Tholeiitic- and boninite-series metabasites of the Nové Město Unit and northern part of the Zábřeh Unit (Orlica–Śnieżnik Dome, Bohemian Massif): petrogenesis and tectonic significance

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Abstract

The Nové Město Unit and the northern part of the Zábřeh Unit comprise back-arc basin mafic rocks metamorphosed during Variscan times. In both units, nearly identical metabasites comprise variously enriched tholeiites (from N-MORB to transitional E-MORB-OIB), high-Ca, low-silica boninites and low-Ti tholeiites. The tholeiites (Ti/V: 22–58, ϵNd_{540} : +7.6 to –4.7) represent 10–15% melting at ca. 30–60 km and temperatures of 1380–1230 °C of a depleted MORB mantle-type (DMM) wedge heterogeneously modified shortly before fusion by OIB-like melts (enriched mantle possibly of EM1–EM2 type) presumably derived from decompression melting of upwelling asthenosphere. Much less common meta-boninites (Ti/V: 6–23, ϵNd_{540} : +6.7 to –2.9) formed by 15–25% re-melting of residual mantle (DMM after ~15% melt extraction) at depths of 40–65 km and temperatures of ~1420–1300 °C. Scarce low-Ti meta-tholeiites (Ti/V: 18–19, ϵNd_{540} : +7.1) resulted from <10% melting of an unenriched DMM-type source or re-melting of residual mantle (after <15% of former melting). Trace elements and Nd isotope compositions imply random fluxing of tholeiitic- and boninitic magma sources by components released from a subducted slab. The metasomatic enrichment (Th, LREE–MREE) was induced not only by sediment-derived melts but also by fluids supplied by subducted sediments or juvenile crust. The Nové Město–Zábřeh association of metabasites points to an easterly prolongation (in present-day coordinates) of the Cadomian subduction system of the Teplá–Barrandian. Boninite-type magmatism and OIB-like input into mantle beneath an extensional back-arc basin suggest an upflow of hot asthenosphere through subducted ridge (slab window) followed by a cessation of subduction zone activity.

Keywords Tholeiites · Boninites · Trace elements · Nd isotopes · Back-arc basin · Orlica–Śnieżnik dome

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Introduction

The association of tholeiites and boninites commonly occurs in many subduction-related ophiolites, in orogenic sutures delineating ancient subduction-accretion belts at active continental margins, and in fore-arc domains, e.g., the Izu–Bonin–Mariana system (e.g., Bédard 1999; König et al. 2010; Dilek and Furnes 2014). The internal relationships and transitions between the rock types occurring in the Izu–Bonin–Mariana system (MORB-type basalts, low-Ti island arc tholeiites, boninites, calc-alkaline magmas, etc.) has resulted in chemostratigraphic models which emphasize boninitic melt generation concurrent with subduction initiation (e.g., Ishizuka et al. 2006; Diley and Thy 2009; Reagan et al. 2017). However, there are also reports of boninite–tholeiite suites formed at later periods of supra-subduction zone activity (Woelkl et al. 2018) and in back-arc domains (Xia et al. 2012; Hajná et al. 2013). Specifically, it

Fig. 1 Geological sketch map of **a** the Nové Město Unit (NMU; after Mazur et al. 2005) and **b** the Zábřeh Unit (ZU; after Buriánek et al. 2003). The inset shows the location of the units within the Sudetes and the Bohemian Massif (after Mazur et al. 2005)

has been proposed that the appearance of a variegated rock assemblage including boninites, MORB-type and arc tholeiites and alkaline OIB-type basalts is linked to cessation of subduction zone activity due to collision of an active divergent ridge with the trench followed by the opening of a slab window. (e.g., Thorkelson 1996; König et al. 2010; Hajná et al. 2018; Windley and Xiao 2018). Furthermore, the rare boninites are particularly interesting as they are believed to originate from the extremely depleted, refractory portion of the mantle wedge fluxed by copious melts and fluids released from the subducted slab (e.g., Hickey and Frey 1982). Consequently, they primarily reflect the nature of the slab components, their elemental abundances and migration through the mantle wedge (e.g., Crawford et al. 1989; Plank 2005; König et al. 2010). The accompanying tholeiitic magmas are frequently derived from fertile sources and their geochemical features are to great extent controlled by contributions from the mantle wedge. Thus, boninites and associated rocks offer valuable insights into the supra-subduction zone environment; they are highly effective markers of the magmatic- and tectonic processes taking place in arc systems at convergent margins.

Our current study focuses on the Nové Město and Zábřeh Units forming the metavolcano-sedimentary envelope around the core of the Orlica–Śnieżnik Dome (Fig. 1c) where ca. 500 Ma orthogneisses are intercalated with the 530–560 Ma volcano-sedimentary succession (Chopin et al. 2012). Recent geochemical studies have shown that the core has Saxothuringian affinities (Mazur et al. 2012, 2015; Szczepański and Ilnicki 2014) and comprises metabasites that formed during the transition from the Cadomian back-arc basin environment to incipient Early Palaeozoic rifting (Ilnicki et al. 2013). They argued that these magmatic episodes were linked to the cessation of supra-subduction zone activity triggered by ridge–trench collision, opening of a slab window and upwelling of sub-slab asthenosphere. In contrast, much less is known about the envelope. Though rifting- or back-arc basin settings for the metabasic rocks of the Nové Město have been proposed (Opletal et al. 1990; Floyd et al. 1996; Ilnicki 2013), the Zábřeh Unit metabasites lack any comprehensive investigation. Thus, new bulk-rock geochemical- and Nd isotopic data for metabasites in the northern part of the Zábřeh Unit that augment the extended dataset of Ilnicki (2013) are presented here. The geochemical features of these rocks show them to be tholeiites, low-Ti tholeiites and boninites. The latter are reported for the first time from the envelope of the Orlica–Śnieżnik Dome. The results are discussed below in terms of subduction

zone input and mantle source characteristics. Based on geochemical modeling, a petrogenetic model is proposed which involves a two-stage development of the back-arc domain terminated by the ridge subduction, and a slab window opening and generation of boninitic magma at the end of the subduction zone activity. We also argue that regional correlations unequivocally recognize the Nové Město and Zábřeh Units to be an easterly extension of the Teplá–Barrandian Unit and part of the Cadomian active margin located between the Davle arc complex and the Gondwana mainland (see Hajná et al. 2018).

Geologic setting

The Sudetes expose a Neoproterozoic volcano-sedimentary succession and metamorphosed Cambro-Ordovician granites that are interpreted to represent various crustal domains. From NW to SE, these rocks belong to the Saxothuringian Domain, including low- to medium-grade complexes of the Izera–Karkonosze Complex and the Orlica–Śnieżnik Dome and the Brunovistulian domain embodying the East Sudetes (Fig. 1; e.g., Mazur et al. 2010, 2012, 2015; Szczepański and Ilnicki 2014). However, rock successions that mantle the Orlica–Śnieżnik Dome on the west and south have been considered to represent fragments of the Teplá–Barrandian Domain (Cháb et al. 1995; Mazur et al. 2005). These comprise low- to medium-grade volcano-sedimentary successions in the Nové Město Unit in the west and the Zábřeh Unit in the south (Fig. 1). To the west, the Orlica–Śnieżnik Dome is rimmed by a low-grade NE–SW to NNW–SSE trending belt comprising metapelites and basic- and acid metavolcanics of the Nové Město Unit of inferred Neoproterozoic age (e.g., Buriánek et al. 2003). This succession is intruded by Carboniferous granodiorites and tonalites (Bachliński and Hałas 2002). The southern part of the Orlica–Śnieżnik Dome is bordered by the Zábřeh Unit including WNW–ESE belts of a metamorphosed, low- to medium-grade volcano-sedimentary succession (Verner et al. 2009). The whole succession in the Zábřeh Unit comprises, in the north, amphibolites, paragneisses and calc-silicate schists intruded by granitoid sheets which, in the south, pass into metapelites, phyllites and acid metavolcanic rocks (Buriánek et al. 2003; Verner et al. 2009).

The metabasalts in the Nové Město Unit have been described as varying from WPB- to MORB-like tholeiites showing various degrees of crustal contamination (Floyd et al. 1996). The latter feature enabled the conclusion that the metabasalts are representative of an early phase of the early Palaeozoic fragmentation of Gondwana when oceanic crust had not fully developed (Floyd et al. 1996). However, recently published data have shown that metabasalts of the Nové Město Unit grade from E-MORB and N-MORB to

OIB types that originated in a back-arc basin (Ilnicki 2013). This accords with a recent interpretation of the metabasalts in the western part of the Orlica–Śnieżnik Dome (Ilnicki et al. 2013). Limited geochemical data for amphibolites in the Zábřeh Unit point to MORB-type metabasalts in the northern part of the unit grading to WP-type metabasalts in the southern part (Melichar and Hanžl 1997).

Protolith ages for the rocks in both the Nové Město and the Zábřeh Units are unknown. However, their lithological compositions are believed to correspond to those of the Teplá–Barrandian Domain (e.g., Mísař and Dudek 1993; Buriánek et al. 2003). This domain is a crustal segment located between the Saxothuringian to the NE and the Moldanubian domains to the SW. Its Neoproterozoic basement is commonly interpreted to be a fragment of the Avalonian–Cadomian belt developed along the northern active margin of Gondwana during the late Neoproterozoic to earliest Cambrian (e.g., Nance et al. 2010). In general, the Neoproterozoic volcano-sedimentary succession in the Teplá–Barrandian Domain is believed to represent, from NW to SE, remnants of a metaophiolitic complex (Mariánské Lázně Complex), an accretionary wedge (Blovicé Formation), a volcanic arc (Davle Formation) and intra-arc and back-arc basins (Štěchovice Group and Svrcnice Formation; e.g., Sláma et al. 2008; Hajná et al. 2018). Geochemically, the basaltic blocks in this melange are moderately LREE-enriched within-plate basalts and basalts generated in an intraoceanic, suprasubduction zone to back-arc basin setting (Pin and Waldhausrová 2007). The Davle Group includes low-Ti tholeiitic basalts with an island arc signature, rare boninites, calc-alkaline andesites, dacites and Na-rhyolites. The ages of the successions in this volcanic complex range from 610 ± 17 to 563 ± 7 Ma (Sláma et al. 2008; Hajná et al. 2018). The overlying Štěchovice Group comprises siliciclastics with rare rhyolitic pebbles of felsic volcanic rocks and granites. Detrital zircons in these rocks reveal maximum depositional ages of 580 Ma (Hajná et al. 2018).

Analytical methods

The study is based on 102 samples from the Nové Město Unit and 16 samples from the northern part of the Zábřeh Unit. A set of 37 samples (29 from the Nové Město Unit and 8 from the Zábřeh Unit; Fig. 1) selected for major- and trace element analysis includes all the main lithologies in both units. These samples show minimal retrogression alteration. They were cut with a diamond saw to remove secondary veins and weathered surfaces, washed, crushed in a steel jaw-crusher and powdered in an agate ball mill. The whole-rock major- and trace element concentrations were determined at the laboratories of Acme Ltd, Vancouver,

Canada. The powdered samples were fused with lithium metaborate, digested in dilute nitric acid and analyzed on a Perkin-Elmer Elan 9000 ICP-mass spectrometer. The results are in Table S1.

Whole-rock Sm–Nd isotope data were measured by thermal ionization mass spectrometry (TIMS) at the CNRS Laboratories in Clermont-Ferrand and Nîmes (France). A total of 17 samples represent all types of metabasites (12 meta-tholeiites, 2 low-Ti meta-tholeiites and 3 meta-boninites). The rock powders were decomposed by fusion in an induction furnace with a lithium metaborate flux following the procedure of LeFèvre and Pin (2005). A combination of cation-exchange and extraction chromatography techniques, adapted from those detailed by Pin and Santos Zalduegui (1997), was used to separate Sm and Nd from matrix elements and from each other. Concentrations of Sm were determined by isotope dilution with a ^{149}Sm -enriched tracer and an upgraded VG54E mass spectrometer (Clermont-Ferrand). Concentrations of Nd, and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios, were measured with a ^{150}Nd -enriched tracer and a Triton TI spectrometer (GIS Laboratory, Nîmes) with normalization to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. The JNdi-1 standard (Japanese Geological Survey) gave a value of $^{143}\text{Nd}/^{144}\text{Nd} = 0.512101 \pm 4$ (2 standard error). A batch of samples was analyzed using MC-ICP-MS instead of TIMS. In brief, values of $^{143}\text{Nd}/^{144}\text{Nd}$ were measured from a purified Nd fraction with a Neptune Plus instrument using standard static multi-collection methods with mass bias correction by normalization to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$, and are given relative to $^{143}\text{Nd}/^{144}\text{Nd} = 0.512115$ for the JNdi-1 isotope reference. On an aliquot of the LREE fraction separated from major- and other trace elements using a TRU Spec extraction chromatographic column, $^{147}\text{Sm}/^{144}\text{Nd}$ values were deduced from measured $^{147}\text{Sm}/^{146}\text{Nd}$ values following a procedure adapted from Pin et al. (1995) and Sanchez et al. (2012). The results are in Table S2.

Results

Petrographic outline

The investigated metabasalts are mostly amphibolites and greenstones. The latter are preserved in the western part of the Nové Město Unit and indicate an increase in metamorphic grade towards the core of the Orlica–Śnieżnik Dome. In the Zábřeh Unit, all the collected metabasalts are amphibolites.

The metabasalts of the Nové Město Unit are medium- to coarse-grained and comprise mostly amphibole, plagioclase, chlorite, epidote and subordinate quartz, sphene or ilmenite, rare garnet porphyroblasts and calcite. These rocks range from undeformed and massive to strongly deformed with

a pronounced foliation. Primary textures preserved in less deformed varieties indicate protoliths of porphyritic basalts with subordinate dolerites and gabbros.

The metabasites of the Zábřeh Unit are medium- to coarse-grained mostly finely laminated rocks. Some contain amphibole porphyroblasts. The most typical mineral assemblage comprises amphibole, plagioclase, epidote and subordinate quartz, sphene or ilmenite, and occasional calcite. Several samples contain fine-grained pyroxene blasts as laminae or thin lenses elongated parallel to the lamination. Though they may represent original magmatic grains recrystallized, the textures suggest that the pyroxene grains are metamorphic.

Geochemical characteristics

Metabasites of the Nové Město Unit

The Nové Město metabasites are characterized by a narrow range (46.2–52.9 wt%) of SiO_2 typical of basaltic compositions and by fairly variable contents of TiO_2 (0.3–3.9 wt%), MgO (3.6–11.5 wt%), $\text{Fe}_2\text{O}_3^{\text{tot}}$ (7.2–14.9 wt%) and P_2O_5 (< 0.5 wt%; Table 1S). Their $\text{Mg\#}$ (molar $100\text{MgO}/(\text{MgO} + \text{FeO})$, assuming $\text{Fe}_2\text{O}_3/\text{FeO} = 0.15$) indicate significant fractionation as the values vary considerably from 75 to 37. Consequently, on Harker diagrams, the rocks show negative correlations of TiO_2 , P_2O_5 and Fe_2O_3 with $\text{Mg\#}$ and less distinct, slightly positive correlations for Al_2O_3 and CaO (Fig. S1). The concentrations of compatible elements (in ppm), i.e., Cr (60–630), Ni (23–162), Co (24–58) and V (194–479) and their variation against incompatible elements (e.g., Y, not shown) suggest fractional crystallization

of mafic minerals (olivine, clinopyroxene and possibly spinel). However, the systematic increase of chondrite-normalized La/Sm vs La concentration (Fig. S2) indicates that the degree of partial melting also controlled the chemical composition of the rocks.

The metabasites are characterized by variable contents of incompatible elements (REE and HFSE) exemplified by the concentration ranges of ΣREE (6–203 ppm) or Zr (12–369 ppm). The compositional diversity of the rocks is conspicuous on the Zr/TiO_2 vs Nb/Y diagram of Winchester and Floyd (1977; Fig. 2a) and is further emphasized by other elemental ratios. The prevailing group of samples plots in the andesite/basalts field and shows subalkaline affinities ($\text{Nb}/\text{Y} = 0.11\text{--}0.33$). These rocks also have moderate Ti/V (22–49), Zr/Nb (15–32), Zr/Y (2.71–5.68), Nb/Yb (1.11–3.21) and La/Nb (0.94–1.38). Furthermore, their REE chondrite-normalized (CN) profiles and primitive mantle-normalized multi-element diagrams (not shown) display, in most cases, variable yet generally mild enrichment of LREE over MREE and HREE. Distinct LREE depletion is less common ($[\text{La}/\text{Sm}]_{\text{CN}} = 0.75\text{--}1.58$; $[\text{La}/\text{Yb}]_{\text{CN}} = 1.02\text{--}2.63$). The resulting REE patterns are flat or mostly show a gentle negative slope at ~ 20 to $60\times$ chondrite for LREE and ~ 12 to $25\times$ chondrite for HREE (Fig. 3). The fractionation of MREE from HREE is rather weak ($[\text{Tb}/\text{Yb}]_{\text{CN}} = 1.20\text{--}1.48$) and denotes a spinel-bearing mantle source free of residual garnet during the melting event. Values of the Eu anomaly range from absent to fairly positive ($\text{Eu}/\text{Eu}^* = 0.98\text{--}1.29$, aver. 1.14 ± 0.12) and, assuming a divalent oxidation state of Eu, suggest that some samples record a significant accumulation of plagioclase in the magma chamber. On the N-MORB-normalized diagrams, a negative Nb anomaly is

Fig. 2 **a**, Zr/TiO_2 vs Nb/Y plot (Winchester and Floyd 1977) and **b** V-Ti diagram (Shervais 1982) for the metabasites analyzed. Symbols: blue—the Nové Město Unit meta-tholeiites, yellow—the Zábřeh Unit meta-tholeiites, green—low-Ti meta-tholeiites, red—meta-boninites

Fig. 3 Chondrite-normalized REE and N-MORB-normalized multi-element patterns for meta-tholeiites from the Nové Město Unit (**a**, **b**) and the Zábřeh Unit (**c**, **d**), and for meta-boninites and low-Ti meta-

tholeiites from both units (**e**, **f**). Profiles for OIB and N-MORB are given for comparison. The normalization chondrite- and N-MORB values are from Sun and McDonough (1989)

common and profiles show moderate enrichment at ~ 2 to $10\times N$ -MORB for the most incompatible elements and ~ 0.7 to $1.2\times N$ -MORB for HREE corresponding to transitional magmas of E-MORB affinity (Fig. 3). Independent of the Nb depletion, the dominant group of rocks has a radiogenic Nd isotope signature (initial ϵNd_{540} values from +2.6 to +5.9) reflecting a depleted mantle source on a time-integrated basis. For sample LKL3, an even more radiogenic isotope composition (ϵNd_{540} : +6.2) couples with a distinct tholeiitic affinity (Nb/Y = 0.05; Fig. 2a) and a close resemblance to N-MORB composition in terms of the incompatible-element patterns (though with negative Nb and P anomalies) and elemental ratios (Table 1S and Fig. 3). Notably, sample SKV4 (ϵNd_{540} = +5.8) shows a remarkably high concentrations of incompatible elements (LREE = $\sim 100\times$ chondrite, HREE = $\sim 40\times$ chondrite), suggesting that this sample represents strongly fractionated melt (Mg# 43; low content of compatible elements: Cr = 130 ppm and Ni = 46 ppm) derived from a depleted mantle source on a secular basis.

A subgroup of samples (KNO2, KNO3) has geochemical features consistent with mildly alkaline-type magmas, enriched relative to E-MORB and akin to within-plate basalts (Table 1S; Figs. 2, 3 and 4). Compared to other Nové Město metabasites, they have the highest Nb/Y (0.54–0.64), Zr/Y (7.52–7.72), Nb/Yb (5.76–6.57; Fig. 5), much higher Ti/V (52–58), the lowest Zr/Nb (12–14) but similar values of Th/Nb (0.09) and La/Nb (0.97–1.08). Their patterns on all normalized incompatible-element diagrams are steep and negative due to pronounced fractionation of LREE over HREE ($[La/Yb]_{CN}$ = 4.45–4.59). Moreover, the value of $[Tb/Yb]_{CN}$ (1.66–1.74) suggests that garnet may have been a residual phase in the mantle source. The rocks also show only a slight depletion in Nb and a modest enrichment in Zr and Hf. However, the mildly radiogenic ϵNd_{540} value (+2.8) of sample KNO3 indicates a mantle source depleted for a long time. The geochemical features of these samples suggest that their source could have experienced relatively recent enrichment by incompatible element-rich components, e.g., alkaline, low-degree partial melts.

Another subgroup (samples LKL7 and SKV15) stands in marked contrast to the rest. Their contents of TiO_2 (0.29–0.46 wt%) and of MgO (9.26–11.50 wt% and Mg# of 71–74) are at the low- and high ends of the data spectrum, respectively (Table 1S; Fig. 4d, e and S1). Their REE and HFSE concentrations are also the lowest amongst the studied, i.e., ΣREE (6–12 ppm), HREE (2–4 ppm), Zr (12–23 ppm), Y (4.3–6.7 ppm) and Nb (0.3 ppm) in sample LKL7 (Nb below the detection limit of 0.2 ppm in SKV15). Accordingly, values of Ti/V (12–23), Zr/Y (2.79–3.43), Nb/Y (0.04), Nb/Yb (0.35) and La/Nb (4.00) are the lowest and those of Zr/Nb (77) and Th/Nb (0.77) the highest in the suite. Cr contents vary widely (90–1390 ppm), but those of Ni (70–113 ppm) are moderate. The REE profiles

show only a slight positive slope in the MREE–HREE segment ($[La/Yb]_{CN}$ = 1.00, $[La/Sm]_{CN}$ = 1.16–1.17, $[Tb/Yb]_{CN}$ = 0.95–1.00) at very low levels relative to chondrite (~ 1 to $5\times$ chondrite; Fig. 3e). The overall strong depletion in incompatible elements is prominent on N-MORB-normalized plots (at ~ 0.11 to $0.39\times N$ -MORB; Fig. 3f) with deep negative Nb anomalies, positive Th and La anomalies and weak positive Zr, Hf, Eu and Ti anomalies evident. Moderate (ϵNd_{540} = +2.9 for LKL7) or strongly radiogenic Nd isotope signatures (ϵNd_{540} = +6.7 for SKV15; Table 2S) imply a depleted mantle source presumably variously affected by a contrasting, non-radiogenic Nd isotope component with a low initial ϵNd and Sm/Nd, e.g., recycled crustal material (e.g., Zindler and Hart 1986; Taylor and McLennan 1995). The low TiO_2 contents, high Mg#, CaO/ Al_2O_3 of 0.8–1.1, Al_2O_3/TiO_2 of 22.4–56.4 and strongly depleted HREE and HFSE concentrations of the subgroup point to a close resemblance to high-Ca boninitic-type basalts (Figs S1 and 4). These particular geochemical features are, to a degree, shared by sample KNO4 (Table 1s; Figs. 3 and 4).

Metabasites of the Zábřeh Unit

The metabasites from the northern part of the Zábřeh Unit display strong geochemical similarities to those of the Nové Město Unit. SiO_2 contents (46.4–54.6 wt%) correspond mainly to those of basalts with high Al_2O_3 (14.6–18.6 wt%) and variable TiO_2 (0.2–2.4 wt%), MgO (4.6–9.4 wt%), $Fe_2O_3^{tot}$ (7.2–13.3 wt%) and P_2O_5 (<0.4 wt%). The range of Mg# (74–45) and the trends on Harker diagrams (Fig. S1) coupled with the concentrations of compatible elements (e.g., Cr 80–400 ppm and Ni 47–274 ppm) could be attributed to fractionation of predominantly olivine and clinopyroxene ($\pm$ spinel). However, these features might also reflect increasing degrees of partial melting as signaled by the positive trend between $[La/Sm]_{CN}$ and La (Fig. S2).

Incompatible trace-element concentrations and their ratios reveal a substantial compositional diversity of the Zábřeh metabasites matching that seen in the Nové Město Unit (Table 1S; Figs. 2, 3, 4, 5 and S1–S3). Values of Nb/Y (0.04–0.71) and their position on the classification diagram (Fig. 2) denote a prevailing tholeiitic basalt affinity with a subgroup of transitional mildly alkaline rocks (samples ZBH2, ZBH6). The chondrite- (Fig. 3c) and primitive mantle-normalized (not shown) diagrams show profiles sloping from positive ($[La/Yb]_{CN}$ = 4.60–6.14 and $[La/Sm]_{CN}$ = 1.75–2.15 for mildly alkaline rocks) to slightly negative ($[La/Yb]_{CN}$ = 1.08–1.18 and $[La/Sm]_{CN}$ = 0.80–0.96 for tholeiitic rocks) due to variable degrees of enrichment of LREE over MREE–HREE. A weak fractionation of MREE to HREE ($[Tb/Yb]_{CN}$ = 1.16–1.66) is indicative of spinel-bearing peridotite-facies mantle, i.e., a mantle source devoid of residual garnet; only a higher $[Tb/Yb]_{CN}$ (1.80–1.81) for

Fig. 4 Discriminant diagrams for the metabasites of the Nové Město and Zábřeh Units. **a** Nb–Zr–Y (Meschede 1986). **b** Hf–Th–Nb (Wood 1980). **c** Y–La–Nb (Cabanis and Lecolle 1989). **d** Zr/Hf vs Ti (boninite and low-Ti IAT fields after Escuder-Viruete et al. 2011). **e** Al_2O_3/TiO_2 vs TiO_2 (Hickey and Frey 1982). **f** Cr vs Y (Dilek et al. 2007). **g** Zr vs Ti (Dilek and Furnes 2009). **h** Th_N vs Nb_N and **i** Yb_N vs Dy_N (Saccani 2015); subscript N stands for composition normalized to N-MORB (values from Sun and McDonough 1989). *Alk-WPB* alka-

line within-plate basalts, *CAB* calc-alkaline basalts, *CB* continental flood basalts, *CRAB* continental rift alkaline basalts, *E-MORB* enriched MORB, *IAB* island arc basalts, *IAT* island arc tholeiites, *N-MORB* normal MORB, *OIB* ocean island basalts, *P-MORB* plume MORB, *VAT* volcanic arc tholeiites, *VAB* volcanic arc basalts, *WPB* within-plate basalts, *WPT* within-plate tholeiites, *Th-WPB* tholeiitic within-plate basalts. Symbols as in Fig. 2

mildly alkaline metabasites may imply a garnet-bearing source. An evident positive Eu anomaly ($Eu/Eu^* 1.04$ – 1.12 , aver. 1.09 ± 0.03) attests to some minor plagioclase accumulation in the fractionated mineral assemblage. The Zábřeh

metabasites display considerable variation in depletion in Nb relative to La and Th ($Th/Nb = 0.07$ – 0.12 up to 0.30 , even 0.51). On the N-MORB-normalized plots (Fig. 3d), these rocks mostly display patterns transitional between

Fig. 5 **a** Th/Yb versus Nb/Yb diagram (Pearce and Peate 1995). Heavy diagonal lines of constant Th/Nb denote the array of basalts from non-subduction settings derived from enriched- (e.g., OIB) or depleted mantle (e.g., MORB) sources. The plot shows assimilation-fractional crystallisation trajectories (AFC, De Paolo 1981; partition coefficients from compilation of Ersoy and Helvacı 2010) modeled for the least-fractionated samples of the Nové Město (LKL3 – NM) and Zábřeh Units (ZBH13 – ZBH). The mean composition of the Nové Město (NM) phyllites from Maliszewski and Ilnicki (2019). Modal composition of fractionating assemblage calculated using the

program rhyolite-MELTS v.1.0.x, (Gualda et al. 2012; Ghiorso and Gualda 2015) assuming anhydrous conditions, f_{O_2} = QFM at 1 kbar. **b** Nb/Y vs Zr/Y diagram. The $\Delta Nb=0$ line separating enriched (E-MORB, OIB) from depleted (N-MORB, arc-type) sources after Fitton (2007). **c** TiO_2/Yb vs Nb/Yb diagram of Pearce (2008) with OIB (deep melting array) and N-MORB (shallow melting array). Dashed line separates alkaline- (Alk) and tholeiitic (Tho) compositions. The OIB, E-MORB and N-MORB values are from Sun and McDonough (1989). Symbols as in Fig. 2. Further explanation in text

E-MORB and OIB, consistent with their elemental ratios, i.e., $Ti/V = 37\text{--}58$, $Zr/Nb = 10\text{--}33$, $Zr/Y = 3.70\text{--}7.44$, $Nb/Yb = 1.09\text{--}7.57$, $La/Nb = 1.01\text{--}2.14$. The strong- to moderate-radiogenic Nd isotope composition and values of ϵNd_{540} ranging from +7.6 to +1.9 point to the variable involvement of a non-radiogenic, presumably crustal component. Though sample ZBH3 has a strong negative ϵNd_{540} of -4.7 , its trace-element characteristics are intermediate between those of E-MORB and OIB ($[La/Yb]_{CN} = 4.60$, $[La/Sm]_{CN} = 1.68$, with evident Zr–Hf, Ti, Y and Nb negative anomalies).

Like the boninitic-type basalts from the Nové Město Unit, sample ZBH12 is strongly depleted in incompatible elements relative to N-MORB ($LREE = \sim 0.32$ to $0.56 \times N\text{-MORB}$ and $HREE = \sim 0.13$ to $0.17 \times N\text{-MORB}$) and distinct negative Nb, Zr and Ti anomalies (Fig. 3f). Its exceptional composition among the Zábřeh metabasites is manifested by the low TiO_2 content (0.2 wt%), $\Sigma REE = 10$ ppm, $[Tb/Yb]_{CN} = 0.79$ and $Ti/V = 6$ and by the high Mg# (74) reflecting its primitive nature (Figs. b and S1). The Nd isotopic composition is non-radiogenic with an ϵNd_{540} value of -2.9 . Sample ZBH4 with its TiO_2 content (0.56 wt%), Mg# (69), low ΣREE (29 ppm), Ti/V (18), Zr/Nb (68) and Th/Nb (0.30) shows depletion in incompatible elements, but is characterized by higher abundances of LREE at ~ 0.80 to $1.00 \times N\text{-MORB}$ and HREE at ~ 0.63 to $0.70 \times N\text{-MORB}$ (Fig. 3) than sample ZBH12. The time-integrated depletion of its mantle source is documented by a ϵNd_{540} value of +7.1, and a flat N-MORB-normalized profile with evident negative Nb and

Ti anomalies (Fig. 3f) is akin to that of low-Ti tholeiite of island arc affinity (Fig. 4).

Petrogenetic interpretation

The concentrations of major- and trace elements and the inter-elemental relationships outlined above divide the metabasites into two main groups, namely, (1) variably enriched tholeiites and (2) boninite-type metabasalts. These two groups are accompanied by rare low-Ti tholeiites with geochemical characteristics intermediate between the two (Figs. 3 and 4). Moreover, the data clearly show that, in the Nové Město and Zábřeh Units, neither of the two groups show any significant differences in composition. Thus, in the following discussion, the tholeiitic- and boninitic-group rocks from both units will be interpreted jointly and, further on in the text, referred to as the meta-tholeiites and the meta-boninites, respectively.

Metabasites in both units underwent extensive metamorphism up to amphibolite facies conditions at medium pressures (Mazur et al. 2005; Chopin et al. 2012; Ilnicki 2013). Under such conditions, some major elements (Si, Na, K, Ca) and trace elements (Rb, Cs, Sr, Ba, U, Pb) may well have been mobilized. Dispersion of points for some of these elements on Figures S1 and S2, and of LOI values (Table S1), confirm their mobility under post-solidus conditions. In contrast, the presumed immobile REE and HFSE (e.g., Winchester and Floyd 1977; Pearce 2014) show positive and tight trends (Figs S2 and S3) indicating that their original- or

near-original magmatic concentrations have been retained. Hence, the following discussion and petrogenetic interpretation will rely on REE and HFSE in the main.

Effects of crustal contamination

The Nové Město and Zábřeh metabasites were emplaced into a sedimentary series comprising phyllites, metagreywackes and paragneisses. Despite their considerable volume, the mafic magmas could have been subject to contamination. When melts are derived from a depleted mantle source, they may be more susceptible to such (e.g., Pearce 2008). Thus, before any discussion on melt source and generation, the possible influence of contamination will be evaluated. Specifically, contamination by continental crust leads to higher concentrations of Th and to elevated values of Th/Yb (e.g., Wilson 1993) and especially Th/Nb (e.g., Pin and Paquette 1997). Consequently, magma compositions are displaced above the diagonal MORB–OIB mantle array on the Th/Yb vs Nb/Yb plot, especially when subducted crust releases fluids or melts into the mantle (Pearce 2008, 2014). However, the assimilation of crustal rocks produces trends that may be diagonal and oblique to the mantle array, curved and less steep than those stemming from subduction addition alone (see Fig. 5 in Pearce 2008).

The negative Nb, Ti anomalies of the meta-tholeiites (Fig. 3) and the Th/Nb of <0.22 of sample SKV12 or even 0.44 of sample SKV19 imply some crustal contribution to the magmas, as is also suggested by low value of ϵNd_{540} (+3.5) for the latter sample. However, the majority of the meta-tholeiites plot within the diagonal mantle array (Fig. 5a), while their Th/Nb (0.07–0.12) and La/Nb (0.94–1.33) values are confined to a narrow range between and close to N-MORB or OIB values (Th/Nb 0.05 and 0.08; La/Nb 0.77 and 1.07, respectively; Sun and McDonough 1989). The systematics of ϵNd_{540} vs Th/Nb or vs La/Nb (not shown) preclude significant assimilation of crust material. The majority of the meta-tholeiite samples define a tight- and nearly vertical trend more likely consistent with mantle source heterogeneity rather than any substantial involvement of an old crustal component with elevated Th/Nb and low ϵNd (i.e., low secular Sm/Nd; Pin and Waldhausrova 2007). Although some samples plot randomly at various distances from the mantle array and towards higher values Th/Yb on the Th/Yb vs Nb/Yb plot (Fig. 5a), they do not define any coherent trend, either vertical or diagonal. Moreover, they do not follow the curves calculated for assimilation–fractional crystallization (AFC; DePaolo 1981). The AFC model presupposes assimilation of phyllites and metagreywackes of the Nové Město Unit (data from Maliszewski and Ilnicki 2019) by the most primitive Nové Město- (sample LKL13; Mg# = 66; Zr = 90 ppm) and Zábřeh magmas (ZBH13; Mg# = 68; Zr = 132 ppm). For each sample, the modal

composition of the fractionated phases was obtained using the MELTS program (rhyolite-MELTS v.1.0.x; Gualda et al. 2012; Ghiorso and Gualda 2015) for isobaric, low-pressure fractionation at 1 kbar and at temperatures ranging from liquidus down to when <10% liquid remained (Fig. 5a). Regardless of the assumed assimilation/crystallization ratio (i.e., r values of 0.1 and 0.4 for low- and high crustal input, respectively), the calculated trajectories do not account for the dispersion of points on the plots. Even though some samples lie close to the curves, the models suggest either insignificant contamination, i.e., low r values, or unreasonably high values of melt fractionation (~70–80%) that would result in fractionated melts much richer in silica than is seen (Table 1S). Thus, it may be concluded that the degree of contamination by continental crust had little effect on tholeiite-magma compositions. Subduction-related metasomatism seems to offer a better explanation for the geochemical character of the meta-tholeiite protoliths as the meta-boninites and low-Ti meta-tholeiites have particularly elevated Th/Yb implying incorporation of subduction-derived components into their sources.

Subduction-related contribution

Mafic rocks from intra-oceanic settings are less prone to substantial crustal contamination. As discrimination diagrams show (Fig. 4), the rocks studied here have compositional affinities to arc-related basalts or form continuous trends from variably enriched or depleted N-MORB-type tholeiites to island arc tholeiites or to boninites. It is proposed, therefore, that several features observed in the meta-tholeiites and meta-boninites, e.g., enrichment in Th and LREE and depletion in Nb and Ti, point to the significant influence of subduction zone activity. Island arc-related magmas and lavas may record contributions from a variety of subducted material, e.g., fresh- or hydrothermally altered oceanic crust and subducted sediments, affecting their variably enriched or depleted mantle wedge (Hawkesworth et al. 1993, 1997). Thus, the degree of the subduction zone involvement in the meta-tholeiites and meta-boninites merits examination.

The most conspicuous feature of arc magmas is their relative depletion in HFSE, notably Nb and Ta but also Zr, Hf, Ti and Y, coupled with enrichment in LILE and LREE–MREE (e.g., Pearce and Parkinson 1993; Pearce et al. 1995). Studies on incompatible element behavior have shown that Nb, Ta, Zr, Hf, Ti and Y are particularly resistant to mobilization by aqueous fluids released and circulating in supra-subduction zone realms (e.g., Pearce and Peate 1995). In contrast, LILE, Th and REE, particularly LREE, are readily mobilized and may contribute to variously metasomatized potential sources of arc-related magmas (e.g., Brennan et al. 1995). Otherwise, mantle-wedge material would be chemically and isotopically similar to depleted MORB-type mantle, as is

often observed in back-arc basin basalts (Hawkesworth et al. 1993; 1997).

Assessment of subduction input

Based on these assumptions, which comply with the concept of conservative (HFSE, HREE and compatible elements Cr, Ni, Co, V, Sc) and non-conservative (LILE, LREE–MREE) elements of Pearce and Peate (1995), the relative contributions from the subduction zone and from the mantle wedge to the basic magmas may be assessed. Particularly useful in this context is the “baseline approach” of Pearce and Parkinson (1993) which relies on the construction of a line connecting the conservative, mantle-derived elements of an individual sample in the N-MORB-normalized diagrams. With extrapolation and interpolation, the line visualizes the primary mantle composition prior to metasomatic modification, while the area above the baseline reflects the slab contribution of a given element. Differences in the pattern of the baseline for the samples of the studied suite reflect a heterogeneous distribution and input of the subducted slab-derived components (Fig. S4) which, in the meta-tholeiites, varies from barely perceptible (e.g., samples LKL1, LKL13, NHR1, KNO2, KNO3, ZBH6, ZBH13) and weak (e.g., LKL15, SKV1, SKV19, LKL18.1, ZBH2, ZBH10) to obvious (e.g., NHR10, OLE1, LKL3, ZBH3). In the low-Ti meta-tholeiites (ZBH4, KNO4) and in the meta-boninites (LKL7, SKV15, ZBH12), the addition is significant, though varied. Moreover, the bivariate Yb-normalized diagrams (Fig. S6) show that the subduction contribution reaches ~70–90% of the Th, ~50–70% of the La and > ~25% of the Nd. The mantle source was affected by components enriched in LREE ($\pm$ MREE) and LILE (Th), but not HFSE.

Slab-derived melts vs fluids

Subducted slab and overlying sediments are commonly considered principal sources of melts and fluids which, liberated, combine and flux the mantle wedge and enrich it (e.g., Hawkesworth et al. 1993, 1997; Elliott 2003). The composition and specific trace element- and isotopic signatures of a metasomatizing agent depend heavily on its physical state, mantle-wedge conditions and, predominantly, the type of entity that released it (Hawkesworth et al. 1993).

Melts generated from subducted, comparatively young, ensimatic crust, i.e., fresh and sediment-poor, relatively hot MORB-type slab, should retain highly radiogenic Nd signatures. Interacting with the DMM-type mantle, they would not significantly alter its isotopic composition. Hence, melts produced from such sources that reveal significant addition of subduction-derived component in their incompatible-element composition, are deemed to preserve their original, positive ϵ Nd values. In fact, the samples (meta-tholeiites

LKL16 + 4.1, LKL7 + 2.9, ZBH3 – 4.7; meta-boninites LKL7 + 2.9, ZBH12 – 2.9) with a distinct subduction component have lowered- or even negative values of ϵ Nd, implying an input from material less radiogenic than juvenile crust on a time-integrated basis. In contrast, there are also samples (meta-tholeiite LKL3 + 6.2; low-Ti meta-tholeiite ZBH4 + 7.1; meta-boninite SKV15 + 6.7) which display similar degrees of subduction-derived addition to the source as indicated by their baseline layout (Fig. S4), but which have strong radiogenic Nd compositions indicating the influence of melts derived from relatively young MORB-type slab. During fusion of the slab, however, the incompatible elements (REE, HFSE) are likely to fractionate appreciably. Consequently, magmas produced from mantle wedge metasomatized by slab-melt should yield high La/Yb, Nb/Zr and Nb/Y (e.g., Stolz et al. 1996; Hawkesworth et al. 1997). The highly radiogenic signatures of samples LKL3, ZBH4 and SKV15 contrast with their low Nb/Y (< 0.05), Nb/Zr (0.01–0.02), La/Yb (0.69–1.40) and seem to preclude such an addition to their source. An alternative plausible explanation, however, would envisage hydrous fluids released from subducted juvenile crust fluxing the mantle source. Such a process is not likely to significantly disturb the Nd isotopic signatures of essentially DMM-type mantle wedge (e.g., Crawford et al. 1989; Hawkesworth et al. 1993).

The overall positive trend observed in the ϵ Nd₅₄₀ vs $^{147}\text{Sm}/^{144}\text{Nd}$ plot (Fig. 6b) suggests that the prevailing component in the metasomatizing material was less radiogenic, attesting to a predominant role for melts or fluids released from crust-derived sediments. Melts produced at the expense of subducted sediment are much more effective than fluids in extracting LREE and HFSE (e.g., Brennan et al. 1995; Elliott 2003; Johnson and Plank 2000). Moreover, in contrast to DMM (Th 0.0079 ppm, Th/Nd 0.0136; Workman and Hart 2005) subducted sediments are on average enriched in Th (8.1 ppm, Th/Nd 0.29 in global subducting sediment; GLOSS-II, Plank 2014). During melting of the subducted sediments and due to differences in incompatibility, the liquids produced are preferentially enriched in Th relative to Nd or Zr and in La relative to Sm (e.g., Johnson and Plank 2000). Thus, variation in Th/Nd, Th/Zr or Th/Nb vs $[\text{La}/\text{Sm}]_{\text{CN}}$ may serve as useful discriminators of influx into the mantle wedge of melts derived from subducted sediment. These melts are also clearly discerned because hydrous fluids released from the slab usually have lower values of Th/Nd (< 0.15 in fluids compared to > 0.25 in melts; Wolkl et al. 2018). Furthermore, if the subducted sediments are significantly less radiogenic than the DMM (e.g., Zindler and Hart 1986), the trends resulting from the influx of sediment-derived melts into mantle wedge should be negative on ϵ Nd vs Th/Nd or Th/Zr plots. The studied samples have Th/Nd values confined to narrow range of 0.01–0.09 and mostly follow positive- and steep trends on

Fig. 6 Variation diagrams: **a** ϵNd_{540} vs Th/Nd . The Th/Nd values for fluids and melts from Woelkl et al. (2018). **b** ϵNd_{540} vs $^{147}\text{Sm}/^{144}\text{Nd}$. **c** $[\text{La}/\text{Sm}]_{\text{CN}}$ vs Th/Zr . **d** $(\text{Hf}/\text{Sm})_{\text{PM}}$ vs $(\text{Ta}/\text{La})_{\text{PM}}$. Fields after He et al. (2018), N-MORB and OIB data as in Fig. 5. Subscripts PM and CN stand for data normalized to, respectively, primitive mantle and chondrite (values from Sun and McDonough 1989). **e** Ce/Pb vs $\text{La}/$

Nd . Fields after Kumar and Rathna (2008). **f** Th/La vs Sm/La . Mantle array from Plank (2005), global subducting sediment, GLOSS-II from Plank (2014). The two dashed lines are regression lines for samples most marked by sediment-derived input. Symbols as in Fig. 2. Further explanation in text

the $[\text{La}/\text{Sm}]_{\text{CN}}$ vs Th/Zr or ϵNd vs Th/Nd plots (Fig. 6a, c). However, there is a clear horizontal dispersion of the points (Fig. 6a, c) because the meta-boninites (LKL7, ZBH12), the low-Ti meta-tholeiite (KNO4) and some meta-tholeiites (e.g., OLE2, LKL1, LKL4, LKL16, SKV12, SKV19, ZBH8) show higher values of Th/Nd (< 0.14) and Th/Zr (< 0.014). In addition, there is a very good positive correlation between Th/Nd and Th/Zr (not shown). These features all coherently corroborate enrichment of the mantle source with sediment-derived melt. Likewise, variation in $[\text{Hf}/\text{Sm}]_{\text{PM}}$ vs $[\text{Ta}/\text{La}]_{\text{PM}}$ points to melt-induced metasomatism as the data mostly follow a trend (Fig. 6d) consistent with melt effectively extracting HFSE and subsequently fluxing the mantle sources. This conclusion is further supported by some negative correlation between Nd isotope composition and Th/Nd or Th/Zr (Fig. 6a). Such an effect is expected when melt derived from non-radiogenic sediment is added to a DMM-type mantle source (e.g., Woelkl et al. 2018). Nevertheless, some samples suggest that they either lacked such a component or that input was limited, introducing the possibility of hydrous fluids being a further potential source of subduction-driven metasomatic modification of their mantle sources.

Fluid-related metasomatism of mantle sources may be recognized due to the selective ability of hydrous solutions to extract and transport predominantly LILE (Rb, Ba, Sr, Cs, Th, Pb, U, Na, K) and, to a lesser extent, LREE-MREE (La, Ce, Nd, Sm, Eu) while not affecting essentially immobile HFSE (Nb, Ta, Zr, Hf, Ti, Y; e.g., Pearce and Parkinson 1993; Brennan et al. 1995; Peace and Peate 1995). Thus, fluxed portions of mantle, and of arc-related magmas produced from them, will have LILE/REE or LILE/HFSE distinctly higher than mantle metasomatized by sediment melt. Variations in Ba/Th , Sr/Nd , Ce/Pb and Nb/U , especially, serve as very sensitive tracers of aqueous fluid involvement (e.g., Hawkesworth et al. 1997; Elliott 2003). Low Ce/Pb and Nb/U , well below the N-MORB values of ~ 25 and ~ 50 , respectively (Sun and McDonough 1989), commonly signal a substantial addition of Pb and U where mantle wedge is fluxed by components with high water contents (e.g., Escrig et al. 2012). In the rocks studied, values of Nb/U (44.2–1.8) and Ce/Pb (9.1–0.4; Fig. 6e) indicate variable though ubiquitous input of hydrous solutions expelled from the down-going slab. Interestingly, the data from some rocks (e.g., SKV6, SKV17, NHR10, ZBH1, ZBH3) imply that their respective mantle sources were metasomatized solely by fluids while others (e.g., tholeiites LKL16, SKV12, SKV19, ZBH8; low-Ti meta-tholeiite KNO4; meta-boninite ZBH12) reveal input from both sediment melts and fluids. A weak positive correlation between these ratios and Zr/Y suggests an augmented fluid input into more depleted mantle sources. It must be noted, however, that the applicability of LILE-based tracers is limited in metamorphic rocks as LILE are potentially mobile under low-grade metamorphism

(see above). Nevertheless, the tight positive trends on the $[\text{La}/\text{Sm}]_{\text{CN}}$ vs Th/Zr plot (Fig. 6c) and the nearly vertical trend on the ϵNd_{540} vs Th/Nd plot (Fig. 6a) are in line with the inferences drawn from the variations in Ce/Pb or Nb/U . Moreover, the degree of spread of points towards decreasing values of $[\text{Hf}/\text{Sm}]_{\text{PM}}$ on the $[\text{Hf}/\text{Sm}]_{\text{PM}}$ vs $[\text{Ta}/\text{La}]_{\text{PM}}$ plot confirms that mantle wedge sources could have been modified by hydrous fluids (Fig. 6d).

The chemistry of the subducted sediment may be explored using the Th/La vs Sm/La plot (Fig. 6f). The approach assumes that excess Th, and consequently, high Th/La in arc magmas are inherited from subducted sediments which usually have low Sm/La (~ 0.20 , Plank 2014). Mantle-derived basalts (N- and E-MORB, OIB) because of their low Th/La but varied Sm/La reflecting source depletion, plot as a nearly horizontal array (Fig. 6f). Depending on the proportions of sediment and mantle involved, both Th/La and Sm/La from arc basalts create linear mixing trends anchored at bulk-sediment composition and pristine mantle source. The samples of meta-tholeiite and meta-boninite marked by sediment-derived input (as melt or fluid) to their respective sources define two trends which, when unmixed, point to sediment with a Th/La of ~ 0.27 – 0.32 , very close to the value of global subducting sediment, GLOSS-II (0.28; Plank 2014). As argued by Plank (2005), this value may be the same as that of the local trench sediment subsequently recycled into the arc. Additionally, the regressed line intersects the mantle array and indicates melts with Sm/La from 0.7–0.8 to ~ 1.5 . Provided that N-MORB and E-MORB values range from ~ 1.0 to ~ 0.4 , respectively (Sun and McDonough 1989), it may be inferred that the tapped sources for protoliths of both the meta-tholeiites and meta-boninites span the range from slightly enriched- to noticeably depleted mantle (section “Melt sources”).

Melt sources

The activity of a subduction zone affects and to various degrees controls the budget of LREE, MREE and LILE in the mantle sources of mafic arc magmas. This places constraints on incompatible- and compatible trace element-based assessments of mantle sources and melt-generation processes. The trace element- and isotope compositions of the meta-tholeiites and the meta-boninites provide compelling evidence that a proportion of LREE, MREE (and presumably LILE) was extracted in the form of melts or fluids from down-going slab and supplied to their respective mantle sources. In contrast, scrutiny of HREE and HFSE showed that these may be, to a large degree, deemed conservative and, thus, that their abundances can provide important clues concerning mantle-wedge composition prior to subduction-related metasomatism. Several useful indicators based on abundances and proportions of HFSE (e.g., Zr, Ti, Nb, Y)

and HREE (e.g., Tb, Yb) have been devised with reference to arc-related environments. Being insensitive to the degree of fractional crystallization, these proxies (e.g., Nb/Yb, Zr/Y, Zr/Nb, Nb/Y and the ΔNd parameter of Fitton et al. 1997) efficiently fingerprint source heterogeneity (enrichment or depletion), degree of partial melting or alkalinity, depth of melting or input from enriched components (e.g., Ti/Yb; Pearce and Parkinson 1993; Pearce et al. 1995; Fitton et al. 1997; Pearce and Stern 2006; Pearce 2008, 2014). Potential mantle sources, the degree of partial melting and any presence of residual phases (garnet, amphibole) can be evaluated using normalized conservative-element FMM-normalized plots, FMM being fertile MORB mantle, i.e., the global convecting upper mantle reservoir that is the source of N-MORBs (Pearce and Parkinson 1993).

Nové Město and Zábřeh meta-tholeiites

The profiles on multi-element PM- and N-MORB-normalized diagrams (Fig. 3), variation of Zr/Nb and Nb/Y and the distribution of samples within the mantle array on the Th/Yb vs Nb/Yb plot (Fig. 5a), and the spread of data on TiO_2/Yb vs Nb/Yb plots (Fig. 5c), suggest that the meta-tholeiite protoliths were produced from mantle regions showing variable enrichment. The enriching component was not related to subduction activity and must have been heterogeneously distributed within the predominant DMM. Thus, the parental magmas of meta-tholeiites produced from such mantle sources encompass a whole spectrum of geochemical features ranging from transitional between OIB and E-MORB and/or between E-MORB and N-MORB, and N-MORB. The marked heterogeneity of the mantle wedge is further confirmed by the varying slopes of baselines (Fig. S4) and by considerable variations in the ΔNb parameter (Fig. 5b). Fitton et al. (1997) ascribed negative ΔNb values to depleted mantle sources (N-MORB and arc type) and positive values to enriched sources (OIB and E-MORB). The ΔNb (-0.64 to $+0.03$) for the meta-tholeiites reflect the variation in the degree of source enrichment. However, despite the enrichment also indicated by other geochemical parameters (e.g., Zr/Nb, Nb/Y), the values for the meta-tholeiites remain essentially negative. Even the samples with mildly alkaline and the most enriched geochemical characteristics (KNO2, KNO3, ZBH2, ZBH6) have ΔNb values ranging from -0.08 to -0.13 that indicate inherent source depletion as is corroborated by prevailing strongly to mildly radiogenic Nd isotope compositions (Table 2S). In contrast, the protolith of sample LKL3 ($\epsilon\text{Nd}_{540} + 6.2$) was derived from a strongly depleted source as its Nb/Yb (0.42) is lower than that of average typical N-MORB (0.72; Sun and McDonough 1989); the LKL3 magma may have been partly derived from sources even

more depleted than DMM, presumably residual after earlier melting (see section “Nové Město and Zábřeh boninites”).

The diagonal scattering of points on the Nb/Y vs Zr/Y plot (Fig. 5b) implies variable degrees of fusion. Due to differences in incompatibility, Zr/Y values are likely to be higher when melting is limited (Pearce and Norry 1979). High values of Zr/Y (6.26–7.72) for the most enriched samples (KNO2, KNO4, ZBH2, ZBH6) suggest low degrees of fusion, and low Zr/Y (1.79–2.71) for samples ZBH8 and LKL3, high degrees. However, most samples show intermediate values indicating moderate, if varied, degrees of melting. The process took place within the spinel stability field. For most samples, $[\text{Tb}/\text{Yb}]_{\text{CN}} < 1.6$ and low TiO_2/Yb values point to shallow melting typical of N-MORB-type basalts (Pearce 2008; Fig. 5c). This is supported by calculated pressures (0.7–1.8 GPa) of magma generation, implying a depth $< \sim 60$ km (Lee et al. 2009; Fig. S5). However, $[\text{Tb}/\text{Yb}]_{\text{CN}}$ values (1.66–1.81) for the mildly alkaline samples and their elevated TiO_2/Yb (Fig. 5c) coupled with the highest calculated pressure (2.4 GPa for OLE1; ~ 80 km) suggest somewhat greater depths corresponding to the spinel–garnet transitional zone. However, apparent deeper levels of melt formation may, in fact, reflect of a more complex path of mantle source enrichment.

The inferences above are confirmed by the FMM-normalized profiles for the meta-tholeiites (Fig. 7). Their patterns, predominantly with elemental abundances $\text{VHI} \gg \text{HI} \geq \text{MI}$ (VHI—very highly incompatible, HI—highly incompatible, MI—moderately incompatible), are consistent with enriched- to unenriched fertile sources (with respect to FMM) which underwent moderate degrees of partial melting ($\sim 10\%$). Four samples (meta-tholeiites LKL3, ZBH8 and low-Ti meta-tholeiites ZBH4 and KNO4) have patterns of $\text{VHI} \geq \text{HI} \geq \text{MI}$ that can be attributed to moderate to high degrees of partial melting ($> 10\%$) of unenriched FMM, or alternatively, to low degrees of melting ($< 5\%$) of a slightly depleted residual source that had earlier lost $\sim 5\%$ of melt. Additionally, in both types of profile, negative anomalies for Y–Yb or Ti are absent, indicating a source devoid of residual garnet or amphibole, respectively. Lack of amphibole may imply a pristine dry lherzolitic source. However, the input from subducted slab must have included some hydration.

Whereas the origin of the depleted meta-tholeiites seems unambiguous, the enrichment of their mantle source(s) requires further examination. Hence, the least fractionated samples (LKL1, LKL12, SKV12, KNO2, ZBH2, ZBH6, ZBH13) representing various degrees of enrichment, but unmodified by subduction-derived components, were compared with calculated geochemical models of melt formation (non-modal aggregated fractional melting) in the spinel stability field. The geochemical features of the meta-tholeiites rule out melting solely of primitive mantle, deemed here a model approximation of a slightly enriched

Fig. 7 FMM-normalized (FMM—fertile MORB mantle) patterns for: **a** meta-tholeiites from the Nové Město Unit, **b** meta-tholeiites from the Zábřeh Unit, **c** meta-boninites and low-Ti meta-tholeiites. Normalizing values and subdivisions from Pearce and Parkinson (1993)

source. Neither did low degree-melting of DMM reproduce the meta-tholeiite compositions (Fig. 8a). However, the decoupling between the enriched characteristics of the meta-tholeiites and their radiogenic Nd isotope compositions ($\epsilon\text{Nd}_{540} = +1.9$ to $+2.6$), reflecting long-term depletion in Nd relative to Sm, suggest relatively recent enrichment of DMM by incompatible element-rich components. Thus, the calculated models assumed addition to DMM, prior to its melting, of low-degree (5%) OIB-like alkaline melt derived from primitive mantle. The results show that mixing of 8–10% of this melt with DMM and later ~10–15% fusion of such a metasomatized reservoir at shallow levels reproduces the enriched meta-tholeiites. These values of partial melting lie within the range for subduction-related lavas (e.g., König et al. 2010). Furthermore, the models explain that the degree of enrichment of the meta-tholeiites strongly depends on depth of alkaline-melt formation, with their intrinsic reservoir remaining the same. The OIB-like melts derived at garnet facies could have metasomatized the source that gave rise to the mildly alkaline magmas represented by samples KNO2, KNO3, ZBH2 and ZBH6 (Fig. 8b). In turn, the mantle region that provided the magmas for the variably enriched tholeiites required an alkaline component generated at shallower levels, at spinel–garnet facies (LKL12, ZBH13; Fig. 8c) or spinel facies (LKL1, SKV12; Fig. 8d). The models appear to reconcile enriched- and depleted reservoir mixing with the shallow vs deep melt-formation depths implied by the diagonal trend on the TiO_2/Yb vs Nb/Yb plot (Fig. 5c). Moreover, uneven distribution and addition of small amounts (<10%) of an OIB-like component to a DMM source could have led to the varied Nd isotope composition of the meta-tholeiites, though the source remained essentially radiogenic. Such a component must have had an ϵNd lower than OIB–HIMU ($\epsilon\text{Nd} = +4$ to $+6$; Zindler and Hart 1986) to account for the Nd isotopic signature in the

meta-tholeiites. Thus, it could be conjectured that the OIB-like ingredient was enriched mantle of EM1- or EM2 type characterized by undoubtedly negative ϵNd values (Zindler and Hart 1986; Hofmann 2014; Willbold and Stracke 2010). It would also explain the extremely non-radiogenic Nd isotope composition of enriched sample ZBH3 ($\epsilon\text{Nd}_{540} = -4.7$) which nevertheless reveals a significant subduction-related input (Fig. S4). Presumably, the ϵNd_{540} value reflects source metasomatism induced by alkaline melt (EM1–EM2) coupled with an addition of subduction-derived material. Likewise, the presence of an EM-type component in the source may also account for the shift of magma composition above the mantle array (Pearce 2008), as observed for the mildly alkaline samples of the meta-tholeiites (Fig. S6).

Nové Město and Zábřeh boninites

The geochemical features of the meta-boninites, e.g., the low content of TiO_2 , HFSE–HREE abundances much lower than in N-MORBs (Fig. 3) and low Nb/Yb, Nb/Y and Zr/Y (Fig. 5) all indicate a much depleted mantle source. Likewise, the FMM-normalized profiles for the meta-boninites have patterns $\text{VHI} < \text{HI} \leq \text{MI}$ typical of depleted sources (residual after ~10–15% melting) re-enriched in VHI and denoting a high degree of melting. The lack of negative Ti anomalies in these profiles points to the absence of residual amphibole in the mantle source. Interestingly, dry- or anhydrous conditions of boninite-source melting have been predicted by phase diagram relationships for high-Ca boninites (Crawford et al. 1989) and confirmed by experimental studies (Fallon and Danyushevsky 2000). Kanayama et al. (2013) have noted that dry, water-undersaturated conditions of fusion pertain to low-Si boninites ($\text{SiO}_2 < 54$ wt%), to which the Nové Město and Zábřeh boninites seemingly belong ($\text{SiO}_2 = 47.4$ – 52.1 wt%).

Fig. 8 REE diagrams with model curves of non-modal aggregated fractional melting in the spinel stability field (Woodhead et al. 1993) and mildly alkaline metabasites (KNO2, ZBH2, ZBH6), least fractionated, variously enriched meta-tholeiites (LKL1, LKL12, SKV12, ZBH13), low-Ti meta-tholeiites (KNO4, ZBH4) and meta-boninites (LKL7, SKV15, ZBH12). Model sources: **a** depleted mantle source (DMM), **b** metasomatized mantle (DMM mixed with 10% of OIB-like melt derived from 5% melting of primitive mantle with residual garnet), **c** metasomatized mantle (DMM mixed with 10% of OIB-like melt obtained from 5% melting of primitive mantle, PM, with residual garnet and spinel), **d** metasomatized mantle (DMM mixed with 8% of OIB-like melt obtained from 5% melting of PM with residual spinel), **e** residual mantle (depleted DMM after 5% non-modal batch

melting in spinel stability field), **f** residual mantle (depleted DMM after 15% non-modal batch melting in spinel stability field). Modal composition and melt mode: for DMM and metasomatized sources modified from Woodhead et al. (1993), for PM from Abdel-Rahman and Kumarapeli (1999), Aldanmaz et al. (2006) and Krienitz et al. (2006), for residual source modified from Woodhead et al. (1993) and Pagé et al. (2009). Mineral/melt partition coefficients for DMM and metasomatized source melting from Pagé et al. (2009) and Halliday et al. (1995); for PM melts from McKenzie and O’Nions (1991). Numbers in italics indicate the degree of partial melting (F). Composition DMM from Workman and Hart (2005) and PM from Sun and McDonough (1989). See text for discussion

The prevailing view is that the petrogenesis of boninites is associated with refractory harzburgitic- or clinopyroxene-poor lherzolitic mantle extremely depleted in incompatible elements (Bédard 1999). Though boninite melts are estimated to form at shallow depths, within the spinel stability field (~ 30 – 50 km), considerable heat input is required (e.g., Hickey and Frey 1982; Crawford et al. 1989; Bédard 1999; Fallon and Danyushevski 2000; Ishizuka et al. 2006; Pearce and Robinson 2010). Given the potential ambient mantle temperature (1350 ± 50 °C; Herzberg et al. 2010), a significant temperature increase is necessary to trigger melting (e.g., Falloon and Danyushevsky 2000). The thermal effect may be associated with lithospheric extension and asthenosphere upwelling in the form of OIB- or DMM-like diapirs within the mantle wedge (e.g., Jenner 1981; Hickey and Frey 1982; Crawford et al. 1989; Bédard 1999). It has also been postulated that substantial inflow of subducted slab-derived melts and fluid into the mantle wedge re-fertilizes it, considerably lowering its solidus temperature (e.g., Pearce and Parkinson 1993; Hawkesworth et al. 1993; Bédard 1999; Dilek and Thy 2009; König et al. 2010).

Estimations of P–T conditions for the generation of the Nové Město- and Zábřeh boninitic magmas give temperatures between 1400 and 1420 °C and pressures of 1.2 – 2.0 GPa (Fig. S5; LKL7 and SKV15) using the geothermobarometer of Lee et al. (2009). Values of mantle potential temperature T_p of boninitic-magma segregation obtained using the PRIMELTS3 software (Herzberg and Asimov 2015) yield temperatures of 1370 – 1500 °C that are close to the range of 1380 – 1460 °C for high-Ca boninites, compositionally similar to the Nové Město and Zábřeh meta-boninites, that occur in North Tonga, Troodos in Cyprus

and Dachadaban in China (Sobolev and Danyushevski 1994; Xia et al. 2012; Figs. 9 and S7). In the case of the Nové Město and Zábřeh, a substantial thermal input is indicated as meta-boninites LKL7 and SKV15 formed at higher temperatures than the meta-tholeiites (Fig. S5) and higher than the average equilibration temperatures of ~ 1300 °C for primitive arc lavas from intra-oceanic subduction zones (Perrin et al. 2016). The calculated T_p for LKL7 and SKV15 also exceeds estimated values for the mantle wedge beneath back-arc basins, e.g., ~ 1350 °C for the Mariana trough and East Scotia ridge (Wiens et al. 2006). However, calculated T_p for meta-boninitic sample ZBH12 suggests much cooler conditions ($T_p \sim 1300$ °C; Fig. S5) and shallow levels (~ 40 km) for melt formation. Its depleted composition (HREE abundances at $\sim 0.17 \times N$ -MORB) indicates a very refractory mantle source likely to provide melt only at much higher temperatures. The difference seems to indicate boninite genesis associated with melts or fluids released into the mantle wedge. When compared (Figs. 3, S4), the subduction impact on sample SKV15 was relatively weak (substantial addition of La only, ϵNd of $+6.7$), moderate for LKL7 (elevated abundances of LREE and Th, ϵNd of $+2.9$) but strong for ZBH12 (high $[La/Sm]_{CN}$ of 1.67 , ϵNd of -2.9). Moreover, the nearly horizontal baseline (Fig. S4) for ZBH12 suggests that not only LREE–MREE, but also some of Nb may have come from the subducted slab to the source. This would explain the marked contrast between the positive ΔNd ($+0.01$) of ZBH12 and the negative ΔNd (-0.64) of LKL7 (Fig. 5b). This underscores the crucial role of subduction input in the origin of the meta-boninites and shows that only HREE may be confidently deemed conservative with respect to mantle-wedge composition.

Fig. 9 TiO_2 vs Zr and Ti/Zr vs Zr/Sm diagram for the meta-boninites compared to high-Ca boninites (Troodos, North Tonga, Dachadaban, Oman and Koh) and low-Ca boninites (Cape Vogel, Nepoui, Mariana

trench, Izu–Bonin–Marian, Chichijima, Site 786B). Compilation from Xia et al. (2012). See text for discussion

The high temperatures (1450–1500 °C) and enrichment of the mantle source of high-Ca boninites in North Tonga have led to some postulates involving an OIB-like mantle plume in their genesis (Samoa plume in the Lau basin; Sobolev and Danyushevsky 1994; Falloon et al. 2008; see also Hickey and Frey 1982). Such a prominent mantle-wedge component (as EM1, EM2 or HIMU) with its abundance of strongly incompatible trace elements (LREE–MREE, HFSE) and distinctive isotopic composition (e.g., Hofmann 2014; Willbold and Stracke 2010) would affect the composition of arc magmas produced. Some features of the meta-boninites, e.g., their moderate-radiogenic to non-radiogenic Nd isotope compositions coupled with their enrichment in LREE–MREE and their slightly elevated Zr, Hf and Ti abundances relative to Sm (Fig. 3), might be similarly interpreted. As discussed above, enriched, mildly alkaline metabasites also implicate input of EM1–EM2-like melts into the mantle wedge (Fig. 8b–d). However, any addition of OIB-like melt into strongly depleted residual-mantle regions would readily result in selective enrichment in HFSE, particularly Nb and Ta. Recently, Golowin et al. (2017) have shown that an addition as small as ~0.06–1.0% of OIB-like (HIMU) melt into a residual mantle source suffices to produce positive Nb–Ta anomalies and distinctly lower ϵ Nd values in boninite-like, low-Ti rocks from the Manihiki Plateau. Given that the meta-boninites have very low Nb concentrations (≤ 0.5 ppm) and high Th/Nb (0.30–0.77) relative to average OIB (Nb=48 ppm, Th/Nb=0.08; Sun and McDonough 1989), the influence of such melts in their origin seems unlikely in the light of the available data. Any substantial addition of such a component would also result in distinctly negative baseline slopes as seen for mildly alkaline samples, but not for meta-boninite samples (Fig. S4). Thus, the negative ϵ Nd values of the meta-boninite samples, as discussed in 5.2.2, are interpreted to fingerprint input from sediment-derived melts (LKL7 and ZBH12) or slab fluids (SKV15) into a region of residual mantle.

To reconstruct the mantle wedge source for the meta-boninites protoliths (prior to subduction-related modification) and estimate the degree of its melting, geochemical modeling was undertaken. The modeling relies on HREE due to their low contents in subduction-derived components and moderate incompatibility (König et al. 2010). The model considers the refractory (residual) nature of the source and any depletion due to previous magmatic events. The petrogenesis of boninites is commonly associated with two-stage melting where less fertile clinopyroxene-poor or harzburgitic residue reflecting earlier extraction of tholeiitic magmas re-melts to provide liquids much depleted with regard to N-MORB in incompatible elements (e.g., Hickey and Frey 1982; Crawford et al. 1989; Bédard 1999; Falloon and Danyushevsky 2000; Pagé et al. 2009). The occurrence of the boninites together with tholeiites suggests

that the boninitic source could have been a residue after 10–15% melting of DMM producing the tholeiitic precursor (Fig. 8b–d). Thus, a residual source after 15% of batch melting (RMM-15, approximation of maximum depletion in the mantle wedge) was calculated with appropriate adjustments of source mineral compositions (Fig. 8f). The FMM-normalized diagrams for the meta-boninites (Fig. 7) suggest that their source could have been less depleted, i.e., residual after ~5% of DMM melting. Accordingly, an appropriate model source (RMM-5) was also calculated (Fig. 8e), providing a lower limit of mantle depletion. The DMM modal composition (modified from Woodhead et al. 1993) applied in the modeling and the mineral melt mode (Pagé et al. 2009) assume the disappearance of clinopyroxene at ~21% melting and, hence, both RMM-5 and RMM-15 remained lherzolitic with lowered contents of the mineral. In the second stage modeling, aggregated non-modal fractional melting was applied. Clinopyroxene exhaustion at 17.1% and 7.4% melting of RMM-5 and RMM-15, respectively, turned the source into a spinel-harzburgite residue which was to be the object of further melting. The calculations assumed dry conditions of melting as there is no indication of amphibole in the source (discussed above in this section). The model melts obtained were then compared with three meta-boninite profiles (Fig. 8e, f). The plots contrast sharply for the LREE and MREE section, which stems from subduction-derived input and depicts the extent of that addition. In contrast, the lines coincide for HREE indicating ~15–25% melting of RMM-15 and 25–35% melting of RMM-5. Both models demonstrate that harzburgitic mantle is required to account for the origin of the boninites. Both show consistently that samples SKV15, ZBH12 could have resulted from an almost uniform but greater extent of melting than sample LKL7. However, the maximum degree of fusion (~35%) predicted by melting of RMM-5 is very high compared to that most often postulated, i.e., ~10–25% (e.g., Bédard 1999; Pagé et al. 2009; König et al. 2010; Escuder-Viruete et al. 2011; Golowin et al. 2017). Even though higher degrees have been reported (< ca. 38%; Escrig et al. 2012), the lower degree of melting seems more plausible and, thus, the model involving the RMM-15 source is preferred here.

The increase in degree of melting suggested by the calculations roughly mirrors the decrease of CaO/Al₂O₃ from 1.14 for LKL7, to 0.81 for SKV15, to 0.64 for ZBH12 and accords with the opinion of Crawford et al. (1989) that a more refractory source or a higher-degree partial melting is characteristic for low-Ca (CaO/Al₂O₃ < 0.75) types of boninite. Nevertheless, when compared to other boninitic rocks of established chemical affinity, e.g., high-Ca boninites from Troodos and North Tonga (König et al. 2008; Falloon et al. 2008) and low-Ca boninites from Cape Vogel in Papua New Guinea (König et al. 2010), the meta-boninites rather follow the high-Ca boninite

trend and have similar Ti/Zr (Figs. 9 and S7). The high Ti/Zr of the meta-boninites (109–145), close to the values for DMM (141) or primitive mantle (116), implies a lack of metasomatic Ti and Zr enrichment in the mantle region (Xia et al. 2012). A marked difference from other high-Ca boninites is evident only for LREE-MREE, a feature that probably reflects compositional variation in the slab-derived enrichments of their respective sources. In contrast to high-Ca boninites, low-Ca boninites have higher Zr/Sm (> 40) and Zr/Hf (> 30), and show a distinct Zr–Hf positive anomaly on N-MORB-normalized plots (Fig. S7). The elevated Zr/Sm, Zr/Hf (and positive Zr–Hf anomaly relative to Sm) have been ascribed to modification of the boninitic source by melts released from slab with amphibolite- or eclogite residues (e.g., Pearce et al. 1992; König et al. 2010; Li et al. 2013). The meta-boninites have low values of Zr/Sm (20.0–34.9) and Zr/Hf (27.5–30.0) similar to other high-Ca boninites, e.g., Troodos (Zr/Sm 16–32, Zr/Hf 22–32; König et al. 2008) and Dachadaban, North Quilian (Zr/Sm 19–31, Zr/Hf 28–38; Xia et al. 2012) that convincingly argue against residual amphibole in melting slab. The lack of a pronounced Zr–Hf anomaly (either positive or negative) in the meta-boninites supposedly excludes the presence of residual rutile in the subducted slab (e.g., König et al. 2010; Li et al. 2013). These features argue against substantial addition of slab melts and strongly support a dominant role for melts or fluids derived from subducted sediment metasomatizing the source of the meta-boninites (see 5.2.2). More importantly, however, they show that Zr, Hf and Ti remained conservative in the meta-boninite source and essentially reflect the pristine composition of residual mantle not disturbed by slab-derived additions.

The modeling further allows for some petrogenetic assessment of the low-Ti meta-tholeiites (samples KNO4 and ZBH4) which occur sporadically with the main groups of metabasites. Their FMM-normalized patterns $VHI \geq HI \approx MI$ (Fig. 7) point to a high degree of partial melting of fertile, un-enriched mantle. However, the models suggest that their HREE abundances are satisfactorily reproduced by melting of lherzolite mantle, either un-enriched (i.e., DMM-type) or residual (depleted by an earlier melt extraction, RMM-5 and RMM-15). With a DMM-type source, the degree of melting could have been moderate and range from ~5 to 10% (Fig. 8a), though re-melting of residual sources also seems viable for both samples. For KNO4, 7–10% fusion yields magmas of similar composition and the results do not depend significantly on the degree of any earlier melting (Fig. 8e, f). ZBH4 has concentrations of HREE reflecting very low ($< 3\%$) degrees of melting of residual mantle.

Tectonic and regional implications

Pervasive Variscan deformation and metamorphism effectively obliterated the original distribution of the different types of metabasite and the spatial relations between them and their surroundings. Because the age of the metabasite protoliths remains unknown, tectonic reconstructions and regional correlations must rely on geochemical features and general petrogenetic analogies.

The metabasites from the Nové Město- and Zábřeh Units are dominated by meta-tholeiites accompanied by rare low-Ti meta-tholeiites and high-Ca meta-boninites. They derive from sources ranging from residual and refractory, to typical depleted MORB mantle (DMM), to variously metasomatized DMM (alkaline melts) involving heterogeneous, randomly distributed input from subducted slab. Continuous trends on discrimination diagrams run from intra-oceanic-towards within-plate fields (Figs. 2b, 4a–c, h) or towards intra-oceanic- and island-arc fields (Fig. 4f, g) accord with the extensional supra-subduction regime of back-arc basins (BAB; e.g., Gribble et al. 1996; Pearce et al. 1995). A recent report on the coexisting Nové Město phyllites and mica schists also points to continental island-arc deposition of their protoliths in a BAB environment (Maliszewski and Ilnicki 2019). It is worth emphasizing that both the Nové Město Unit and the Zábřeh Unit coherently point to the same paleotectonic environment based on the data presented here. The most conspicuous difference concerns the degree of supra-subduction zone input, which should be no surprise given the complex structure of the BAB zone (Pearce and Stern 2006). Otherwise, the nature of the subduction component and OIB-like enrichment are similar, corroborating the genetic connection between the units.

The highly variable magnitude, or even absence, of the subduction signal observed in the metabasites (Fig. S4) is not atypical of the BAB tectonic environment. The distribution of subduction components within the mantle wedge may reflect proximity of the trench, distance to the descending slab (slab depth) and/or circulation and directions of flow to the supra-subduction zone (Pearce et al. 1995; Pearce and Peate 1995; Pearce and Stern 2006; Escrig et al. 2012; Zamboni et al. 2016). Increasing mantle-wedge depletion may also correlate with proximity to the arc front (e.g., Pearce and Stern 2006; Escrig et al. 2012). Due to the prevailing non-residual nature of the meta-tholeiite protolith magma source and variation in the subduction contribution, some distance to the trench (or subducted slab) is postulated. The same appears valid for the high-Ca meta-boninites as boninites emplaced closer to the fore-arc are of low-Ca type and frequently associated with BADR (basalt–andesite–dacite–rhyolite); whereas, those in the back-arc basin farther from the trench are of high-Ca type and occur with abundant mafic volcanics transitional from N- or E-MORB to

island-arc tholeiites. These volcanics are characterized by erratic subduction zone input (Xia et al. 2012).

The within-plate style of enrichment of some meta-tholeiites, though mostly associated with basalts from oceanic islands, seamounts and continental rifts (e.g., McKenzie and O'Nions 1995; Fitton 2007), does not exclude the BAB environment. OIB-like and E-MORB melts, and BAB, have been reported from both modern- and ancient supra-subduction zones (e.g., Pin and Waldhausrova 2007; Ilnicki et al. 2013; Zamboni et al. 2016; Windley and Xiao 2018). Although the origin of OIB-type magmas is commonly attributed to deep mantle-plume activity, may also appear in response to passive upwelling of asthenosphere and decompression melting of dispersed blobs of recycled crustal components (e.g., EM-1 and EM-2 types) carried by the upflow (e.g., Courtillot et al. 2003; Willbold and Stracke 2010; Hofmann 2014). Slab retreat and roll-back may induce a multi-directional flow of such asthenosphere around edges of subducted slab towards BAB or, in extensional regimes, upward diapiric migration (e.g., Pearce and Stern 2006; Pin and Waldhausrova 2007; Zamboni et al. 2016). Hot, sub-slab asthenosphere may also rise into the mantle wedge through slab windows and gaps due to slab detachment or ridge–trench collision; in this way, both heat and embedded components are introduced into the mantle wedge (e.g., Thorkelson 1996; Pin and Waldhausrova 2007; Scalabrino et al. 2009; Windley and Xiao 2018). Our geochemical modeling suggests that the OIB-like melts could have originated due to polybaric decompression melting triggered, most probably, by asthenospheric upwellings. In this way, both the injections of melts metasomatizing the mantle wedge and the heat required for boninite magma generation would be supplied (e.g., Hickey and Frey 1982; Crawford et al. 1989; Falloon and Danyushevsky 2000).

Furthermore, the appearance of boninite-type rocks in the metabasitic suites of the Nové Město- and Zábřeh Units provides crucial regional constraints for our palaeotectonic model. Boninites are exceptionally rare in the Bohemian Massif and, excepting the Central Sudetic ophiolite (Dubíňská 1997), have been found only in the Teplá–Barrandian Unit (Vitková and Kachlík 2001; Kachlík et al. 2001; Sláma et al. 2008). These rocks occur as rare dykes and sills together with low-Ti tholeiites, andesites, dacites and rhyolite in the volcano-sedimentary succession of the Davle volcanic arc (ca. 608–563 Ma) and in the overlying Svrchnice Formation (ca. 560–520 Ma) comprising siliciclastic metasediments and bimodal volcanics of a relic back-arc basin (e.g., Kachlík et al. 2001; Hajná et al. 2018). Boninites represent a high-Ca type, strikingly similar to the meta-tholeiites (Fig. S7), that originates from variably metasomatized depleted mantle ($\epsilon\text{Nd}_{650} = +2.5$ to $+6$; Kachlík et al. 2001; Vitková and Kachlík 2001). The origin of the Teplá–Barrandian boninites is correlated with the final

stages of oblique, Pacific-type subduction of the Cadomian arc and accretion along the northwestern margin of Gondwana (e.g., Hajná et al. 2018). Intense arc activity in the Davle complex ceased at ca. 563 Ma in response to either a change in plate convergence from frontal to more oblique (Hajná et al. 2017) or a switch to flat-slab subduction (Hajná et al. 2018). However, subduction continued until a period of sediment accretion at ca. 527 Ma was immediately followed by emplacement of boninite dykes triggered by hot-ridge subduction at ca. 524–520 Ma and slab break-off. However, the age of these boninites is unknown but is constrained to ca. 544–524 Ma by the maximum ages of the host metasediments and of the meta-rhyolites of the overlying succession (Hajná et al. 2013).

In our opinion, a two-stage tectonic model which reconciles the BAB environment, the observed magma spectrum, the available regional inferences and a pivotal role for the boninites can explain the origin of the Nové Město- and Zábřeh metabasites (Fig. 10). During the first stage, tholeiitic magmas originated from a fertile, spinel-bearing DMM-type source at various depths (Fig. S5) due to upward migration of depleted mantle-wedge asthenosphere in a BAB extensional regime (Fig. 10a). The source was affected by metasomatism due to, firstly, subduction zone-related melts or fluids from subducted sediments associated with minor fluids from subducted juvenile crust and, secondly, OIB-like components from low-degree decompression melts derived from EM1-EM2 entities dispersed in the asthenosphere. The latter required asthenospheric upwelling and polybaric melting achievable by slab retreat and, ultimately, slab detachment. However, an alternative explanation based on tectonic reconstruction for the Teplá–Barrandian which assumes opening of the slab window due to oblique ridge–trench collision and marked by boninitic intrusions (Hajná et al. 2018) is favored here. Consequently, the second stage of our model begins with the upward flow of sub-slab asthenosphere through a slab window into the BAB zone (Fig. 10b). This would supply both OIB-type melts to modify the mantle wedge source and increased heat flow to trigger shallow melting of refractory regions. Eventually, this strongly heterogeneous reservoir would produce, respectively, enriched mildly alkaline- and boninite magmas. Emplacement of the latter, as in the Teplá–Barrandian, would define the final stages of BAB development as ridge–trench collision led to cessation of subduction zone activity.

Consequently, we argue that the unique presence of meta-boninites in the Nové Město- and Zábřeh Units unequivocally identifies them as part of the Teplá–Barrandian Unit, a relationship hitherto postulated only on lithological grounds (e.g., Cháb et al. 1995). Presumably, together they constituted a portion of the Cadomian active margin where Iapetus slab subducted below the Gondwana upper plate, with the Nové Město- and Zábřeh Units in more distant (relative

Fig. 10 Tectonic model for the Nové Město- and Zábřeh metabasites. Further explanation in text

to the trench) and mature parts of the BAB. Thus, in geodynamic models for the Teplá–Barrandian Unit, it would be a BAB domain located between the Davle arc complex and the Gondwana mainland (Fig. 13 in Hajná et al. 2017; 2018). It is now mostly truncated by the Central Bohemian pluton or buried below the Carboniferous sediments of the Intra-Sudetic Basin and Cretaceous sediments of the North Bohemian Basin. Though the distance of the two units to Gondwana is difficult to estimate, the proportions of supracrustal rocks and metabasites may suggest that the Zábřeh unit lay closest to the continent (Figs. 1 and 10b).

In summary, the structure of the Orlica–Śnieżnik Dome comprising units of Teplá–Barrandian affinity amalgamated during Variscan times with the Saxothuringian core (Chopin et al. 2012; Szczepański and Ilnicki 2014) records the diachronic cessation subduction zone activity preceded by BAB magmatism, and ridge–trench collision in once separated domains of the Avalonian–Cadomian belt (Hajná et al. 2018). Evidence of these events provided by the the Orlica–Śnieżnik Dome core metabasites (Ilnicki et al. 2013) reveals a history analogous to that presented here. However, the fact that the core of the Orlica–Śnieżnik Dome lacks

boninites points to variations in temperature conditions and differing magnitudes of subduction input and offers, perhaps, an insight into the contrasting geometry and subduction style of the Teplá–Barrandian and Saxothuringian domains.

Conclusions

1. Metabasites from the Nové Město- and Zábřeh Units (west and south, respectively, envelope of the Orlica–Śnieżnik Dome, Central Sudetes) have nearly identical geochemical characteristics corresponding to variously enriched tholeiites and high-Ca, low-silica boninites and subordinate low-Ti tholeiites. Their genesis is related to a mature extensional back-arc basin located at some distance from the trench.
2. Fertile, albeit depleted, MORB mantle (DMM) was most probably the source of the tholeiitic melts. Geochemical modeling suggests that these parental magmas could have formed due to 10–15% shallow melting of the source region (1380–1230 °C at 1.8–0.7 GPa). Shortly before fusion, the source was heterogeneously metaso-

matized by small amounts (8–10%) of OIB-like melts extracted at various depths (garnet to spinel stability field) from enriched components (possibly EM1-EM2 type) in the mantle wedge.

3. High-Ca meta-boninites most probably reflect 15–25% re-melting of residual mantle, i.e., DMM after ~ 15% extraction of tholeiitic melt at 1420–1400 °C to 1300 °C and pressures from 2.0 to 1.2 GPa. Geochemical models suggest that due to high degrees of melting the initial lherzolite source exhausted clinopyroxene and boninitic magma segregated from harzburgitic residue. The solidus of the refractory boninite source was likely lowered by subduction-related input.
4. The low-Ti meta-tholeiites may be attributed to < 10% melting of DMM-type source or to re-melting of residual mantle remaining after < 15% of former melting.
5. Tholeiitic- and boninitic magma sources were heterogeneously and randomly metasomatized in the main by melts and fluids released from subducted sediments into mantle wedge or from subducted juvenile crust. The inferred sediment composition, in terms of Th/La, compares to that of subducting sediments at trenches globally (GLOSS-II of Plank 2014).
6. The meta-tholeiites and meta-boninites of the Nové Město and Zábřeh Units point to strong genetic links between the envelope of the Orlica–Śnieżnik dome and the Teplá–Barrandian domain where volcanic arcs of the Cadomian subduction system are preserved. The inference is that both units are a vestigial, easterly prolongation of that system. The emplacement of high-Ca boninites and presumably polybaric OIB-like input into mantle beneath an extensional back-arc basin may mark the upflow of hot, sub-slab asthenosphere through a slab window opened in the course of ridge–trench collision, and subsequent cessation of subduction zone activity.

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