamorphic rocks. They form veins and bodies of several centimeters to tens of meters in length which intruded partly subparallel, partly discordant to the foliation of the surrounding rocks. The pegmatites consist of quartz and feldspar only, the aplites also contain biotite. The pegmatites were often isoclinally folded with axial planes parallel to the foliation of the host rocks, or they were sheared under ductile and

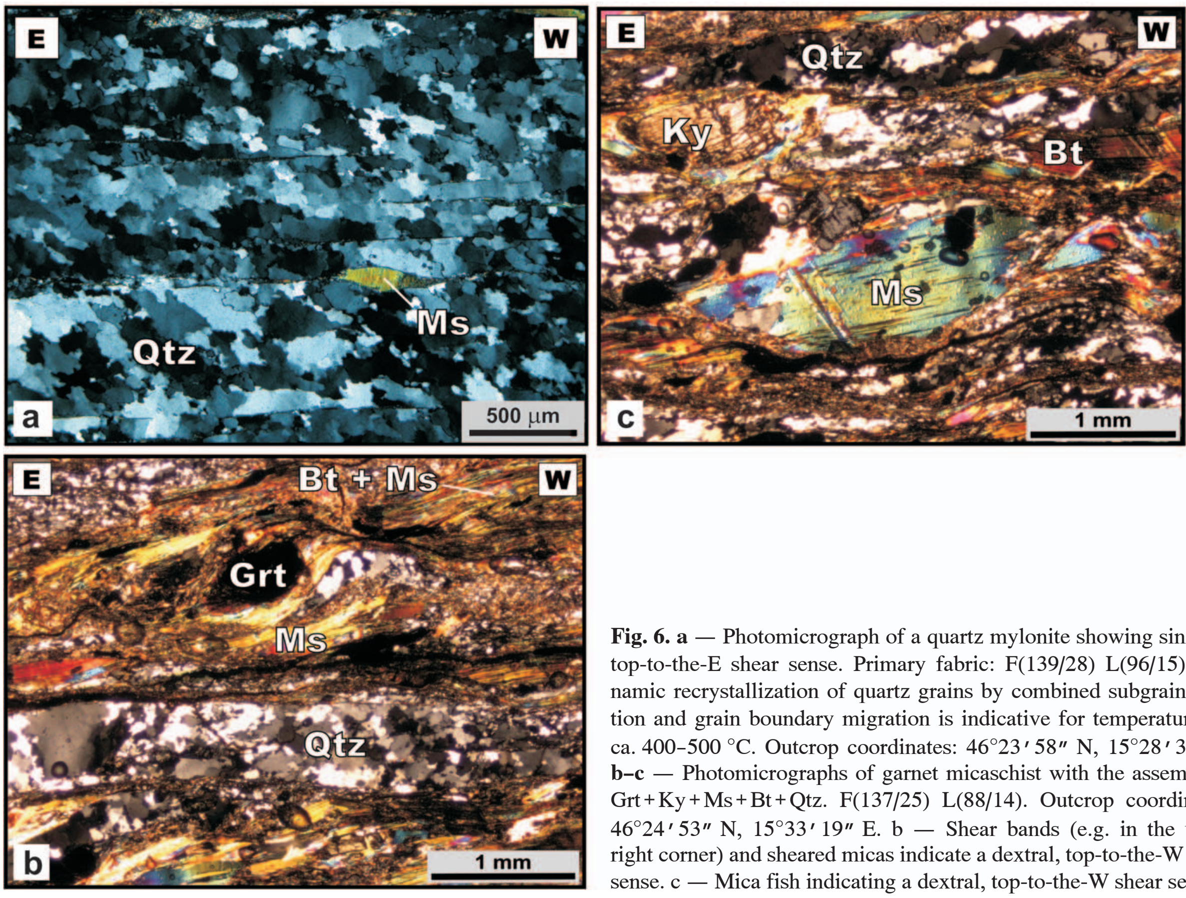

Fig. 6. a — Photomicrograph of a quartz mylonite showing sinistral, top-to-the-E shear sense. Primary fabric: F(139/28) L(96/15). Dynamic recrystallization of quartz grains by combined subgrain rotation and grain boundary migration is indicative for temperatures of ca. 400–500 °C. Outcrop coordinates: 46°23′58″ N, 15°28′34″ E. **b–c** — Photomicrographs of garnet micaschist with the assemblage Grt+Ky+Ms+Bt+Qtz. F(137/25) L(88/14). Outcrop coordinates: 46°24′53″ N, 15°33′19″ E. b — Shear bands (e.g. in the upper right corner) and sheared micas indicate a dextral, top-to-the-W shear sense. c — Mica fish indicating a dextral, top-to-the-W shear sense.

brittle conditions. There are also pegmatites that appear as strongly sheared lenses of some decimeters length within biotite gneisses. The aplites are mostly undeformed.

Deformation structures

The metamorphic rocks generally display a strong and penetrative foliation, with the exception of most of the eclogites, some amphibolites, and the serpentinites. Microstructures related to the foliation record amphibolite- to upper-greenschist-facies conditions, as indicated by grain-boundary migration deformation in quartz layers (Fig. 6a) and dynamic recrystallization of plagioclase. In contrast, the foliation in the eclogites formed under eclogite-facies conditions and is typically discordant to the younger, amphibolite-facies foliation of the host rocks (Fig. 4b). Apart from this, the foliation of the metamorphic rocks dips at a shallow to moderate angle to the south-southwest, or less frequently to the southeast (Fig. 7a).

The magmatic rocks of the Pohorje Pluton are in many places foliated as well. This foliation is generally weaker than that in the metamorphic rocks. The orientation of the foliation is similar to that in the metamorphic rocks but more scattered (Fig. 7b). The foliation in the pluton formed under greenschist-facies conditions (Fodor et al. 2008). In the Bistrica dell in the area between cross-sections 1 and 2, foliations in the granodiorite dip at angles of 12°–37° to the SW and S whereas stretching lineations mostly dip SE at angles of

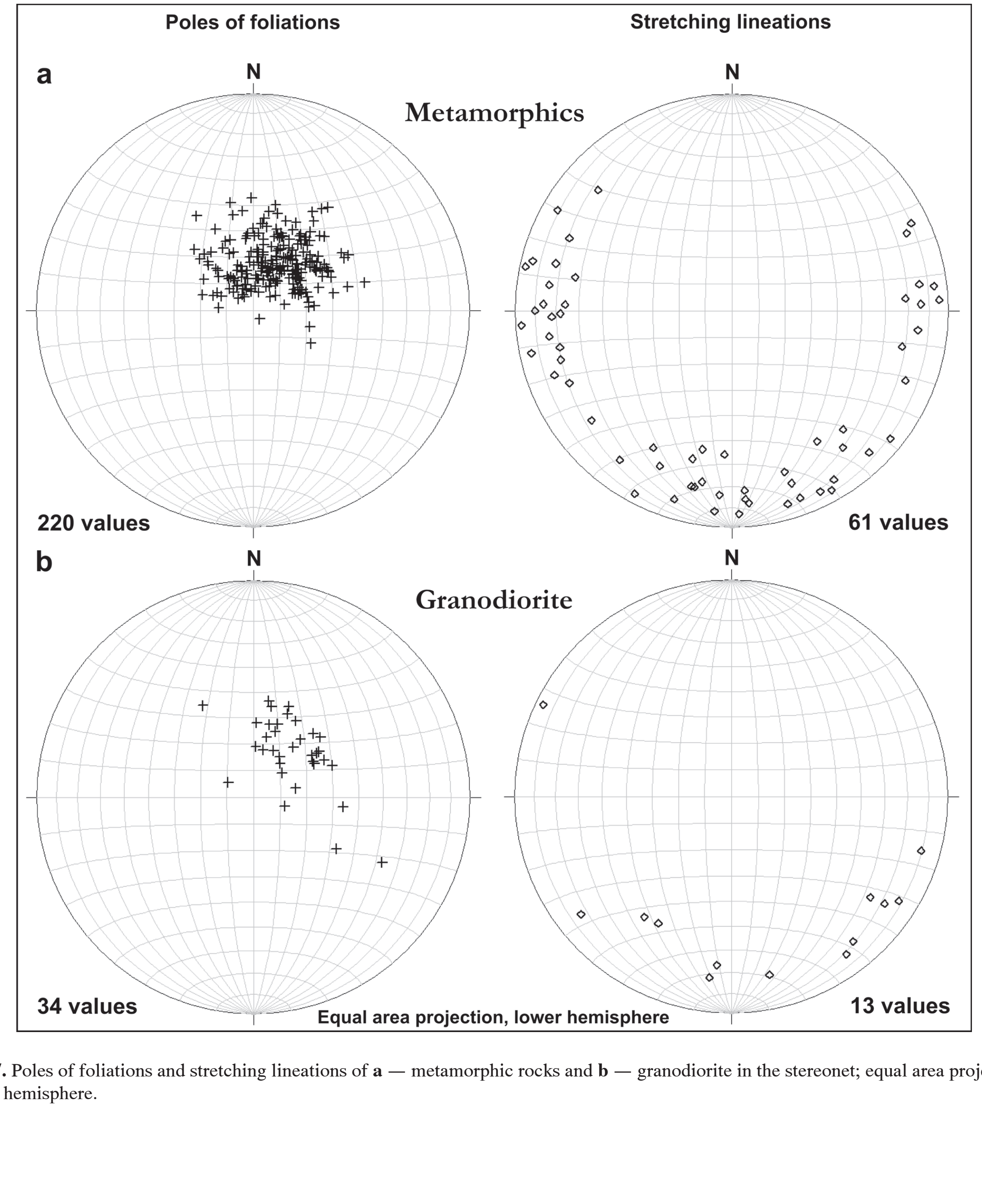

Fig. 7. Poles of foliations and stretching lineations of **a** — metamorphic rocks and **b** — granodiorite in the stereonet; equal area projection, lower hemisphere.

10°–22°; the shear-sense criteria show a top-to-the-SE sense of shearing.

The stretching lineation in the metamorphic rocks shows irregular orientation within the foliation (Fig. 7). Samples with E-W-striking lineation often show a top-to-the-E shear sense (Fig. 6a) but the opposite is observed as well (Fig. 6b and c). We were unable to assign a distinct direction of the lineation to some particular stage of the tectonic evolution. This is probably due to a polyphase deformation history with several shearing events and different shear directions which reoriented older lineations. Miocene (post-intrusive) stretching lineations in the magmatic rocks of the Pohorje Pluton are also variably oriented but rather weakly developed.

Outcrop-scale folds occur only rarely. Some folded pegmatite dykes can be observed; their axial planes are parallel to the foliation of the metamorphic rocks. For example, Fig. 5b shows an isoclinally folded pegmatite with S-dipping axial plane subparallel to the foliation of the surrounding amphibolite. Fig. 5c shows a pegmatite in gneiss which was sheared under brittle conditions, displaying top-to-the-E sense of shear as a result of Miocene extension. The presence of large-scale, tight folds along the northern border of the SBUC is inferred from structural field relations as desribed below.

Relations between the pluton and the metamorphic rocks

The contacts between the pluton and its metamorphic country rocks are in general roughly parallel to the foliation of the pluton and the country rocks. Both the northeastern and the southwestern contacts dip southwest to south at moderate angles. Therefore, the granodiorite body in the investigated area displays a tabular shape dipping towards the southwest, strongly thinning towards the east and finally wedging out. As mentioned above, Al-in-hornblende barometry indicates that the depth of the granitoid intrusion increases from the northwest to the southeast. Accordingly, the "tail" of the pluton is the deepest exposed part of the intrusion. Since the foliation in the pluton is much weaker than in the country rocks and the contacts are sub-parallel to the foliation, it appears that in the study area the rising melt roughly followed the pre-existing foliation of the metamorphic rocks. According to the map of Mioč & Žnidarčič (1977), north of the investigated area the gneissic country rocks are folded into a large, approximately E-W trending open antiform, which we refer to as the Pohorje Antiform in the following. The trace of this antiform is in the gneisses but towards the west it enters the pluton. West of this point, the pluton appears as the core of the antiform; its northern contact is dipping to the north and its southern contact to the south, in both cases approximately parallel to the foliation of the country rocks. This indicates that the Pohorje Antiform was formed at least partly after the intrusion of the pluton and therefore must be of Neogene age (see also Fodor et al. 2003). Further northwest the pluton becomes discordant, cutting the foliation of the metamorphic rocks (according to the map of Mioč & Žnidarčič 1977) and also the Cretaceous low-angle normal fault at the base of the Upper Austroalpine. The Pohorje Antiform may be interpreted as a large-scale antiformal corrugation resulting from the contemporaneous E-W extension and N-S shortening (Fodor et al. 2003), like the ones observed in the footwall of the Simplon Line in the western Central Alps (Mancktelow & Pavlis 1994).

Relations between the SBUC and the surrounding rocks

Although the main part of the SBUC is formed by ultramafic rocks, several lenses of eclogite occur within it. In addition to these internal eclogite lenses, the three largest bodies of mafic rocks are in direct contact with the serpentinite (Fig. 2). One of these is located at the western end of the SBUC associated with the garnet peridotites. The other two are located on the northern boundary of the SBUC and extend northwards into the gneisses. The amphibolitized parts of eclogites are mostly in contact with the gneisses whereas well preserved eclogites are mostly in contact with the serpentinite, within the SBUC. Therefore we assume that amphibolitization of eclogites was facilitated by deformation focused along the contact between eclogites and gneisses. The ultramafic rocks were serpentinized after amphibolite-facies overprint and after regional ductile deformation, possibly during the intrusion of the Pohorje Pluton.

Along the southwestern border of the SBUC, the gneisses show a S- to SW-dipping foliation and must be structurally above the SBUC. Along the northern border the foliation of the gneisses is generally dipping to the south which indicates that the gneisses are structurally below the SBUC. Therefore, the SBUC occupies the core of a tight antiform with a south-dipping axial plane, which is termed the Slovenska Bistrica Antiform in the following. Locally, however, the outcrops along the northern border of the SBUC show that eclogites and amphibolites of the SBUC lie below the gneisses. Therefore, we assume that the northern contact is folded and that the

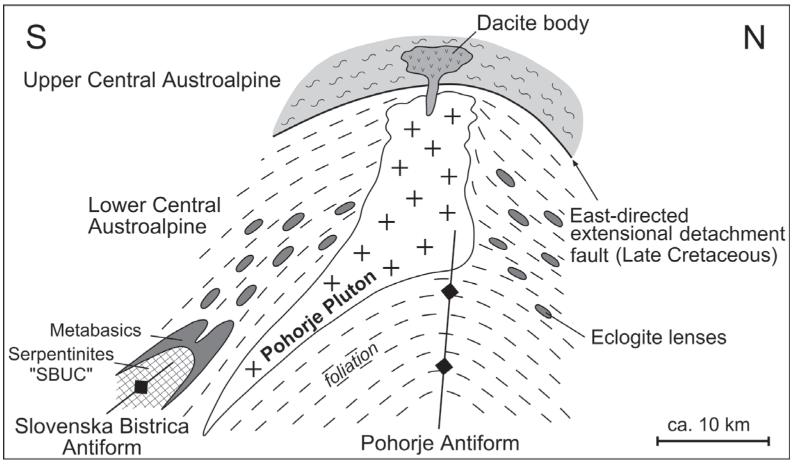

Fig. 8. Sketch of the structural relations in the Pohorje Mountains.

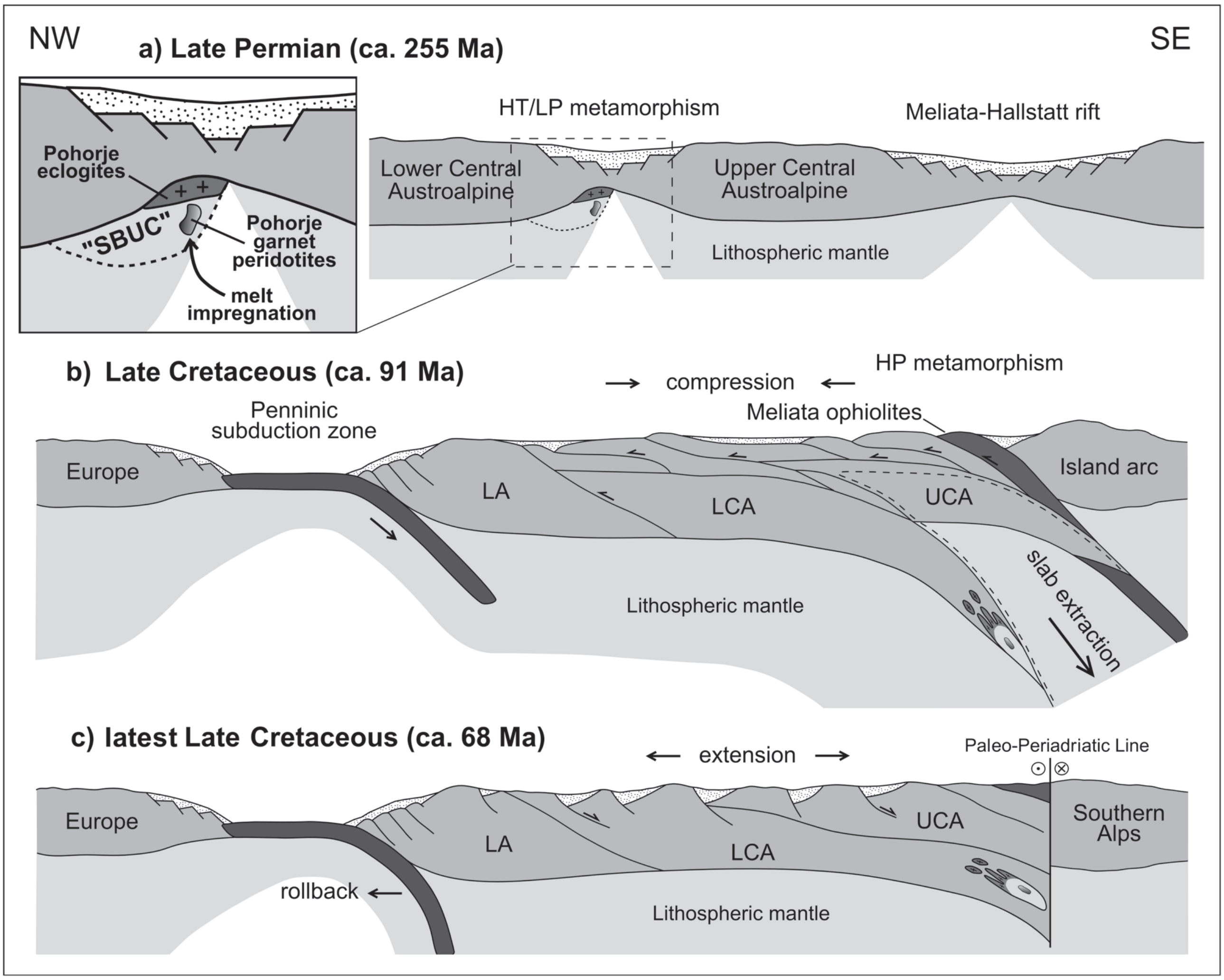

Fig. 9. Tectonic scenario for the evolution of the Austroalpine units. **a** — Late Permian: Development of a rift between the Lower Central Austroalpine (LCA) and the Upper Central Austroalpine (UCA); HT/LP metamorphism of basement rocks; emplacement of gabbroic bodies at the base of continental crust; refertilization of depleted mantle rocks (SBUC) by melt impregnation. **b** — Late Cretaceous: Intracontinental subduction of LCA under UCA; (U)HP metamorphism of LCA units; extraction of the UCA lower crustal and mantle wedge; sketch modified after Janák et al. (2006). **c** — Latest Late Cretaceous: Exhumation of HP-rocks to lower/mid-crustal levels as a result of slab extraction and extension within the Austroalpine units due to rollback of the Penninic subduction zone. The island arc in the SE has been replaced by the Southern Alps due to sinistral strike-slip movement along the Paleo-Periadriatic Line.

"fingers" of mafic rocks which extend northwards into the gneisses partly represent fold cores. The map-scale geometry suggests that the fold axes trend east-west (Fig. 2).

The foliation in the gneisses at the western border of the map area dips uniformly towards the south to southwest at moderate to low angles, although the axial trace of the Slovenska Bistrica Antiform projects into this area. From this we conclude that the foliation of the gneisses is not deformed by the antiform but represents its axial planar foliation (Fig. 8). This foliation formed under amphibolite- to upper greenschist-facies conditions, at least during the late stages of its development which may have started under eclogite-facies conditions. Consequently, the same is true for the Slovenska Bistrica Antiform. In contrast, the Pohorje Antiform is folding the foliation of gneisses (Fig. 8) and therefore the Slovenska Bistrica Antiform is older than the Pohorje Antiform.

Discussion

The field relations suggest that the SBUC forms the core of the Slovenska Bistrica Antiform. This antiform is mantled by the gneiss-dominated series. The highest pressures of the Cretaceous metamorphism in eclogites (~3.0 GPa according to Janák et al. 2004) were determined from the vicinity of the SBUC. Even higher pressures of 4.0 GPa are recorded by the garnet peridotites from the core of the Slovenska Bistrica Antiform. Therefore, we assume that the Slovenska Bistrica Antiform developed during the exhumation of the deeply subducted rocks and accommodated some part of this exhumation, possibly in the way of an upward-directed channel flow (see Janák et al. 2009; Fig. 13c) accompanying slab extraction (Froitzheim et al. 2003; see also Roffeis et al. 2008 for the Koralpe) as the major exhumation mechanism (Fig. 9b).

Unfolding of the Slovenska Bistrica Antiform leads to the following tectonostratigraphy: (1) at the base, the ultramafic rocks of the SBUC, with internal eclogite lenses; (2) above, relatively large eclogite bodies which are partly connected with the internal eclogites of the SBUC; and (3) at the top, mixed gneisses, schists and marble with smaller eclogite lenses. Such a tectonostratigraphy resembles the one observed in former crust-mantle boundary complexes like the Ivrea Zone in the Western Alps. There, peridotites of the uppermost mantle (e.g. at the localities Finero and Balmuccia) are closely associated with gabbroic bodies and are overlain by various gneisses interlayered with marbles and metabasic rocks. All of these were affected by Permian-age HT-LP metamorphism (Handy et al. 1999). As mentioned above, HT-LP metamorphism is indicated for the metapelites in the study area by the presence of Permian to Triassic metamorphic zircon cores (Janák et al. 2009). In contrast to the Ivrea Zone, such a crust-mantle boundary assemblage in Pohorje may have been subducted, metamorphosed under (U)HP conditions, and exhumed (Fig. 9). In this interpretation, the association of ultramafic (serpentinites, garnet peridotites) and mafic (eclogites, amphibolites) rocks in the SBUC would be a primary feature, in the way that the uppermost mantle was invaded, probably in the course of Permian rifting, by mafic melts generated at a deeper level of the mantle. Impregnation by such melts could also explain the refertilization of the ultramafic rocks, in particular the garnet peridotites, as indicated by their major and trace element composition (Janák et al. 2006; De Hoog et al. 2009; see also Müntener et al. 2004).

Although the above presented scenario for crustal emplacement of the SBUC seems to be the most likely, there are also some difficulties with this model. A Permian age of the gabbroic precursors of the eclogites has not been determined in Pohorje, only the Cretaceous age of metamorphism (Miller et al. 2005; Thöni et al. 2008). The chemical composition of eclogites shows an oceanic affinity (Hinterlechner-Ravnik 1982) and N-MORB characteristics (Sassi et al. 2004) and serpentinites show a high degree of melt depletion which is more typical for an oceanic than a subcontinental lithospheric mantle origin (De Hoog et al. 2009). There is no evidence on the *P-T* conditions of the Permian metamorphism and initial stage of Cretaceous subduction in Pohorje; these are obscured by the HP-UHP metamorphism. Janák et al. (2006) showed that garnet exsolution from clinopyroxene in peridotite occurred under *P-T* conditions of 2.5 GPa and 700–750 °C, before subduction culminated at 4 GPa and 900 °C. They proposed that the exsolution process may correspond to the incorporation of a high-temperature peridotite into a subducting crust. Experiments show that garnet exsolution from clinopyroxene is essentially a consequence of cooling (Harte & Gurney 1975) and therefore unlikely to occur at rising temperature. Further study is therefore needed to resolve these problems.

Conclusions

The extent of the SBUC has been revised clarifying that the occurrence of garnet peridotites is restricted to localities within the body of serpentinized ultramafics. The serpentinites are closely associated with large eclogite bodies which we interpret as former metagabbros underplated during the Permian rifting. This coherent ultramafic/mafic body is interpreted as being derived from near-MOHO uppermost mantle and subducted with continental crust *en bloc* to (U)HP depth during the Cretaceous orogeny. Following the (U)HP metamorphism, the SBUC was folded together with the overlying gneiss-dominated series during exhumation and emplaced in the core of the tight to isoclinal, northward closing Slovenska Bistrica Antiform. Later in the Miocene the Pohorje Pluton intruded and finally, probably in the Neogene, the gneissic series together with the pluton were deformed into the upright Pohorje Antiform. This structure, resembling a metamorphic core complex, resulted from E-W extension and contemporaneous N-S shortening.

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