# High-temperature overprint in (U)HPM rocks exhumed from subduction zones

Faryad, S.W.; Cuthbert, S.J.

*Published in:*
Earth-Science Reviews

*DOI:*
10.1016/j.earscirev.2020.103108

Published: 31/03/2020

*Document Version*
Peer reviewed version

High-temperature overprint in (U)HPM rocks exhumed from subduction zones; a product of isothermal decompression or a consequence of slab break-off (slab rollback)?

Faryad, S. W.[1] & Cuthbert, S.J.[2]

[1]Institute of Petrology and Structural Geology, Charles University, Prague, 12843, Czech Republic

e-mail: faryad@natur.cuni.cz

[2]School of Computing, Engineering and Physical Sciences, University of the West of Scotland, Paisley PA1 2BE, United Kingdom

ABSTRACT

This paper presents and discusses petrological observations from high- to ultrahigh-pressure (U)HP metamorphic terrains in relation to existing geophysical and numerical models for subduction and exhumation processes in orogenic belts. The interpretations are mostly based on observations from gneiss terrains bearing abundant bodies mafic (meta-)eclogite and ultramafic garnet peridotite and pyroxenite, exposed in collisional orogens. The inclusions and compositional zoning of minerals are considered to be first order information that is needed to constrain PT paths of HP-UHP rocks and reconstruct the related geodynamic models for subduction and exhumation of crustal and mantle rocks. The Bohemian Massif of the European Variscides is used as the basis for a model example to explain these processes, but (U)HP rocks from various other terrains are taken into consideration to discuss available PT paths in relation to proposed subduction and exhumation rates of (U)HP rocks based on geophysical and geochronological data. Primarily information used in this respect include textural relations and preserved prograde zoning in minerals from many (U)HP rocks, which reveal that a relatively cool geothermal gradient typical of subduction zones tended to prevail during the prograde and peak pressure segments of PT paths prior to initiation of exhumation and may have continued, even with cooling, if exhumation rates were rapid. The commonly applied interpretation of isothermal decompression during exhumation is critically appraised, considering whether a simple thermal relaxation (and radiogenic heating) during exhumation is responsible for formation of post-peak pressure, retrograde mineral assemblages and textures observed in (U)HP rocks. We go on to consider whether this can satisfactorily explain the often pervasive medium-pressure, high-temperature metamorphic re-equilibration of (U)HP rocks or whether an additional, external source of heat is a better explanation. We conclude that the commonly observed high-temperature metamorphic overprint exhibited by (U)HP rocks occurs mostly after rocks have been exhumed from the subduction channel and have reached normal crustal positions, when mantle upwelling resulting from slab breakoff (delamination) or slab rollback takes place at the onset of continent-continent collision. We also explore contrasting PT trajectories for mantle rocks that have been entrained into crustal material during their subduction or exhumation; PT paths of mantle and subducted crustal rocks tend to converge as mantle rocks impinge upon the cooler subduction zone and, once entrained, share a common evolution that depends on the exhumation mechanism and rate. Considering all of the data presented in this work we conclude that the diverse, polyphase metamorphic evolution exhibited by (U)HP terrains, embodied in the PT paths of HP and UHP rocks, has important consequences for reconstructing their changing thermal regimes and provides important constraints for geodynamic models involving subduction and the transition to collision.

*Keywords: subduction, metamorphism, exhumation rate, thermal overprint*

## 1. Introduction

Our understanding of subduction and orogenic processes derives from diverse types of information encompassing geophysical, structural, petrological, geochemical and geochronological data from both modern and ancient geosystems. Minerals and their textures in high pressure or ultra-high pressure (U)HP metamorphic rocks provide quantitative evidence about the thermal regime during subduction, the depths that the rocks reached and their rates of exhumation. (U)HP minerals (omphacite or jadeite, glaucophane, lawsonite and coesite) are very sensitive to back reaction due to pressure and temperature changes during exhumation, but their decomposition or destabilization depends also on deformation and fluid availability. The presence and preservation of most (U)HP minerals are indicative of a low geothermal gradient in a subduction zone environment and a fast exhumation rate. However, these rocks commonly display a pervasive amphibolite to high-temperature (HT) granulite facies overprint of the (U)HP mineral assemblages that was evidently imposed during exhumation, yet the mechanism causing the warmer thermal regime remains unclear. To analyse the significance of these observations in (U)HP rocks and attempt an interpretation that honours all the available data, there is a need to review the results obtained by petrological research along with relevant geophysical and geochronological data and proposed geodynamic models.

Major factors that influence the thermal regime of subduction systems include the rate of subduction (i.e. the rate of underflow of cool lithosphere into the ambient hotter mantle), the age of the subducting lithosphere, subduction angle, coupling and decoupling of the subducted slab, subduction of spreading ridges and magmatic arcs and subduction of continental lithosphere (e.g. Wada and Wang, 2009; Stern, 2011; Suenage et al., 2018). It is generally accepted that the subduction zone thermal gradient is significantly cooler than the surrounding mantle. The reaction progress among minerals during metamorphism may be enhanced or constrained by factors such as rates of pressure and temperature change (in addition to local effects of fluid and deformation). The net metamorphic response is recorded in their constituent mineral phases and their compositions which, through the application of geothermobarometric and petrochronologic methods, can be used to reconstruct pressure-temperature-time (P-T-t) paths. Positive changes in estimated pressure over time give the burial rate, i.e. the vertical component of velocity along the subduction vector, which is a function of plate convergence rate and subduction angle integrated over time. Temperature changes over any pressure interval during burial can be related to the mechanism; for example long-term, steady state subduction of oceanic lithosphere tends to establish a relatively cool thermal regime and high P/T. We will argue below that such a regime may continue during the early stage of continental subduction as the continental margin enters the subduction channel. Negative changes in calculated metamorphic pressure over time give the exhumation rate, which will depend upon the mechanism by which the lithostatic load is removed. The transition from steady state subduction to collision changes the thermal regime because underflow of cold oceanic lithosphere slows and ceases as buoyant continental crust enters the subduction channel. Other factors now begin to dominate the thermal regime, including thermal relaxation, radiogenic heating, slab break-off and magmatic heat advection, all operating in the context of translation towards the cold Earth's surface.

Rates and durations of burial and exhumation require geochronological data that can tie estimated pressures to time, or at least bracket segments of the P-T path to a time interval. This is often challenging because minerals or assemblages that are reliable indicators of pressure are not always good geochronometers (and *vice versa*). The use of petrochronological approaches that relate the major modal minerals used in P-T estimates to the accessory minerals (zircon, monazite etc.) that are good geochronometers via their trace element compositions offer promising solutions to this problem (Foster et al., 2000; Rubatto, et al., 2001; Engi, 2017). In high temperature terrains this approach is made difficult by diffusional modification of mineral compositional zoning and resetting of isotope systems, but application of diffusion-based "geospeedometers" (e.g. Chakraborty, 2008) to mineral compositional zoning offer an alternative to isotopic analysis in estimating cooling rates, which might help to reconstruct P-T-t paths. A wide range of burial and/or exhumation rates (0.01 to 14 $cm.a^{-1}$) have been estimated using geochronological data (see Hetzal and Romer, 2000; Gerya et al., 2002; Doglioni et al., 2007; Wilke et al., 2010; Zirakparvar et al., 2011). This range may be geologically significant, but it is important to be aware that diffusional modification is probably a major cause of uncertainty in estimation of such rates and may contribute to the diversity of values. Nevertheless, in most cases fast exhumation rates, similar to burial rates during subduction, are deduced (Hetzel and Romer, 2000; Rubato and Herman, 2001; Gerya and Stöckhert, 2002).

Exhumation of (U)HP rocks requires a mechanism to overcome the downward drag from the descending oceanic lithosphere, such as delamination of buoyant continental crust from the subducting lower lithosphere and subsequent return up along the subduction channel (e.g. Gerya et al., 2008; Brueckner and Cuthbert, 2013), diapiric rise through the mantle wedge (Ellis et al., 2001) or wholesale eduction as a buoyant response to slab break-off (Duretz et al., 2012; Bottrill et al., 2014). The exhumation mechanism and rate will have a significant effect on the thermal evolution through thermal relaxation or enhanced mantle heat input (e.g. via slab breakoff, asthenospheric upwelling and magmatic advection). Various decompressional P-T path scenarios including isothermal decompression, heating or even cooling can be resolvably recorded in metamorphic minerals. Rapid uprise of initially cool UHP rocks can prevent heating as P decreases, while slow uprise or stalling will allow T to rise by thermal relaxation. Slab break-off or lithospheric delamination may result in a major, rapid advection of heat into the exhuming crust. Prolonged heating and a major rise in T is likely to result in a metamorphic response that pervasively modifies the phase assemblage and may even involve partial melting. In such cases the mineralogical record of the prograde (subduction) and peak P stages may be more or less obliterated. Exhumation involving decompression and cooling along a low temperature gradient similar to that for a long-lived subduction zone, accompanied by fast exhumation as indicated by recent petrological studies from many (U)HP terrains (e.g. Davis and Whitney, 2006; Jedlicka et al., 2016; Li et al., 2018; Faryad et al., 2019) appears to prevent substantial modification of minerals that formed during the peak pressure conditions. Alternatively, a P-T path with isothermal decompression from maximum T attained at peak P, followed by slow exhumation, will result in compositional modification of minerals that may render them unsuitable for any pressure and temperature estimates.

Following the above reasoning, the aim of this paper is to examine available P-T-t paths constrained for (U)HP terranes and critically evaluate their interpretation in relation to the thermal regime in subduction zones and the exhumation rates of (U)HP rocks, taking into account recently published numerical models of subduction and exhumation from various terranes. In particular, we focus on the commonly observed late heating recorded in P-T-t paths for (U)HP rocks during exhumation noted above. We analyse these processes in relation to natural examples of observed (U)HP phases and their textures from a well-documented (U)HP terrane with a pervasive HT overprint up to granulite facies - the Moldanubian Zone (MZ) of the European Variscides (Faryad et al., 2010, 2018). Our approach to the problem begins on the basis that (U)HP metamorphism takes place in a subduction zone with a relatively cold geotherm. We go on to examine possible scenarios for the subsequent tectonic evolution of the orogeny as collision continues, focusing on the possible consequences of break-off, rollback or delamination of the subducted oceanic lithosphere (Davies and von Blanckenburg, 1995; Duretz et al., 2012; Nakakuki and Mura, 2013) .

**2. PT paths of (U)HP rocks**

Key questions relating to subduction zone metamorphism and its estimated PT paths are whether the minerals selected for pressure and temperature calculation for different segments along the PT path preserve equilibrium compositions and parageneses for those physical conditions, and if these can be attributed to generally accepted subduction geotherms. In the following we discuss PT paths of both crustal and mantle rocks subducted and/or exhumed from mantle depths.

*2.1. PT paths of crustal rocks.*

Most well-preserved low-temperature, high pressure (LT/HP) rocks indicate a pressure and temperature increase that is documented by prograde mineral reactions that took place during subduction (e.g. assemblages that have evolved from blue amphibole, lawsonite and jadeite to those with omphacite, zoisite and garnet in mafic rocks, or from chlorite and carpholite to chloritoid, kyanite and garnet in pelitic rocks) or by compositional changes in minerals. Retrograde reactions indicated by blue amphibole overgrowing omphacite, as observed in many eclogites (e.g. van Straaten et al., 2008), or lawsonite with inclusions of omphacite and glaucophane (Davis and Whitney, 2006) suggest cooling during exhumation (Fig. 1a). Such prograde and retrograde, LT/HP paths fit well with the calculated thermal gradient and positions of isotherms along a subduction zone (e.g., Peacock, 2002; Stern, 2002). Depending on the age of oceanic crust, the slab at its contact with the mantle wedge can reach temperatures in the range of 200–500 °C and 300–700 °C at depths of 100 km and 150 km, respectively (Fig. 2). Similar gradients will remain little-changed at the end of oceanic subduction and the onset of continent-continent collision (Chi and Reed, 2008). If rocks (mainly dry igneous or high-grade metamorphics) are not subject to deformation during subduction, the mineral reaction progress is limited and the original minerals may persist up to higher PT conditions. Good examples of partial transformations of gabbro to eclogite are known from the Alps (Bucher and Grapes, 2009; Proyer and Postl, 2010; Engi et al., 2018); from coesite eclogite in the Sulu terrane (Zhang and Liou, 2004); from the Western Gneiss Region of the Scandinavian Caledonides (Terry & Robinson, 2004) and from Papua New Guinea (Faryad et al., 2019). In the last case, all minerals crystallized in the coesite stability field and no zoning of major components in garnet was developed. Eclogitization along thin shear zones in well preserved pre-orogenic granulite has also been described from the Lindås Nappe in the Norwegian Caledonides (Austrheim and Griffin, 1985) in which the transformation was aided by ingress of an aqueous fluid (Austrheim, 1987).

In addition to cooling during decompression (Fig. 1a), there are a number of (U)HP terranes for which a PT path with isothermal or nearly isothermal decompression during exhumation (Fig. 1b) has been deduced (Bousquet, 2008; Liu et al., 2015, Dong et al., 2019). As the (U)HP phases could have re-equilbrated during exhumation, it is not always clear if the rocks had already reached their peak temperature during peak pressure conditions and then decompression during exhumation to upper crustal levels was nearly isothermal (dashed paths in Fig. 1b), or if the amphibolite to granulite facies overprint was a separate event at relatively low pressures (solid paths, in Fig. 1b) that occurred after their exhumation (see Faryad et al., 2018). In the case of isothermal decompression at a high temperature, a phase formed at peak pressure conditions can undergo re-equilibration, so application of conventional thermobarometric methods will lead to mixed results or indicate the last stage of re-equilibration. An example in which isothermal decompression at high-temperatures would be an unlikely interpretation can be the presence of prograde zoning in garnet as found in many amphibolite-granulite facies rocks that show evidence for earlier (U)HP metamorphism (Perraki and Faryad, 2014; Jedlicka et al., 2016). Multicomponent diffusion, especially for prolonged periods of time, becomes very effective at higher temperatures (Chakraborty and Ganguly, 1991; Lasaga, 1998; Cherniak and Watson, 2003; Zhang and Chemiak, 2010) so any zoning is likely to be smoothed out, thus well-developed prograde zoning precludes isothermal decompression at high T's. In contrast, flat or subdued zoning patterns tend to support prolonged high-T during decompression.

There are many examples of polyphase evolution of (U)HP terranes in which a medium-pressure overprint occurred later, when the rocks had already been exhumed to crustal levels. The best examples are some blueschists and eclogites from Central Turkey (Whitney et al.,

2011) where, after exhumation during which cooling occurred, they underwent Barrovian-type metamorphism (SM2 in Fig. 1b). Even the world's youngest (Late Miocene) coesite eclogites from Papua New Guinea (NG in Fig. 1b) show heating from 650 °C to 750 °C after they were exhumed to about 1.5 GPa (Faryad et al., 2019). Amphibolite facies overprinting of eclogite is well-known from the Lepontin Dome (Adula nappe) in the Central Alps (LD, Fig. 1b), where c.40 Ma old eclogite facies rocks were overprinted by amphibolite facies metamorphism at c.35–32 Ma (Gebauer, 1999; Wiederkeher et al., 2008). In the Western Gneiss Region giant (U)HP terrain a partial amphibolite-facies overprint in the southern, lower-T, HP part of the outcrop where eclogites have prograde glaucophane inclusions in garnet (Krogh, 1980), PT paths indicate cooling during exhumation (Engvik and Andersen, 2000; Labrousse et al., 2004) but in the northern part of the region where peak UHP (coesite and diamond) eclogite T was highest there is an often pervasive granulite-facies overprint with partial melting, recording a modest increase in T during decompression (WG in Fig. 1b, Butler et al., 2018; Engvik et al., 2018). Here, the high-T, medium P overprint appears to relate to the peak prograde conditions attained, but where there is not yet good evidence for the HT overprint being a distinct temperature pulse; rather a gradual increase in T during decompression is indicated by the currently available evidence. In the Bohemian Massif the high-temperature re-equilibration at 900–1000 °C occurred at 1.6–1.8 GPa (see Kotková, 2007; O'Brien, 2008; Faryad and Žák, 2016). Following the discovery of microdiamond and coesite in these rocks (Kotková et al., 2011; Perraki and Faryad, 2014), their exhumation from mantle depths was interpreted in different ways. A nearly isothermal decompression from 4.5 GPa/1100 °C to 1.5 GPa/1050 °C (EG in Fig. 1b) was considered by Haifler and Kotková (2016), but exhumation along a relatively cold geothermal gradient (Fig. 2) and a high temperature overprint (MG and ME in Fig. 1b) at crustal levels has been proposed by Faryad et al. (2015). Faryad and Fišera (2015) showed that some eclogites were affected by a short-lived granulite facies overprint after their exhumation and partial retrogression (Fig. 3). The eclogite facies garnet with prograde zoning, associated with omphacite in the matrix, is cut by micro-veins (a) formed of granulite facies minerals (olivine, spinel and pure anorthite, see d). They also showed that the fractures were first filled by amphibole (c) that was later recrystallised during a combination of metasomatic reactions with the host garnet into symmetric zones with olivine + spinel in the central part and anorthite + spinel at the contact with garnet.

From the above it can be concluded that recrystallization of rocks during subduction and exhumation is controlled not only by pressure and temperature changes, but deformation and fluid access that facilitate formation or breakdown of minerals. Where these processes are inefficient, relics of mineral assemblages can survive late overprinting and allow points along the PT path to be calculated using geothermobarometric methods. Ideally, several PT points are necessary to resolve the full form of a PT path, but in reality this is rarely possible. PT paths constrained only by two points are a great simplification and can be misleading, because important parts of the PT loop can be missed, for example if the rocks have been affected by a late thermal overprint. Hence significant errors in constraining a PT paths will result from thermodynamic modelling (such as through the use of pseudosection methods) that is not based upon detailed evaluation of the textural relations among minerals, or from exchange thermobarometry where the possible effects of diffusional modification are not considered.

*2.2. PT paths of mantle rocks*

Many (U)HP terranes contain fragments of mantle peridotite and pyroxenite within felsic crustal lithologies. The ultramafic rocks can be further divided into C-type from the continental slab and M-type from the mantle wedge (Carswell et al., 1983; Zhang et al., 2000; Zhang et al., 2000; Bodinier and Godard, 2014). The former type, previously emplaced into the subducted continental crust, would have a similar P-T path to the subducted/exhumed continental crust. A PT trajectory of the latter type is likely to differ from that of their host crustal rocks because of their different source locations and motion pathways, hence the P-T evolution of such (U)HP terranes becomes more complex. First, cooling would be expected as the mantle rock comes into proximity with the subduction zone where the geotherm has lower T/P than the adjacent mantle (Fig. 2 and see section 3). In most cases, they are thought to be entrained in crustal rocks during subduction (see Brueckner, 1998), and could be simply exhumed by passive transport with upgoing crustal material, in which case they would have a common thermal evolution with the crustal host rocks (Fig. 4a). Such PT paths have already been proposed for some ultramafic rocks (paths 1a and 1b in Fig. 4a) from the Sulu UHP terrane (Zhang and Liou, 2003, Li et al 2018) and from the WGR of the Norwegian Caledonides (Brueckner, 1998; Spengler et al., 2006; Scambelluri et al., 2008; Brueckner et al., 2010).

In the Bohemian Massif, it has long been assumed that UHP garnet peridotite and garnet pyroxenite were emplaced into felsic granulite after their exhumation to crustal levels (Medaris et al., 1990, 2006; Nakamura, 2004). However, it has been shown that some spinel peridotite with layers of pyroxenite were emplaced into felsic crustal rocks during subduction (Faryad et al., 2009; 2013a). This was confirmed by mineral textures, mainly indicating transformation of spinel into garnet in peridotite (Fig. 4b) and unmixing and formation of exsolution lamellae of garnet along specific crystallographic directions of Al-rich ortho- and clinopyroxene in relatively dry pyroxenite (Fig. 4c). In the advanced stages of recrystallization, the pyroxenite is totally transformed into garnet pyroxenite. If pyroxenite or other mafic layers in peridotite are first hydrated, new garnet and clinopyroxene with compositional zoning and/or multiphase inclusions may form during subsequent continued subduction and exhumation. Fig. 4d-g shows examples of minerals and textures from mafic-ultramafic dyke of basaltic clinopyroxenite composition formed during subduction and subsequent heating during exhumation (Faryad et al., 2013, 2018). The high-pressure Na-rich clinopyroxene porphyroblast (Fig 4d) is rimmed by diopside which together with orthopyroxene and plagioclase in the matrix crystallized or recrystallized during granulite facies heating (Path 3 in Fig. 4a). The garnet porphyroblasts contain inclusions of various hydrous and anhydrous phases (amphibole, micas, carbonates or relicts of ortho- and clinopyroxene, spinel) that have been transformed *in-situ* into other phases during subduction and later granulite facies overprint (see omphacite formation at contact with amphibole, Fig. 4e). As these hydrous phases reacted with the host garnet during their subsequent evolution, they recrystallized or transformed into other phases and created a negative shape within garnet (Fig. 4f). Such inclusions with negative shapes can be misidentified as melt inclusions, but the wide compositional variations and textures oppose such an interpretation. In addition to orthopyroxene, clinopyroxene and plagioclase, new garnet with high Mg and low Ca contents (garnet II in Fig. 4g) rimming old garnet (garnet I) can form during granulite facies overprint.

Hence as for crustal materials, PT paths derived from mantle rocks involved in (U)HP terrains provide a unique opportunity to constrain and deduce key aspects of the geotectonic evolution of the subduction system if metamorphic minerals formed during various stages (isobaric cooling, subduction, exhumation and/or a later thermal overprint) are clearly distinguished. Deformation and the access of fluid during subduction will have a significant effect on the partial or total re-equilibration of mantle rocks and hence the preservation of the metamorphic record available to allow sufficient resolution of PT paths.

## 3. Thermal regime along the interface of subduction slab

From the examples set out above, formation and exhumation of rocks along a subduction zone cooler than the surrounding mantle can allow preservation of (U)HP phases, while isothermal decompression at high temperature from peak pressure, perhaps involving heating, will lead to pervasive re-equilibration and decomposition of (U)HP minerals and their textures. The thermal structure of subduction zones depends on the age and speed of the incoming oceanic lithosphere, shear stresses across the subduction interface, induced convection in the overlaying mantle wedge, geometry of subduction, enthalphies of metamorphic reactions, fluid migration through the subduction zone and radioactive heating (Peacock, 1996; Stern, 2002). Following Kibry et al. (1991), depression of mantle isotherms is proportional to the thermal parameter $\phi = A(V_n{*}\sin\,\delta)$, where A is the age of subducted slab at the trench, $V_n$ is the convergence rate perpendicular to the trench and $\delta$ is the dip of the subduction zone. A subduction zone that rapidly digests old and cold lithosphere (Fig. 2a) is much colder at a given depth than one that slowly subducts young lithosphere (Fig. 2b). These models of subduction zone thermal structures are supported by seismic imaging (Stern, 2002).

Fig. 5a, b indicate detailed profiles across the slab interface with the mantle wedge at depths of 100 and 150 km for two end-member, cold and warm subduction zone scenarios, respectively (Peacock and Wang, 1999; Stern, 2002). The temperature reached by slab in a cold subduction zone (fast subduction, old crust) at the depth of 100 and 150 km is around 400 and 600 $^{o}$C, respectively. In a warm and slow subduction zone, temperatures at such depths are greater, estimated at 750 and 850 $^{o}$C. Numerical calculations, using isoviscous mantle-wedge rheology and olivine mantle-wedge rheology, performed by Peacock et al. (2005) for a relatively young slab (15-25 Ma) beneath NW Costa Rica indicated that temperatures reached by the 7 km thick slab below the interface vary in the range from 634 to 367 °C and 791 to 403 $^{o}$C, respectively (Fig. 5c, d). The temperature step at around 2 GPa is due to mantle corner flow as estimated for this subduction zone. This has also been found in some other generalised numerical models for subduction zones (e.g. Gerya et al., 2002) in which indicate a high-temperature geotherm at depth of >150 km is indicated due to mantle corner flow. Nevertheless, it is noteworthy that both end-member models shown in Fig. 6 c,d predict lower temperatures at depths of 100 and 150 km than those reached by most of the granulite facies overprints recorded in (U)HP terrains (Section 2 above).

The low down-slab thermal gradient for subduction zones, as estimated above, is supported by P-T paths obtained for many blueschists, or even eclogite facies rocks formed from subducted slab. Crystallization or recrystallization of mantle peridotite entrained into subduction zones mostly occur by isobaric cooling. One of the best examples of estimated temperature conditions of mantle rocks above the subducted slab was described from the WGR by Spengler et al. (2009). Here, Paleoarchaean garnet pyroxenites within mantle garnet peridotite that was accreted to the Laurentian shield lower lithosphere in the Mesoproterozoic (Brueckner et al., 2010) have undergone Scandian recrystallization and re-equilibrated to sub-geotherm temperatures (for Archaean cratons) at c. 870 $^{o}$C and 6.3 GPa and evolved by cooling to c. 800$^{o}$C and 3.8GPa, converging with P-T conditions in local crustal UHP eclogites. This is consistent with re-equilibration of hot mantle rocks in a cooler subduction zone environment. If the HP or UHP massif with fragments of mantle rocks is subsequently overprinted by granulite facies metamorphism during exhumation to a lower crustal environment, the minerals in the mantle ultramafic rocks are also likely to undergo re-equilibration (Faryad et al., 2018).

The presence of blueschist facies metasediments with carpholite or glaucophane and jadeite from various high-pressure terranes (e.g., Theye and Seidel, 1991; Faryad, 1995; Vidal and Theye, 1996; Goffe et al., 1998) and from basement rocks that reached (U)HP conditions at relatively low thermal gradient (e.g., Krogh, 1980, Schertl et al., 1991, Castelli et al., 2007; Xia et., 2012; Jedlicka et al. 2015) suggests that there is no or subordinate difference in thermal regime between oceanic and continental subduction systems, at least during early stages of continental subduction. This was confirmed also by comparison of subducted continental margins from three HP belts in the New Caledonia, Oman and Corsica (Agard et al (2013). These authors showed that thermal regime of all three continental subduction systems is largely invariant through time and independent from the initial geodynamic setting. They also concluded that continental material subducted over a short time period (i.e., ~ 10 My) represents cold underplated material with a thermal regime of continental subduction of about ~ 8–10 °C/km.

## 4. Subduction and exhumation rates

In addition to the thermal regime along the subduction zone, subduction and exhumation rates are crucial controls on the PT paths of (U)HP rocks. In the case of fast (cold) subduction, the rocks are heated slowly and, depending on the thickness of slab or crustal slice, the rocks might show a significantly decrease in temperature with increasing distance from the interface to the mantle. As discussed above, the thermal structure of a subduction zone and its evolution depend, to a large extent, upon the flux of cool lithosphere into the mantle, which, if defined by the motion vector down the plane of the subduction channel, is equivalent to the subduction rate (rate of loss of lithosphere at a trench, equivalent to the horizontal convergence rate). According to Hoareau et al. (2015), the mean subduction rate during closure of the Neotethys in the Paleocene (65 to 56 Ma) had a constant convergence rate of ≈ 5.5 $cm.a^{-1}$. Increased rates (up to 8.3 $cm.a^{-1}$) are computed between 56 and 53 Ma, before a gradual decrease down to 3 $cm.a^{-1}$ at 35 Ma. The India-Asia convergence, which reached up to 16.7 $cm.a^{-1}$ at 53–52 Ma, exerted the main control on high early Cenozoic subduction rates. However, petrological and geochronological data can only give rates of vertical translation (change in P over time) so, for comparison, the subduction rate must be expressed in the form of its vertical component of motion. This depends on subduction angle. Given that most subduction zones have dips of 25-50°, vertical subduction rates will be between roughly one half and three quarters of the convergence rate. If the slab steepens significantly at the onset of collision (see, for example Bottrill et al., 2012) the vertical subduction rate may approach the convergence rate. Subduction rates higher than 3.5 $cm.a^{-1}$ are in accordance with global plate convergence rates (Matthews et al., 2016). Based on the results of numerical experiments by Yamato et al. (2009), subduction rates of small-scale subduction zones are faster than that of plate convergence.

In contrast to rapid subduction (at rates of 5 – 15 $cm.yr^{-1}$) of oceanic slabs, convergence rates of continental slabs are much slower, sometimes not exceeding a few $mm.yr^{-1}$ (Burov et al., 2001). Some authors (e.g. Kylander-Clark et al., 2012) consider a link between size of ultrahigh-pressure terranes and their subduction/exhumation rates, where small and thin terranes are subducted and exhumed faster than large and thick terranes. Small, thin terranes can be created during the early stages of continental subduction when the volume of negatively buoyant, subducting oceanic lithosphere is still relatively large, thus forces that pull the subducting lithosphere down prevail and rapid, steep-angle subduction results. Large, thick terranes may form during the later stages of continent collision when subduction of thick, positively buoyant continental lithosphere leads to slow, gentle-angled subduction. Thermal weakening and anatexis may influence the mechanical behaviour of the lithosphere: In the case of oceanic subduction, the slab has no time to heat up by thermal diffusion from the surrounding asthenosphere. As a consequence, it loses its strength only at a great depth. However, during slower continental subduction the lithosphere may heat up, thermally weaken and drip-off before it reaches the UHP depth (e.g., Yamato et al., 2008, Bottrill et al., 2014). Heating and associated anatexis may also be important for the mechanical behaviour of exhuming continental crust, where it may result in weakening and detachment of terranes or even wholesale ductile extrusion (e.g. Grujic et al., 2011).

Exhumation rates proposed based on geochronological data indicate a wide variation ranging from a few $mm.a^{-1}$ (e.g. Frederico et al., 2005; Agard et al., 2009; Kylander-Clerk and Hacker, 2014) up to several cm $a^{-1}$ (Rubatto and Herman, 2001). To estimate the time-scale of exhumation, at least two ages from different minerals formed during (U)HP and amphibolite-granulite facies conditions, respectively, are needed. Apart from Sm-Nd and Lu-Hf ages from garnet that grows mostly during the eclogite facies stage, time-relations of formation of other minerals used for age dating are usually difficult to establish. However, in some well-studied HP terranes where abundant age data were obtained by a combination of methods including ion microprobe, high subduction/exhumation rates were estimated. The best constrained age of HP metamorphism and exhumation rate come from Lu–Hf dating in garnets in the youngest (Late Miocene) UHP rocks from Papua New Guinea, yielding 7.1±0.7 Ma (Zirakparvar et al., 2011). A second age of 3.0–2.5 Ma obtained using U-Pb dating in zircon from a leucosome cross cutting the UHP rocks (Gordon et al., 2012), indicates that the UHP rocks were already emplaced in an upper crustal position at that time. The approximate total distance of vertical transport of about 90 km (from garnet formation in the coesite stability field at 3 GPa (Zirakparvar et al., 2011)) to the upper crustal (0.3 – 0.2 GPa) over 4 Ma yields minimum exhumation rates of at least 2.25 cm.a$^{-1}$. Some high exhumation rates ($\geq$ 1–5 cm.a$^{-1}$) come from UHP rocks in the Dora Maira Massif in the Western Alps (Gebauer et al., 1997; Rubatto and Hermann, 2001) or even 8-14 cm.a$^{-1}$from UHP rocks in the Kaghan Valley in the western Himalaya (Wilke, 2010). According to Malusa et al. (2011), faster exhumation rates than that of subduction may be attributed to localisation of extension within the weak portion of the upper plate, at the rear of the accretionary wedge.

A great advance in understanding subduction and exhumation processes has been achieved by numerical or analogue modelling (e.g., Gerya and Stockhert, 2002; Mishin et al., 2008; Li, 2014), but the results allow a wide range of subduction and exhumation rates. Some authors (Gerya and Stockhert, 2002) deduce that the subduction and exhumation rates could be about 0.17 to 0.29 of the plate convergence rate, which is due to the transport of material by forced flow in the subduction channel. However, they also show that the return flux may significantly exceed subduction flux if high pressure metamorphic rocks are exhumed as crustal slices (thrust nappes), as shown in the analogue experiments of Chemenda et al. (1995).

Several attempts have been made to calculate cooling rates during exhumation using the effect of diffusion upon zoning profiles in garnet (Chakraborty and Ganguli, 1992; Carlson, 2006). Faryad and Chakraborty (2005) used volume diffusion to estimate the time scale for diffusion across the interface of the core and rim zones of garnet from the Eastern Alps, the core formed by Variscan medium-pressure and the rim by Alpine high-pressure metamorphic events. They calculated an average rate of 4.2 cm.a$^{-1}$ for subduction and exhumation, assuming that they both occurred at the same velocity. This rate, obtained for continental basement rocks involved in a subduction zone, is close to those estimated for subduction of oceanic crust (Stern, 2002). A similar rate was obtained by diffusion modelling for two garnets with an amphibolite facies core and eclogite facies rim in the Marianske Lazne Complex (Bohemian Massif, Faryad, 2012). The presence of prograde zoned garnet formed in (U)HP rocks with a granulite facies overprint (Fig. 6) in the Bohemian Massif (Jedlicka et al., 2016) is further evidence of fast subduction and exhumation rates, because a longer residence time at high T would have relaxed or erased any strong compositional gradients. Except for mineral inclusions (phengite, coesite, microdiamond, Perraki and Faryad, 2014) in garnet or in zircon, this rock shows a strong granulite facies overprint that occurred during exhumation in crustal positions at 1.2 – 1.6 GPa. Thermodynamic modelling indicates exhumation of the rocks at a relatively low temperature and then formation of new garnet rimming the old (U)HP garnet during the granulite facies stage. Because of the fast diffusion coefficients of major elements, the two garnets were recognised by their annular peak of Y and HREE (Fig. 6b). It was also shown that the granulite facies event was too short to homogenise even the Mn zoning (the element with fastest diffusion coefficient) in garnet with a radius of 1.25 mm.

In summary, subduction and exhumation rates are fundamentally controlled by the rates of plate convergence, which correspond reasonably well with values of > 1 $cm.a^{-1}$ estimated using available geochronological data. Isotopic age dating of minerals without detailed evaluation of their textural records along the relevant PT path can lead to significant error. Constraining the age or rate can be complicated by using minerals and/or rock samples that might represent different time sectors of a long-lasting subduction system or even relics from pre-orogenic events.

## 5. Reconciling petrological observation, geophysical data and geochronology

### *5.1. Field and petrological observations of (U)HP rocks*

From the distribution of (U)HP rocks along Phanerozoic subduction zones, it is clear that subducting slabs sink into mantle and only insignificant amounts of HP rocks are returned back to the surface. Their exhumation mostly occurs when continental crust enters the subduction zone. (U)HP rocks are present in masses of various sizes from a few cm up to many tens of km, usually in the form of relics within large masses where the UHP mineralogy has been destroyed by retrograde metamorphism. Following emplacement into the main orogenic edifice they have undergone re-equilibration within crustal positions. Because of amphibolite or even granulite facies metamorphism (Figs. 1b, 3, 4) and often pervasive post-(U)HP deformation, the (U)HP phases and textures are often only preserved in low-strain or unhydrated domains. The (U)HP rocks have sometimes been interpreted as tectonic blocks that are emplaced in low- to medium-grade rocks of accretionary complexes (Ernst, 1970; Gansser, 1974). Numerous discoveries of coesite and microdiamond in surrounding gneisses and granulites (e.g. Wain et al., 1997; Dobrzhinetskaya et al., 1995; Okay et al., 1989; Zhang et al., 1997; Cuthbert et al., 2000; Nasdala and Masonne, 2000; Xu et al., 2003; Kotková et al., 2011; Dobrzhinetskaya and Faryad, 2011; Janák et al., 2013; Perraki and Faryad, 2014; Klonowska et al., 2017) indicated that the (U)HP metamorphism is not restricted to small pods and bodies but are parts of large coherent slices exhumed from a subduction zone where they had reached mantle depths, as suggested already by Cuthbert et al. (1983) and Griffin et al. (1985).

Among the best and most complex examples supporting subduction and exhumation of (U)HP rocks as coherent slices at the end of collisional orogeny are the Bohemian Massif (Faryad et al., 2015), the WGR, Norway (Young, 2017) and Dabie-Sulu, China (Zheng et al., 2018). In the Bohemian Massif, where deeper parts of the Variscan collision orogen in Europe are exposed, numerous bodies of retrogressed eclogites and felsic granulites, exhibiting evidence of (U)HP conditions, are present. In the Moldanubian Zone, (U)HP rocks occur within gneisses and migmatites and they can be traced along three parallel SSW-NNE trending belts (Fig. 7a). The central belt is represented by more than 200 bodies of retrogressed eclogites that mostly associate with spinel-bearing serpentinite (Faryad et al., 2013b). Bodies of granulite (up to 30 x 20 km in size) and granulite gneisses with lenses and fragments of garnet peridotite, garnet pyroxenite and eclogite are distributed along the eastern and western borders of this zone. Based on their geochemistry, the eclogites with spinel peridotite (from central belt) derived from subducted oceanic crust rocks (Medaris et al., 1995). They mostly show amphibolite facies recrystallization and re-equilibration, with PT conditions similar to that in the surrounding gneiss. Several large bodies of eclogite and granulite microdiamond gneiss (see Faryad, 2011 and references therein) are present in the Saxothuringian Zone. Regarding their lithology and PT conditions, some eclogite, but mainly granulite with lenses and boudins of garnet peridotite and garnet pyroxenite, are similar to those in the Moldanubian Zone.  Some low-to medium grade surrounding rocks in this zone show evidence of an earlier blueschist facies metamorphism (Faryad and Kachlík, 2013).

The preservation prograde zoning garnet in felsic granulite from the Bohemian Massif, despite their exhumation from mantle depths and subsequent heating (Faryad, Perraki, 2014; Nahodilová et al., 2014; Jedlicka et al., 2015; Jedlicka and Faryad, 2017), is unique evidence for a relative cool geotherm along a subduction zone and for a short-living heating process that it was not enough to homogenize even the major component zoning in garnet (Fig. 4). The interplay of mantle melting and high-temperature metamorphism is a possible mechanism for amphibolite to granulite facies heating. It is supported by the coincidence of syn-orogenic mafic-ultramafic intrusions and granulite facies metamorphism (Fig. 7b). A c.340 Ma age for the peak of granulite facies metamorphism is well-known from abundant geochronological data (see Schulmann et al., 2005; Teipel et al., 2012). Coronitic troctolite and olivine gabbro (number 1 and 3 in Fig. 7a) of similar age were recently reported by Faryad et al. (2015; 2016).

These ultramafic and mafic intrusives (II in Fig. 7b) were mostly recrystallized in amphibolite facies conditions and had previously been interpreted as part of old basement units. They associate with felsic granulite that was partly exhumed from UHP depths (I in Fig. 7b) and due to interaction with mafic-ultramafic magma were heated to granulite facies conditions (III in Fig. 7b). The coronitic phases (ortho-and clinopyroxene, spinel, garnet, sapphirine, plagioclase), formed by cooling and recrystallization in PT conditions similar or close to those of the surrounding granulite. Fast exhumation after this thermal overprint in lower to middle crustal levels is supported by the overlap of ages of coronitic (metamorphosed) mafic and ultramafic bodies and of unmetamorphosed ultramafic massifs (up to 10 km in size) (Ackerman et al., 2013). In addition, there are numerous lamprophyre dykes and high K and Mg syenite plutons that were intruded (Fig. 7a) after consolidation and exhumation of (U)HP rocks and yield age of 345–337 Ma for their crystallization (Holub et al., 2007; Kubinová et al. 2017). According to Kubinová and Faryad (2019), some lamprophyres were derived by partial melting of enriched mantle that had previously been refertilised by subduction fluids or melts, and they were a precursor of the high K-Mg quartz syenite magma, which further evolved and assimilated with crustal material. The Variscan orogeny was terminated by underthrusting of the Brunovistolian Block beneath the Moldanubian Zone and formation of granite plutons (330-300 Ma) in the central part of the Moldanubian Zone.

### *5.2. Exhumation model and heat source for thermal overprint of (U)HP rocks*

An amphibolite or granulite facies overprint in HP and UHP rocks during their exhumation is known from many orogenic belts, but the source of this heating mostly remains unclear. By a combination of petrological observation and age dating, Walsh and Hacker (2004) found a regional “supra-Barrovian” or even Buchan-type metamorphic overprint of (U)HP rocks from the WGR. Their interpretation relies on two different ages, but the effect of this second metamorphic event on the modification of HP minerals was not analysed. In the northernmost WGR where peak pressures >4GPa are recorded, peak temperature at peak pressure is 800-900 $^{o}$C and possibly hotter, and temperature for a granulite overprint at ~1-1.5GPa exceeds 900$^{o}$C (Butler et al., 2018; Engvik et al., 2018; Dabekaussen, 2009), but the middle part of the apparently „isothermal“ decompression path was not constrained and could permit alternative paths including cooling prior to late heating, indeed this is consistent with garnet zoning in eclogites with a granulite overprint near Molde in the WGR that show distinct zoning, interpreted by Engvik et al. (2018) as growth zoning due to heating during decompression. Preservation of the zoning would, we suggest, indicate that this heating was short-lived, thus avoiding relaxation of the compositional gradients. According to Möller et al. (2015), eclogites from the Sveconorwegian Orogen were exhumed with surrounding migmatised gneiss by melt-assisted extrusion as a hot, magmatic nappe. Little et al. (2001) proposed a partial exhumation model of (U)HP rocks from Papua New Guinea by diapir from the depths of 100–60 km and melting at crustal levels. A recent study by Liao et al (2018) indicated that heating and melt formation was result of divergent motion of the upper plate. Liu et al. (2013) considered that UHP rocks (3.8 GPa/650 °C) from the Dabie Mountains were heated to 800 °C after their exhumation to a crustal position (1.6 GPa, Fig. 1b). (U)HP rocks from Kaghan Valley (western Himalaya) were heated after their rapid exhumation (almost 1 Ma) from a depth of 3.5 GPa to 1.2 GPa (Wilke et al., 2010). The Barrovian type thermal overprint of blueschist and eclogite in the Sivrihisar massif, Turkey (Whitney et al., 2011) suggest that the heating process is not restricted only to (U)HP rock, but LT/HP rocks can be also affected by such process.

During the past twenty years, many exhumation models of HP–UHP rocks have been proposed (e.g. Ernst, 1988; Rubatto and Hermann, 2001; Baldwin et al., 2004). They are mostly based on numerical calculations (Burov et al., 2001; Roselle and Engi, 2002; Gerya et al., 2002; Mishin et al., 2008; Bottrill et al., 2014) or analogue modelling (e.g. Chemenda, 1995, Schellart and Strak, 2016, Boutelier, and Cruden, 2017). Some of these models predict slab break-off (Davies and Blanckenburg, 1995; Ernst et al., 1997) or slab rollback (Stegman et al., 2006; Duretz and Gerya, 2013) that might explain the thermal overprint of (U)HP rocks. Some numerical models predict material fluxes through the subduction channel, from which they may escape upwards at various levels into positions where the rocks can reach a high temperature by laterally spreading as plume into the hot mantle (e.g. Gerya et al., 2008). These models predict relatively slow exhumation rates (a few $mm.a^{-1}$), similar to those proposed on the basis of geochronological data. On the other hand, analogue models and numerical models involving slab break-off or slab rollback predict exhumation of crustal slices into the accretionary complex (van Hunen and Alan, 2011; Sizova et al., 2019) or wholesale eduction (Duretz et al., 2012; Bottrill et al, 2014) and the exhumation rates can be as fast as that of subduction rates (several $cm.a^{-1}$).

Petrological data indicating preservation of prograde zoning in garnet suggest that slab breakoff (slab delamination) or slab rollback (Fig. 8) seem offer plausible mechanisms to explain the observed textural and phase relations. All these models show mantle upwelling into the mantle wedge. Slab breakoff (Fig. 8a, b) results from entry of continental crust into the subduction channel and its insertion beneath the mantle wedge leads to a change of the stress regime and rupture of the subducted slab (Davies and Blanckenburg, 1995). As the lower part of the slab sinks away, the upper part moves first in the reverse direction and then uplifts together with the whole accretionary complex. This process is accompanied by the development of deep return flow and back propagation of thrusts. Brueckner and Cuthbert (2013) envisaged a similar mechanism in the WGR in which the collisional orogenic wedge was disrupted by the exhuming UHP crust. Heating of partially exhumed (U)HP rocks (Figs 1b, 3) can be caused by mantle melt that has penetrated the base of the wedge. Grujic et al. (2011) proposed a similar mechanism for young, granulitised eclogites in the eastern Himalaya, where delamination and associated mafic magmatism during the Miocene caused extensive partial melting below the northern Tibetan Plateau, followed by southward extrusion of the lower part of the thickened crust with a cargo of eclogite pods. In the case of slab rollback, where a subducting slab migrates in the opposite direction to its overall plate motion, it drives extension and thinning of the overriding plate and upward extrusion of asthenospheric mantle (Brun et al., 2016; Smith et al., 2017; Sternai et al., 2014). According Sizova et al (2019), where UHP rocks were exhumed to the lower-crustal depths prior to roll-back they may then be conductively heated by up to 200 $^{o}$C by the underlying hot asthenospheric mantle bulge, giving a so-called "β-shaped" P-T path with late heating of the type discussed here.

We conclude that crustal rocks are subducted along a relatively cool thermal (subduction zone) gradient and after returning from peak pressure, they are subjected to short-living HT-UHT overprint (PT paths 1 and 3 in Fig. 3) driven by heat input from hot mantle and mafic magma following slab break-off or rollback. In the case of mantle rocks, formation or recrystallization of minerals could have occurred partly during cooling due to the subduction thermal gradient prior to their involvement into down-going or up-going crustal rocks (PT path 2a).

### *5.3. Implication of (U)HP minerals and their textures in reconstruction of metamorphic processes in subduction zone*

From the above discussion, (U)HP minerals and their textures provide the first order information and direct evidence about the thermal regime along subduction zones and later collisional events that occurred along an orogenic zone. The results obtained from well-studied (U)HP terranes fit well with geophysical data on thermal gradients and relevant subduction and exhumation rates. Reconstruction of subduction and or exhumation events based only on geochronological data have several pitfalls. There is a limited number of dateable minerals (e.g. garnet, mica, etc) that form during the prograde stage or peak pressure conditions. Garnet is one of the most common and abundant phases in (U)HP rocks and it preferentially accommodates significant amounts of trace elements. It tends to crystallize during subduction and reduces the availability of components for necessary for the formation of accessory phases (e.g. zircon Slama et al., 2007), unless the garnet is decomposed or the rocks are affected by a new metamorphic process. Therefore, accessory phase like zircon and monazite can date pre-subduction or post-peak-pressure events. On the other hand, there are examples (e.g., Ducea et al., 2003; Smith et al., 2013), where garnet has been used successfully to date the prograde stage of (U)HP metamorphism. If rocks are not affected by deformation or fluid infiltration, mica present in (U)HP rocks can date prograde stage, but as hydrous phases they easily undergo recrystallization and/or re-equilibration. The slow (<$cm^{-1}$) subduction and exhumation rates proposed for some (U)HP terranes could be due to age data obtained from different phases or even different samples that correspond to different time segments during subduction orogeny. Ideally, the best means of calculating both subduction and exhumation rates could be geospeedometry using a single phase (e.g. garnet). Garnet showing two-phase growth zoning with a compositional gap formed during two metamorphic events (Faryad and Chakraborty, 2005) could be used, or garnet from a single metamorphic event if some prograde zoning is still preserved. This method, combining thermodynamic and diffusion modelling, was first proposed by Gaidies et al (2008) and later by Faryad et al (2019). It uses a predicted prograde PT path calculated on the basis of bulk rock chemistry and zoning in garnet using Perpl_X thermodynamic modelling software (Connolly, 2005) and then calculates the diffusional modification of the zoning based upon the modelled PT-path. Application of this method to eclogites with preserved prograde zoning or two stage garnet growth offers the potential to calculate subduction and exhumation rates in future studies.

An important outcome from the above discussion is that isothermal decompression at high T, or an externally sourced thermal pulse, leads to partial or total re-equilibration of minerals formed during prograde or peak pressure stages. Hence significant caution is necessary in the construction of P-T paths where data points are scarce on the decompression path, and some apparently isothermal decompression paths such as those shown in Fig. 1 may conceal more complex trajectories involving a late higher-temperature excursion. It seems possible that an HT metamorphic overprint of (U)HP rocks due to heat input from mantle derived magma after their partial exhumation is a common process, but this can be difficult to recognize without detail petrography and careful examination of mineral textures. A possible objection to this hypothesis is the current lack of evidence for syn-orogenic mafic-ultramafic magmatism in many of these UHP complexes. But as shown by Faryad et al., (2015, 2016), some mafic ultramafic bodies associate with granulite might easily be mistaken for old, pre-orogenic mafic intrusions, especially if they have undergone recrystallization and deformation during emplacement, and they may only be detected by careful field, petrographic and geochronological investigation. Is it worth mentioning that, in slab breakoff, direct conductive heat transfer from hot asthenosphere may also be a major contributor to the thermal input (as suggested, for example, by Grujic et al., 2011 for the Himalaya).

## 6. Conclusions

Combining petrological observations from (U)HP rocks of the Bohemian Massif with their field relationships, geophysical observations and geochronological data, and taking into consideration observations on (U)HP rocks in many other orogenic belts, the following can be concluded:

1. Formation and exhumation of (U)HP rocks usually occurs along a relatively cool subduction zone. In the case of crustal material, the rocks are heated during subduction, but during exhumation they cool back, unless the heat is supplied by mantle melt penetrating the subduction zone or underplating the (U)HP complex following emplacement in lower to middle crust positions.
2. Mantle rocks at the contact with the down-going slab are relatively cool, which is consistent with a subduction zone thermal regime. Their recrystallization partly occurrs prior to their entrainment into down- or up-going felsic continental material. The mantle rocks could be exhumed from different depths, but most of them are captured by down-going crustal rocks and recrystallise due to both cooling and pressure increase. Cooling during decompression occurs if the mantle rocks are entrained into crustal rocks during their exhumation.
3. Most HP rocks are exhumed as coherent slices along a cool subduction zone. The commonly-observed granulite overprint indicates that they underwent an increase in T in the lower to middle crustal position as a result of advection of heat in mantle melt generated due to slab break-off or slab rollback. Because of the short duration of magmatic heating and lack of deformation in the central parts of the slices, the rocks tend to undergo only partial recrystallization and can preserve prograde zoning in minerals such as garnet. Simple thermal relaxation and radiogenic heating without mantle melt invasion may lead to only limited heating taking place during decompression.
4. Subduction and exhumation rates are in the range of a few cm per year, mainly reflecting the rate of adjacent plate convergence, but sometimes enhanced by local mechanisms operating within the orogenic wedge. Together with the relatively low thermal gradient along the subduction zone, the fast exhumation rate is another factor favouring the preservation of

prograde zoning garnet in many (U)HP rocks. If followed by a rapid and fast-decaying thermal pulse during exhumation due to magmatic heating, prograde garnet zoning is more likely to be preserved in spite of the high temperatures attained, while longer-lasting thermal relaxation in the absence of magmatic heating may modify or remove prograde zoning, at least at an equivalent exhumation rate.

**Acknowledgment**

This work was supported by the Czech Science Foundation (research project number 18-03160S). SC acknowledges financial support from the University of the West of Scotland and the Carnegie Trust for the Universities of Scotland. We are very grateful to three anonymous reviewers for constructive comments and helpful suggestions that have led to significant improvements in the manuscript.

**Figure captions**

Fig. 1. Selected exhumation PT paths of (U)HP rocks. (a) cooling during exhumation, (b) almost isothermal decompression (dashed) or heating after partial exhumation (solid). PT paths in (a): DS - Dabie Sulu, Central China (Liu et al., 2007), KM - Kokchatav Massif, Kazakhstan (Zhang et al., 1997), SM1 - Sivrihisar Massif, Central Turkey (Whitney et al., 2011), WD and WS - Dora Maira Massif and Sesia Zone, Western Alps (Agard et al., 2009). PT paths in (b): AT - Altyn Tagh, NW china (Zhang et al., 2001), D1 - Dabie, Central China (Liu et al., 2015), D2 - Dabie, Central China (Liu, et al., 2013), EG - Erzgebirge, Bohemian Massif (Haifler and Kotková, 2016) LD - Lepontin Dome, Central Alps (Wiederkehr et al., 2008), ME - Moldanubian eclogite, Bohemian Massif (Faryad and Fišera, 2016), MG (Moldanubian granulite, Bohemian Massif (Jedlicka et al., 2015), NG – New Guinea (Faryad et al., 2019), NQ - North Qaidam, Western China (Hu et al., 2015), PL - Piemonte Ligurian, Western Alps (Bousquet, 2008), SM2 - Sivrihisar Massif, Central Turkey (Whitney et al., 2011), WG - Western Gneiss Region (Butler et al., 2018; Engvik et al., 2018), WM - Monviso, Western Alps (Agard et al., 2009). Grey thick lines in (a) delimit metamorphic facies (A - amphibolite, B - blueschist, E - eclogite and Gr - granulite).

Fig. 2. Thermal models of end-member (young and hot versus old and cold) subduction zones (redrawn from Peacock, 1996 and Stern,2002). Bold lines represent the top of the subduction slab.

Fig. 3. PT-paths (1-3) of retrogressed eclogite from the Moldanubian Zone with granulite facies overprint as a separate metamorphic process (Frayad and Fišera, 2015). The eclogite facies (dashed ellipse) phases are prograde zoning garnet (gt), rutile (ru), omphacite (om) and quartz (q) in the matrix (a). Decompression and retrogression (path 2) are documented by the formation of plagioclase (pl) + amphibole (amph) + clinopyroxene (cpx) symplectite after omphacite (b) and fractures in garnet (c) filled by amphibole (am). Note that amphibole is preserved in the tip part of the cracks, while the thicker parts are partly recrystallised into clinopyroxene and spinel during granulite facies (path 3) overprint. The wider fractures (d, detail from a) consist of two zones, olivine (ol) + spinel (sp) in the central part and spinel + pure anorthite (an) at the contact with garnet.

Fig. 4. PT paths (a) and microtextures (b-g) of mantle rocks involved in subduction zones. Thin solid (1a, Spengler et al., 2006, Scambelluri, 2008) and dashed lines (1b, Li et al. 2018) are PT paths for mantle rocks from WGR and Sulu. They both indicate first isobaric cooling and then compression with slight increase of temperature during subduction, followed by decompression and cooling during exhumation. Thick dash-dotted PT paths are from the Bohemian Massif (Faryad et al., 2013a, 2018) with textural examples in (b-g). Numbers 2, 2a and 2b refer to mantle rocks involved into down going or up going crustal material from different mantle depths above the slab. (I) indicates spinel peridotite with layers of pyroxenite transformed into garnet peridotite (III) and garnet pyroxenite (II). Number 3 shows granulite facies overprint (see Fig. 4d-g). Figure (b) shows Cr-rich spinel enclosed by garnet during cooling and compression (I to III). Kelyphitic corona of orthopyroxene and Al-rich spinel around garnet indicate later retrograde stage during exhumation. (c) garnet lamellae formation in Al-pyroxene as result of cooling and or compression (I to II) in relatively dry clinopyroxenite layers. (d-g) recrystallization of hydrated mafic dyke of basalt-clinopyroxenite composition. (d) Na-rich clinopyroxene, formed during subduction, is rimmed by diopside and matrix additionally contains orthopyroxene and plagioclase. (e) show garnet with inclusion of recrystallized former hydrous phases. Omphacite forms at the contact with garnet and albite + K-feldspar in the central part of inclusion. (f) negative shape formed by interaction of hydrous phase (transformed to K-feldspar with ternary feldspar (tfs, Na>Ca>K)) with the host garnet. (g) shows two garnet generations representing UHP and granulite facies overprint from the same sample.

Fig. 5. Details of thermal structures in the subduction zone. (a) and (b) are profiles perpendicular to the slab interface at depths of 100 and 150 km across cold and warm subduction zones, respectively, as shown in Fig. 2. The thick lines indicate the interface of slab with mantle wedge. (c) and (d) show P-T paths for subduction lithosphere for a rock located at the top of the subducting plate and at 1 km intervals down to 12 km below the interface (Peacock et al., 2005). The P-T paths are calculated for the slab beneath NW Costa Rica using isoviscous mantle-wedge rheology (c) and olivine mantle-wedge rheology (d).

Fig. 6. Quartz-feldspatic granulite from the coesite and microdiamond locality in the Moldanubian Zone (Perraki and Faryad, 2014) with prograde zoning garnet. The two stage UHP core (gt I) and granulite facies rims (gt II) garnet are characterised by high HREE+Y in the central part of garnet (I) and annular peak at the border with garnet (II) (Jedlicka et al., 2015). Values of the vertical axis are the concentration ratios of major components (alm - almandine, prp - pyrope, grs - grossular, sps - spessartine). Because of different concentration amounts of elements, the vertical axis for HREE+Y is not scaled.

Fig. 7a. schematized geological map of the Bohemian Massif with locations of (U)HP rocks (from Faryad and Kachlik, 2013; Faryad and Žák, 2016). CBPC-Central Bohemian Plutonic Complex (arc related magmatism, 355-345 Ma), MPC-Moldanubian plutonic complex (post-collisional granite, 330-300 Ma). Potasic-ultrapotasic (quartz syenite, melanosyenite) plutons (346-337 Ma) are also shown. Numbers (1-3) are locations of mafic-ultramafic intrusions (~340 Ma). (b) complex P-T diagram showing crystallization history of late-orogenic olivine gabbro and troctolite intrusions (around 340 Ma) with coronae textures formed by spinel-clinopyroxene-garnet-amphibole and orthopyroxene-spinel-sapphirine-garnet-amphibole, respectively, in the Moldanubian Zone (Faryad et al., 2015, 2016). These coeval intrusions of ultramafic and mafic bodies (b) resulted in heating of partially exhumed (UHP) felsic rocks (a) to granulite facies conditions (c). The stability field and solidus boundaries are from Gasparik (2003). Note that garnet stabilises in olivine gabbro by cooling below 900–950 °C. Dashed lines indicate earlier UHP and subsequent granulite facies metamorphism followed by cooling (Perraki and Faryad, 2014; Jedlicka et al., 2015).

Fig. 8. Schematic cross-sections and slab breakoff model (a, b) proposed for subduction and exhumation of crustal and mantle rocks during Variscan Orogeny in the Bohemian Massif (modified from Faryad et al., 2009, 2018). (a) Spinel pyroxenite layers, crystallised from mafic

melt and together with the host peridotite picked by crustal rocks during subduction and recrystallised into garnet pyroxenite. (b) Mantle upwelling as result of slab breakoff and heating of partially exhumed rocks to granulite facies conditions. (c) indicate alternative model of slab rollback (Sizova et al., 2019) with mantle upwelling that might result heating of partially exhumed (U)HP rocks within the mantle wedge.

## References

Ackerman, L., Pašava, J., Erban, V., 2013. Re-Os geochemistry and geochronology of the Ransko gabbro-peridotite massif, Bohemian Massif. Mineralium Deposita 48, 799-804.

Agard, P., Yamato, P., Jolivet, L., Burov, E., 2009. Exhumation of oceanic blueschists and eclogites in subduction zones: timing and mechanisms, Earth Science Reviews 92, 53-79.

Amato, J.M., Johnson, C.M., Baumgartner, L.P., Beard, B.L., 1999. Rapid exhumation of the Zermatt-Saas ophiolite deduced from high-precision Sm-Nd and Rb-Sr geochronology. Earth Planet. Sci. Lett. 171, 425-438.

Angiboust, S., Agard, P. Jolivet, L., Beyssac O. 2009. The Zermatt-Saas ophiolite: the largest (60-km wide) and deepest (c. 70-80 km) continuous slice of oceanic lithosphere detached from a subduction zone? Terra Nova 21, 171-180.

Austrheim, H. 1987. Eclogitization of lower crustal granulites by fluid migration through shear zones. Earth and Planetary Science Letters, 81, 221-232.

Austrheim, H., Griffin, W.L. 1985. Shear deformation and eclogite formation within granulite-facies anorthosites in the Bergen Arcs, western Norway. Chemical Geology, 50, 267-281.

Baldwin, S.L., Monteleone, B., Webb, L.E., Fitzgerald, P.G., Grove, M., Hill, E.J., 2004. Pliocene eclogite exhumation at plate tectonic rates in eastern Papua New Guinea. Nature 431, 263-267.

Bodinier J L, Godard M. 2014. Orogenic, ophiolitic, and abyssal peridotites. In: Holland H D, Turekian K K, eds. Treatise on Geochemistry. 2nd ed. Amsterdam: Elsevier. 103-167.

Bottrill, A. D., van Hunen, J., Allen, M. B. 2012. Insight into collision zone dynamics from topography: numerical modelling results and observations. Solid Earth Discussions 4, 889-917.

Bottrill , AD., van Hunen, J., Cuthbert, S. J., Brueckner, H. K., Allen, M. B., 2014. Plate rotation during continental collision and its relationship with the exhumation of UHP metamorphic terranes: Application to the Norwegian Caledonides Geochem. Geophys. Geosyst. 15, doi:10.1002/2014GC00525.

Bousquet R., 2008. Metamorphic heterogeneities within a same HP unit: overprint effect or metamorphic mix? Lithos 103, 46-69

Boutelier, D., Cruden, A.R., 2017. Slab breakoff: Insights from 3D thermo-mechanical analogue modelling experiments. Tectonophysics 694, 197-213.

Brueckner, H. K., 1998. Sinking intrusion model for the peridotites, garnet pyroxenites and eclogites of Alpe Arami emplacement of garnet-bearing peridotites into continent and Cima di Gagnone, Central Alps, from early Proterozoic collision orogens. Geology 26, 631-634.

Brueckner, H.K., Carswell, D.A., Griffin W.L., 2002. Paleozoic diamonds within a Precambrian peridotite lens in UHP gneisses of the Norwegian Caledonides. Earth and Planetary Science Letters 203, 805-816.

Brueckner, H.K. Carswell, D.A. Griffin, W.L. Medaris Jr., L.G. Van Roermund, H.L.M. Cuthbert, S.J., 2010. The mantle and crustal evolution of two garnet peridotite suites from the Western Gneiss Region, Norwegian Caledonides: An isotopic investigation. Lithos 117, 1-19.

Brueckner, H K., van Roermund, H L. M. 2007. Concurrent HP metamorphism on both margins of Iapetus: Ordovician ages for eclogites and garnet pyroxenites from the Seve Nappe Complex, Swedish Caledonides. Journal of Geological Society 164, 117-128.

Brueckner, H. K., Cuthbert, S.J., 2013. Extension, disruption, and translation of an orogenic wedge by exhumation of large ultrahigh-pressure terranes: Examples from the Norwegian Caledonides. Lithosphere 5, 277-289.Burov, E.B., Jolivet, L., Le Pourhiet, L., Poliakov, A., 2001. A thermemechanical model of exhumation of HP and UHP metamorphic rocks in Alpine mountain belts, Tectonophysics 342, 113-136.

Brun, J.-P., Faccenna, C., Gueydan, F., Sokoutis, D., Philippon, M., Kydonakis, K. and Gorini, C. 2016. The two-stage Aegean extension, from localized to distributed, a result of slab rollback acceleration. Canadian Journal of Earth Sciences, 53, 1142-1157.Bucher, K. H. and Grapes, R. 2009. The Eclogite-facies Allalin Gabbro of the Zermatt-Saas Ophiolite, Western Alps: a Record of Subduction Zone Hydration. Journal of Petrology 50, 1405-1442.

Butler, J.P. Jamieson, R.A. Dunning, G.R. Pecha, M.E. Robinson, P. Steenkamp, H.M. 2018. Timing of metamorphism and exhumation in the Nordøyane ultra-high-pressure domain, Western Gneiss Region, Norway: New constraints from complementary CA-ID-TIMS and LA-MC-ICP-MS geochronology. Lithos 310-311, 153-170.

Burov, E., Jolivet, L., Le Pourhiet, L. and Poliakov, A, 2001. A thermomechanical model of exhumation of high pressure (HP) and ultra-high pressure (UHP) metamorphic rocks in Alpine type collision belts. Tectonophysics 342, 113-136.

Carlson, W.D. 2006. Rates of Fe, Mg, Mn and Ca diffusion in garnet. American Mineralogist 91,1-11.

Carswell D.A., Harvey, M.A., Al-Samman, A. 1983. The petrogenesis of contrasting Fe-Ti and Mg-Cr garnet-peridotite types in the high grade gneiss complex of western Norway. Bull Mineral, 106, 727-750

Carswell D.A., 1986. The Metamorphic Evolution of Mg-Cr Type Norwegian garnet peridotites. Lithos 19, 279-297

Castelli, D., Rolfo, F., Groppo, C. and Compagnoni, R. 2007. Impure marbles from the UHP Brossasco-Isasca Unit (Dora-Maira Massif, western Alps): evidence for Alpine equilibration in the diamond stability field and evaluation of the X(CO2) fluid evolution. Journal of Metamorphic Geology 25, 587-603.

Chakraborty, S., and Ganguly, J. 1991. Compositional zoning and cation diffusion in garnet, in J. Ganguly, ed., Diffusion, Atomic Ordering and Mass Transport: Selected Topics in Geochemistry, Advances in Physical Geochemistry 8, p. 120-175.

Chakraborty S, Ganguly J (1992) Cation diffusion in aluminosilicate garnets: experimental determination in spessartine-almandine diffusion couples, evaluation of effective binary diffusion coefficients, and applications, Contribution to Mineralogy and Petrology 111, 74-86.

Chemenda, A.I., Mattauer, M., Mattavieille, J., Bokun, A.N., 1995. A mechanism for syn-collisional rock exhumation and associated normal faulting: results from physical modelling. Earth Planet. Sci. Lett. 132, 225-232.

Cherniak, D. J., and Watson, E. B. 2003. Diffusion in Zircon, in Zircon: Experiments, Isotopes, and Trace Element Investigations, Rev. Mineral. 53, 113-143.

Chi, W.-C., Reed, D.L. 2008. Evolution of shallow, crustal thermal structure from subduction to collision: An example from Taiwan. Geological Society of America Bulletin 120, 679-690, 335-356.

Clark, C., Fitzsimons, I.C.W., Healy, D. and Harley, S.L. 2011. How Does the Continental Crust Get Really Hot? Elements 7, 235-240.

Clift, P., and Vannucchi, P. 2004. Controls on tectonic accretion versus erosion in subduction zones: Implications for theorigin and recycling of the continental crust. Rev. Geophys.,42, RG2001, doi:10.1029/2003RG000127.

Connolly, J. A. D., 2005. Computation of phase equilibria by linear programming: A tool for geodynamic modeling and its application to subduction zone decarbonation. Earth and Planetary Science Letters 236, 524-541.

Cuthbert, S.J., Harvey, M.A., Carswell, D.A., 1983. A tectonic model for the metamorphic evolution of the Basal Gneiss Complex, western south Norway. Journal of Metamorphic Geology 1, 63-90

Cuthbert S.J, Carswell, D.A, Krogh-Ravna, E.J, Wain, A., 2000. Eclogites and eclogites in the Western Gneiss Region, Norwegian Caledonides. Lithos 52, 165-195;

Dabekaussen, W., 2009. First Evidence for Ultrahigh Pressure Metamorphism on Gossa, Western Gneiss Region, Norway. Unpublished MSc thesis, Faculty of Geosciences, Utrecht University. pp. 128.

Dachs, E., Proyer, A. 2002. Constraints on the duration of high-pressure metamorphism in the Tauern Window from diffusion modelling of discontinuous growth zones in eclogite garnet. J Metamorph Geol 20: 769-780.

Davies, H. J. and von Blanckenburg, F. 1995. Slab breakoff: A model of lithosphere detachment and its test in the magmatism and deformation of collisional orogens. Earth and Planetary Science Letters 129(1-4), 85-102.

Davis, P. B. and Whitney, D. L. 2006. Petrogenesis of lawsonite and epidote eclogite and blueschist, Sivrihisar, Turkey, J. Metamorph. Geol., 24, 823-849.

Dobretsov, N.L. Shatsky, V.S. 2004. Exhumation of high-pressure rocks of the Kokchetav massif: facts and models. Lithos 78, 307- 318.

Dobrzhinetskaya, L. Faryad, S.W. 2011. Frontiers of Ultra-high Pressure Metamorphism: View from Field and Laboratory. In Ultrahigh Pressure Metamorphism: 25 Years After The Discovery Of Coesite And Diamond, (ed. Dobrzhinetskaya, L., Faryad, SW, Wallis, S., Cuthbert, S.). Elsevier, p. 1-40.

Dobrzhinetskya, L.F., Eide, E.A., Larsen, R.B., Sturt, B.A., Trønnes, R.G., Taylor, W.R., Poshukhova, T.V., 1995. Microdiamonds in high-grade metamorphic rocks from the Western Gneiss Region, Norway. Geology 23, 597-600;

Dobrzhinetskaya, L.F. and Faryad, S.W. 2011. Frontiers of Ultra-high Pressure Metamorphism: View from Field and Laboratory. In Ultrahigh Pressure Metamorphism: 25 Years After The Discovery Of Coesite And Diamond, (ed. Dobrzhinetskaya, L., Faryad, SW, Wallis, S., Cuthbert, S.). Elsevier, 1-40.

Doglioni, C. Carminati, E. Cuffaro, M. Scrocca, D. 2007. Subduction kinematics and dynamic constraints Earth-Science Reviews 83, 125-175

Dong, J., Wei, Ch. and Zhang, J. 2019. Ultra high temperature metamorphism of mafic granulites from South Altyn Orogen, West China: A result from the rapid exhumation of deeply subducted continental crust. Journal of Metamorphic Geology 37, 315 -338.

Ducea, M.N., Ganguly, J., Rosenberg, E., Patchett, P.J., Cheng, W. Isachsen, C. 2003. Sm-Nd dating of spatially controlled domains of garnet single crystals: a new method of high-temperature thermochronology. Earth and Planetary Science Letters 2013, 31-42.

Duchene, S., Albarede, F. and Lardeaux, J.M. 1998. Mineral zoning and exhumation history in the Munchberg eclogites (Bohemia), Am J Sci 298, 30-59.

Duretz ,T., Gerya, T., Spakman, W., 2012. Slab detachment in laterally varying subduction zones: 3-D numerical modeling. Journal of Geophysical Research 117, B08411, doi:10.1029/2012JB009137.

Engi, M., Giuntoli, F., Lanari, P., Burn, M., Kunz, B., and Bouvier, A.-S. 2018. Pervasive eclogitization due to brittle deformation and rehydration of subducted basement: Effects on continental recycling? Geochemistry, Geophysics, Geosystems 19, 865-881.

Engvik, A. K., and Andersen, T. B. 2000. Evolution of Caledonian deformation fabrics under eclogite and amphibolite facies at Vardalsneset, Western Gneiss Region, Norway. Journal of Metamorphic Geology 18, 241-257.

Engvik, A.K., Willemoes-Wissing, B. and Lutro, O. 2018. High-temperature, decompressional equilibration of the eclogite facies orogenic root (Western Gneiss Region, Norway). Journal of Metamorphic Geology 36, 529-545.

Ernst, W.G. 1970. Tectonic contact between the Franciscan Mélange and the Great Valley Sequence-Crustal expression of a Late Mesozoic Benioff Zone. Journal of Geophysical Research 75, 886-901.
Ernst, W.G., 1988. Tectonic histories of subduction zones inferred from retrograde blueschist P-T paths. Geology 16, 1081-1084.
Ernst, W. G., Maruyama, S., Wallis, S. 1997. Buoyancy-driven, rapid exhumation of ultrahigh-pressure metamorphosed continental crust. Proceedings of the national academy of sciences of the United States of America 94, 9532-9537.
Faryad, S.W. 1995. Petrology and phase relations of low-grade high-pressure metasediments from the Meliata Unit (west Carpathians, Slovakia). European Journal of Mineralogy 7, 57-74.
Faryad, S.W., 2011. Distribution and geological position of high-/ultrahigh-pressure units within the European Variscan Belt: a review, in: Dobrzhinetskaya, L., Faryad, S.W., Wallis, S., Cuthbert, S. (Eds.), Ultrahigh Pressure Metamorphism: 25 Years After the Discovery of Coesite and Diamond, Elsevier, p. 361-397.
Faryad, S.W. 2012. High-pressure polymetamorphic garnet growth in eclogites from the Mariánské Lázně Complex (Bohemian Massif). European Journal of Mineralogy, 24, 483-497.
Faryad, S.W. and Chakraborty, S. 2005. Duration of Eo-Alpine metamorphic events obtained from multicomponent diffusion modeling of garnet: A case study from the Eastern Alps. Contr. Mineral Petrol. 150, 305-318.
Faryad, S.W., Baldwin, S.L. Jedlicka, R. and Ježek, J. 2019. Two-stage garnet growth in coesite eclogite from the southeastern Papua New Guinea (U)HP terrane and its geodynamic significance. Contributions to Mineralogy and Petrology. 174: 73, doi.10.1007/s00410-019-1612-4
Faryad, S.W., Dolejš D. and Machek, M. 2009. Garnet exsolution in pyroxene from clinopyroxenites in the Moldanubian zone: constraining the early pre-convergence history of ultramafic rocks in the Variscan orogen. Journal of Metamorphic Geology 27, 655-671.
Faryad, S.W., Jedlicka, R. and Collett, S., 2013b. Eclogite facies rocks of the Monotonous unit, clue to Variscan suture in the Moldanubian Zone (Bohemian Massif). Lithos 179, 353-363.
Faryad, S. W. and Fišera, M. 2015. Olivine-bearing symplectites in fractured garnet from eclogite, Moldanubian Zone (Bohemian Massif) - a short-lived, granulite facies event. Journal of Metamorphic Geology 33, 597-612.
Faryad, S.W., Jedlicka, R. and Ettinger, K. 2013a. Subduction of lithospheric upper mantle recorded by solid phase inclusions and compositional zoning in garnet: example from the Bohemian Massif. Gondwana Research 23, 944-955.
Faryad, S.W., Jedlicka, R., Hauzenberger, C. and Racek, M. 2018. High-pressure crystallization vs. recrystallization origin of garnet pyroxenite-eclogite within subduction related lithologies. Mineralogy and Petrology, 112, 603-616.
Faryad, S.W., Ježek, J. 2019. Compositional zoning in garnet and its modification by diffusion during pressure and temperature changes in metamorphic rocks. Lithos 332-333, 287-95.
Faryad, S. W. and Kachlík, V., 2013. New evidence of blueschist facies rocks and their geotectonic implication for Variscan suture(s) in the Bohemian Massif. Journal of Metamorphic Geology 31, 63-82.
Faryad, S.W., Kachlík, V., Sláma, J. and Hoinkes, G. 2015. Implication of corona formation in a metatroctolite to the granulite facies overprint of HP-UHP rocks in the Moldanubian Zone (Bohemian Massif). Journal of Metamorphic Geology 33, 295-310.
Faryad, S.W, Kachlík, V., Sláma J., Jedlicka, R. 2016. Coincidence of gabbro and granulite formation 1 and their implication for Variscan HT metamorphism in the Moldanubian Zone (Bohemian Massif), example from the Kutná Hora Complex. Lithos 264, 56-69.

Faryad, S.W., Nahodilová, R. and Dolejš, D. 2010. Incipient eclogite facies metamorphism in the Moldanubian granulites revealed by mineral inclusions in garnet. Lithos 114, 54-69.
Faryad, S.W and Žák, J. 2016. High-pressure granulites of the Podolsko complex, Bohemian Massif: An example of crustal rocks that were subducted to mantle depths and survived a pervasive mid-crustal high-temperature overprint. Lithos 246-247, 246-260.
Federico, L., Capponi, G., Crispini, L., Scambelluri, M., and Villa, I.M. 2005. 39Ar/40Ar dating of high-pressure rocks from the Ligurian Alps: Evidence for a continuous subduction/exhumation cycle: Earth and Planetary Science Letters, v. 240, p. 668-680, doi: 10.1016/ j.epsl.2005.09.062.Ganguli, 1991
Gaidies, F., de Capitani, C. and Abart, R., 2008. THERIA_G: a software program to numerically model prograde garnet growth. Contributions to Mineralogy and Petrology 155, 657-671.
Gansser, A. 1974. The ophiolitic mélange, a world-wide problem on Tethyan examples. Eclogae Geologicae Helvetiae, 67, 479-507.
Gasparik, T. 2003. Phase diagrams for geoscientists. An atlas of the Earth's interior. Springer, 462 p
Gebauer, D. 1999. Alpine geochronology of the western Alps: new constraintsfor a complex geodynamic evolution. Schweizerische Mineralogische und Petrographische Mitteilungen. 79, 191-202.
Gebauer, D., Schertl, H.P., Brix, M., Schreyer, W., 1997. 35 Ma old ultrahigh-pressure metamorphism and evidence for very rapid exhumation in the Dora Maira Massif, Western Alps. Lithos 41 (1-3), 5-24.

Gerya T. V., Stöckhert B. 2002. Exhumation rates of high pressure metamorphic rocks in subduction channels: the effect of rheology. Geophysical Research Letters 29,DOI: 10.1029/2001GL014307.
Gerya T.V., Perchuk, L.L., Burg J.-P. 2008. Transient hot channels: perpetrating and regurgitating ultrahigh-pressure, high temperature crust-mantle associations in collision belts. Lithos 103, 236-256.
Goffe, B.,Michard, A., Garcia-Duenas, V., Gonzales-Lodeiro, F.Monie, F., Campos, J., Galindo-Zaldivar, J., Jabaloy, A. Martinez-Martinez, J. M. Simancas, J. F. 1998. First evidence of high-pressure, low-temperature metamorphism in the Alpujärride nappes, Betic Cordilleras (S.E. Spain). European Journal of Mineralogy 1, 135-137.
Gordon, S.M., Little, T.A., Hacker, B.R., Bowring, S.A., Korchinski, M., Baldwin, S.L., and Kylander-Clark, A.R.C., 2012, Multi-stage exhumation of young UHP-HP rocks: Timescales of melt crystallization in the D'Entrecasteaux Islands, southeastern Papua New Guinea: Earth and Planetary Science Letters 351-352, 237-246.
Griffin, W. L., Austrheim, H., Brastad, K., Bryhni, I., Krill, A. G., Krogh, E. J., Mørk, M. B. E., Qvale, H., and Tørudbakken, B., 1985. High-pressure metamorphism in the Scandinavian Caledonides, in Gee, D. G., and Sturt, B. A., eds., The Caledonide Orogen: New York, J. Wiley, p. 783-801.
Grujic, D., Warren, C.J., Wooden, J. 2011. Rapid synconvergent exhumation of Miocene-aged lower orogenic crust in the eastern Himalaya. Lithosphere 3, 346-366.
Haifler, J. and Kotková, J. 2016. UHP-UHT peak conditions and near-adiabatic exhumation path of diamond-bearing garnet-clinopyroxene rocks from the Eger Crystalline Complex, North Bohemian Massif. Lithos 248-251, 366-381.
Hacker, B.R. and Gerya, T.V., 2013. Paradigms, new and old, for ultrahigh-pressure tectonism. Tectonophysics 603, 79-88.
Harris, N. 2007. Channel flow and the Himalayan-Tibetan orogen: a critical review. Journal of the Geological Society 164, 511-523.

Hetzal, R. and Romer, R. 2000. A moderate exhumation rate for the high-pressure Maksyutov Complex, southern Urals, Russia. Geological Journal 35,327 - 344.

Hoareau, G. Bomou, B., van Hinsbergen, D. J. J. Carry, N., Marquer, D. Donnadieu, Y. Le Hir, G., Vrielynck, B. and Walter-Simonnet, A.V. 2015. Did high Neo-Tethys subduction rates contribute to early Cenozoic warming? Clim. Past, 11, 1751-1767.

Holub, F. V., Cocherie, A., Rossi, P., 1997. Radiometric dating of granitic rocks from the Central Bohemian Plutonic Complex (Czech Republic): constraints on the chronology of thermal and tectonic events along the Moldanubian-Barrandian boundary. Comptes Rendu Academy of Sciences Paris, Sciences de la terre et des planétes, Earth and Planetary Sciences 325, 19-26.

Hu, R., Wijbrans, J., Brouwer, F., Zhao, L., Wang, M., Qiu, H. 2015. Retrograde etamorphism of the eclogite in North Qaidam, western China: Constraints by joint 40Ar/39Ar in vacuo crushing and stepped heating. Geoscience Frontiers 6, 759-770

Janák, M. - Krogh Ravna, E. J. - Kullerud, K. - Yoshida, K. - Milovský, R. - Hirajima, T. 2013. Discovery of diamond in the Tromsø Nappe, Scandinavian Caledonides (N. Norway). In Journal of Metamorphic Geology 31, 691-703.

Jedlicka, R., Faryad, S. W. 2017. Felsic granulite with layers of eclogite facies rocks in the Bohemian Massif; did they share a common metamorphic history? Lithos 286-287, 408-425.

Jedlicka, Faryad, S.W and Hauzenberger, C. 2015. Prograde Metamorphic History of UHP Granulites from the Moldanubian Zone (Bohemian Massif) Revealed by MajorElement and Y 1 REE Zoning in Garnets. Journal of Petrology 56, 2069-2088.

Kirby SH, Durham WB, Stern LA. 1991. Mantle phase changes and deep-earthquake faulting in subducting lithosphere. Science 252, pp. 216-225.

Klonowska, I., Janák, M., Majka, J., Petrík, I., Froitzheim, N., Gee, D. G., Sasinková, V., 2017. Microdiamond on Åreskutan confirms regional UHP metamorphism in the Seve Nappe Complex of the Scandinavian Caledonides. Journal of Metamorphic Geology 35, (5), 541-564.

Kotková, J., 2007. High-pressure granulites of the Bohemian Massif: Recent advances and open questions. Journal of Geosciences 52, 45-71.

Kotková, J., O'Brien, P., Ziemann, M., 2011. Diamond and coesite discovered in Saxony-type granulite: Solution to the Variscan garnet peridotite enigma. *Geology* 39, 667-670.

Krogh, E. J. 1980. Geochemistry and petrology of glaucophanc bearing eclogites and associated rocks from Sunnfjord, western Norway. Lithos 13, 355-380.

Kubínová, Š., Faryad, S.W. Mineral textures of olivine minette and their significance for crystallization history of parental magma; an example from the Moldanubian Zone (the Bohemian Massif). Mineralogy and Petrology 113, 477-491.

Kubínová, Š, Faryad, S.W., Verner, K., Schmitz, M. and Holub, F. 2017. Ultrapotassic dykes in the Moldanubian Zone and their significance for understanding of the post-collisional mantle dynamics during Variscan orogeny in the Bohemian Massif. Lithos 272-273, 205-221.

Kylander-Clark, A. R., Hacker, B.**,** 2014. Age and significance of felsic dikes from the UHP western gneiss region, Tectonics, 33, 2342, doi:10.1002/2014TC003582.

Kylander-Clark, A.R., Hacker, B.R. Johnson, C.M. Beard, B.L. Lapen, T.J., 2007. Coupled Lu-Hf and Sm-Nd geochronology constrains prograde and exhumation histories of high- and ultrahigh-pressure eclogites from western Norway. Chemical Geology 242, 137-154.

Labrousse L., Jolivet L., Andersen T.B., Agard P., Hébert R., Maluski H., Schärer U.,2004, Pressure-temperature-time deformation history of the exhumation of ultra-high pressure rocks in the Western Gneiss Region, Norway, in Whitney D.L., et al., eds., Gneiss domes in orogeny: Geological Society of America Special Paper 380, 155-184.

Lasaga, A. 1998. Kinetic Theory in the Earth Sciences Princeton University press. 728 pp.
Li, Z.H. 2014. A review on the numerical geodynamic modeling of continental subduction, collision and exhumation. China Earth Sci.57: 47. doi.org/10.1007/s11430-013-4696-0.
Li, H.-Y., Chen, R.-X., Zheng, Y.-F., Hu, Z., and Xu, L. 2018. Crustal metasomatism at the slab-mantle interface in a continental subduction channel: Geochemical evidence from orogenic peridotite in the Sulu orogen. Journal of Geophysical Research: Solid Earth 123, 2174-2198.
Liaoa,J, Malusà, M.G., Zhao, L., Baldwine, S. L., Fitzgerald, P.G., Gerya, T. 2018. Divergent plate motion drives rapid exhumation of (ultra)high pressure rocks. Earth and Planetary Science Letters 491, 67-80.
Liou, J.G., Ernst, W.G., Zhang, R.Y., Tsujimori, T. and Jahn B.M. 2009. Ultrahigh-pressure minerals and metamorphic terranes - The view from China. Journal of Asian Earth Sciences 35, 199-231
Liou, J.G., Zhang, R.Y., Ernst, W.G., 2007. Very-high-pressure orogenic garnet peridotites. Proc. Natl. Acad. Sci. USA 104, 9116-9121.
Little, T.A., Hacker, B.R., Gordon, S.M., Baldwin, S.L. Fitzgerald, P.G., Ellis, S., and Korchinski, M., 2011. Diapiric Exhumation of Earth’s youngest (UHP) eclogites in the gneiss domes of the D'Entrecasteaux Islands, Papua New Guinea. Tectonophysics 510, 39-68.
Liu, Y-C., Deng, L-P., Gu, X-F., Groppo, C., Rolfo, F. 2015. Application of Ti-in-zircon and Zr-in-rutile thermometers to constrain high-temperature metamorphism in eclogites from the Dabie orogen, central China. Gondwana Research 27, 410-423
Liu, Q., Hermann, J., Zhang, J. 2013. Polyphase inclusions in the Shuanghe UHP eclogites formed by subsolidus transformation and incipient melting during exhumation of deeply subducted crust. Lithos 177, 91-109.
Matthews, K.J., Maloney, K.T., Zahirovic, S., Williams, S.E., Seton, M. and Müller, R.D. 2016. Global plate boundary evolution and kinematics since the late Paleozoic. Global and Planetary Change 146, 226-250.
Malusà, M.G., Faccenna, C., Garzanti, E., Polino, R. 2011. Divergence in subduction zones and exhumation of high pressure rocks (Eocene Western Alps). Earth and Planetary Science
Medaris, L.G., Wang, H.F., Mísař, Z., Jelínek, E., 1990. Thermobarometry, diffusion modelling and cooling rates of crustal garnet peridotites: Two examples from the Moldanubian zone of the Bohemian Massif. Lithos 25, 189-202.
Medaris, L. G., Beard, B. L. and Jelínek E. 2006. Mantle-derived, UHP garnet pyroxenite and eclogite in the Moldanubian Gföhl Nappe, Bohemian Massif: a geochemical review, new P-T determinations, and tectonic interpretation. International Geology Review 48, 765-777.
Medaris, G., Jelinek, E., Misar, Z., 1995. Czech eclogites—terrane settings and implications for variscan tectonic evolution of the Bohemian Massif. European Journal of Mineralogy 7, 7-28.
Mishin, Y. A., Gerya, T. v., Burg, J.-P. and Connolly, J. A. D. 2008. Dynamics of double subduction: numerical modeling. Physics of the Earth and Planetary Interiors 171, 280-295.
Möller Ch., Andersson, J. Dyck, D., Lundin, I. A. 2015. Exhumation of an eclogite terrane as a hot migmatitic nappe, Sveconorwegian orogen. Lithos 226, 147-168.
Nasdala, L. and Massonne H.-J. 2000. Microdiamonds from the Saxonian Erzgebirge, Germany: in situ micro-Raman characterisation. Eur. J. Mineral. 12, 495-498.
Nakakuki, T and Mura, E. 2013. Dynamics of slab rollback and induced back-arc basin formation Earth and Planetary Science Letters 361, 287-297.
O’Brien, P.J., 2008. Challenges in high-pressure granulite metamorphism: Reaction textures, compositional zoning, ages and tectonic interpretation with examples from the Bohemian Massif. Journal of Metamorphic Geology 26, 235-251.

Okay, A., Xu, S. and Sengbr, A.M.C., 1989. Coesite from the Dabie Shan eclogites, central China. Eur. J. Mineral. 1, 595-598.
Perraki, M., Faryad, S.W., 2014. First finding of microdiamond, coesite and other UHP phases in felsic granulites in the Moldanubian Zone: Implications for deep subduction and a revised geodynamic model for Variscan Orogeny in the Bohemian Massif. Lithos 202-203, 157-166.
Peacock, S. M. 1996. Thermal and petrologic structure of subduction zones (overview), in Subduction Top to Bottom, edited by G. E. Bebout, pp. 119-134, AGU, Washington, D. C.
Peacock, S. M., Van Keken, P. E. Holloway, S. D. Hacker, B. R. Abers, G. A. and Fergason, R. L. 2005. Thermal structure of the Costa Rica-Nicaragua subduction zone, Phys. Earth Planet. Inter. 149, 187-200.
Peacock, S. M., Wang, K. 1999. Seismic consequences of warm versus cool subduction metamorphism: Examples from southwest and northeast Japan. Science 286, 937-030.
Proyer, A., Postl, W. 2010. Eclogitized Gabbros from Gressenberg, Koralpe, Austria: Transformation phenomena and their interpretation. Mitteilungen des naturwissenschaftlichen Vereines für Steiermark 140, 45-67.
Roselle, G.T. and Engi M. 2002. Ultra high pressure (UHP) terranes: lessons from thermal modeling. Am J Sci 302,410-441.
Rubatto, D. and Hermann, J. 2001. Exhumation as fast as subduction? Geology 29, 3-6
van der Straaten F, Schenk V, John T, Gao J. 2008. Blueschist-facies rehydration of eclogites (Tian Shan, NW-China): Implications for fluid-rock interaction in the subduction channel. Chemical Geology 255, 195-219.
Scambelluri, M., Pettke, T., van Roermund, H.L.M. 2008. Majoritic garnets monitor deep subduction fluid flow and mantle dynamics. Geology 36, 59-62.
Schellart, W.P and Strak, V. 2016. A review of analogue modelling of geodynamic processes: Approaches, scaling, materials and quantification, with an application to subduction experiments. Journal of Geodynamics 100, 7-32.
Schertl, H.-P., Schreyer, W. & Chopin, C., 1991. The pyrope-coesite rocks and their country rocks at Parigi, Dora-Maira Massif, Western Alps: detailed petrography, mineral chemistry and P–T path. Contributions to Mineralogy and Petrology, 108, 1- 21.
Schulmann, K., Kröner, A., Hegner, E., Wendt, I., Konopásek, J., Lexa, O., Štípská, P., 2005. Chronological constraints on the pre-orogenic history, burial and exhumation of deep-seated rocks along the eastern margin of the Variscan Orogen, Bohemian Massif, Czech Republic. American Journal of Science 305, 407-448.
Sizova, E., Hauzenberger, C., Fritz, H., Faryad, S.W. and Gerya, T. 2019. Late orogenic heating of (ultra)high pressure rocks: slab rollback vs. slab breakoff. Geosciences 9, 499; doi:10.3390/geosciences9120499.
Skora, S., Baumgartner, L. P., Mahlen, N. J., Johnson, C. M., Pilet, S., Hellebrand, E. 2006. Diffusion-limited REE uptake by eclogite garnets and its consequences for Lu-Hf and Sm-Nd geochronology. Contributions to Mineralogy and Petrology 152, 703-720.
Sláma, J., Košler, J. and Pedersen, R. B. 2007. Behaviour of zircon in high-grade metamorphic rocks: evidence from Hf isotopes, trace elements and textural studies. Contribution to Mineralogy and Petrology 154, 335-356.
Smit, A.A, Scherer, E.K. and Mezger, K. 2013. Lu-Hf and Sm-Nd garnet geochronology: Chronometric closure and implications for dating petrological processes. Earth and Planetary Science Letters 381,222-233.
Smith, M. E., Carroll, A. R., Jicha, B. R., Cassel, E. J., & Scott, J. J. 2014. Paleogeographic record of Eocene Farallon slab rollback beneath western North America. Geology 42, 1039-1042.

Spengler, D., Van Roermund, H. M. L., Drury, M. R., Ottolini, L., Mason, P. R. D. and Davies, G. R. 2006. Deep origin and hot melting of an Archaean orogenic peridotite massif in Norway. Nature 440, 913-917.
Spengler, D., Brueckner, H.K., Van Roermund, H.L.M., Drury, M.R., Mason, P.R.D. 2009. Long-lived, cold burial of Baltica to 200 km depth. Earth and Planetary Science Letters 281, 27-35.
Stegman, D. R., Freeman, J., Schellart, W. P., Moresi, L. and May, D. 2006. Influence of trench width on subduction hinge retreat rates in 3-D models of slab rollback, Geochem. Geophys. Geosyst. 7, Q03012, doi:10.1029/2005GC001056.
Stern C.R. 2002. Subduction zone. Reviews of Geophysics 40, 3-38.
Stern, C.R. 2011. Subduction erosion: Rates, mechanisms, and its role in arc magmatism and the evolution of the continental crust and mantle, Gondwana Research 20, 284-308.
Sternai, P., Jolivet, L., Menant, A., & Gerya, T. 2014. Driving the upper plate surface deformation by slab rollback and mantle flow. Earth and Planetary Science Letters 405, 110-118.
Suenaga, N., Ji, Y., Yoshioka, S., Feng, D. 2018. Subduction thermal regime, slab dehydration, and seismicity distribution beneath Hikurangi based on 3-D simulations. Journal of Geophysical Research: Solid Earth 123, 3080-3097.
Teipel, U., Finger, F., Rohrmüller, J., 2012. Remnants of Moldanubian HP-HT granulites in the eastern part of the Bavarian Forest (southwestern Bohemian Massif): evidence from SHRIMP zircon dating and whole rock geochemistry. Zeitschrift der Deutschen Gesellschaft für Geowissenschaften 163 137-152.
Terry, M.P. and Robinson, P., 2004. Geometry of eclogite-facies structural features: Implications for production and exhumation of ultrahigh-pressure and high-pressure rocks, Western Gneiss Region, Norway. Tectonics 23, TC2001, doi:10.1029/2002TC001401.
Theye, T. and Seidel, E. 1991. Petrology of low-grade high-pressure metapelites from the External Hellenides (Crete, Peloponnese) A case study with attention to sodic minerals. European Journal of Mineralogy 3, 343 - 366
van Hunen, J. and Allen, M.B. 2011. Continental collision and slab break-off: A comparison of 3-D numerical models with observations. Earth and Planetary Science Letters 302, 27-37.
van Straaten, B.I., Kopylova, M.G., Russell, J.K., Webb, K.J. and Scott Smith, B.H., 2008. Discrimination of diamond resource and non-resource domains in the Victor North pyroclastic kimberlite, Canada. Journal of Volcanology and Geothermal Research 174: 128-138.
Vidal O. and Theye. T. 1996. Petrology of Fe–Mg-carpholite-bearing metasediments from NE Oman. Journal of metamorphic Geology 14, 381-397.
Vrijmoed, J. C., Van Roermund, H. L. M. and Davies, G. R. 2006. Evidence for diamond-grade ultra-high pressure metamorphism and fluid interaction in the Svartberget Fe-Ti garnet peridotite websterite body, Western Gneiss Region, Norway. Mineralogy and Petrology 88, 381-405.
Vrijmoed, J. C.; Austrheim, H.; John, T.; Hin, R. C.; Corfu, F.; Davies, G. R. 2013. Metasomatism in the Ultrahigh-pressure Svartberget Garnet-peridotite (Western Gneiss Region, Norway): Implications for theTransport of Crust-derived Fluids within the Mantle. Journal of Petrology 54, 1815-1848.
Wada, I and Wang, K. 2009. Common depth of slab-mantle decoupling: Reconciling diversity and uniformity of subduction zones. Geochemistry, Geophysics, Geosystems, 10, doi.org/10.1029/2009GC002570.

Wain, A.L., 1997. New evidence for coesite in eclogite and gneisses: defining an ultrahigh pressure province in the Western Gneiss Region of Norway. Geology 25, 927-930.
Walsh, E.O. and Hacker, B.R., 2004, The fate of subducted continental margins: Two-stage exhumation of the high-pressure to ultrahigh-pressure Western Gneiss Region, Norway: Journal of Metamorphic Geology 22, 671-687.
Whitney, D. L., Teyssier, C. Toraman, E. Seaton, N. C. A. and Fayon, A. K. 2011. Metamorphic and tectonic evolution of a structurally continuous blueschist-to-Barrovian terrane, Sivrihisar massif, Turkey, J. Metamorph. Geol. 29, 193-212.
Wiederkehr, M, Bousquet, R, Schmid1, S. M. and Berger, A. 2008. From subduction to collision: thermal overprint of HP/LT meta-sediments in the north-eastern Lepontine Dome (Swiss Alps) and consequences regarding the tectono-metamorphic evolution of the Alpine orogenic wedge. Swiss J. Geosci. 101, 127-155.
Wilke, F., O'Brien, P., Gerdes, A., Timmerman, M., Such, M., Ahmed Khan, M. 2010. The multistage exhumation history of the Kaghan Valley UHP series, NW Himalaya, Pakistan from U-Pb and $^{40}Ar/^{39}Ar$ ages. European Journal of Mineralogy 22, 703-719
Xia, Q-X., Zheng, Y-F., Lu, X-N., Hu, Z. and Xu, H.Formation of metamorphic and metamorphosed garnets in the low-T/UHP metagranite during continental collision in the Dabie orogen. Lithos 136–139, 73-92.
Xu, S., Liu, Y., Chen, G., Compagnoni, R., Rolfo, F., He, M., Liu, H., 2003. New finding of micro-diamonds in eclogites from Dabie-Sulu region in central eastern China. Chinese Science Bulletin 48, 988-994.
Yamato, P. Husson, L. Braun, J. Loiselet, C. and Thieulot, C. 2009. Influence of surrounding plates on 3D subduction dynamics. Geophysical Research Letters 36, L07303.
Young, D.J., 2017. Structure of the (ultra)high-pressure Western Gneiss Region, Norway: Imbrication during Caledonian continental margin subduction. Geological Society of America Bulletin 130, 926-940.
Zhang, J., Zhang, Z., Xu, Z., Yang, J. and Cui, J. 2001. Petrology and geochronology of eclogites from the western segment of the Altyn Tagh, northwestern China. Lithos 56, 187-206
Zhang, R.Y. and Liou, J.G., 2003. Clinopyroxenite from the Sulu ultrahigh-pressure terrane, eastern China: origin and evolution of garnet exsolution in clinopyroxene: American Mineralogist 88, 1591-1600.
Zhang, R.Y. and Liou, J.G. 2004. Partial transformation of gabbro to coesite-bearing eclogite from Yangkou, the Sulu terrane, eastern China. Journal of metamorphic Geology 15, 183-202.
Zhang, R.Y., Liou, J.G., Ernst, W.G., Coleman, R.G., Sobolev, N.V., Shatsky, V.S., 1997. Metamorphic evolution of diamond-bearing rocks from the Kokchetav Massif, northern Kazakhstan. Journal of Metamorphic Geology 15, 479-496.
Zhang R Y, Liou J G, Yang J S, Yui T F. 2000. Petrochemical constraints for dual origin of garnet peridotites from the Dabie-Sulu UHP terrane, eastern-central China. Journal of Metamorphic Geolology 18, 149-166.
Zhang, Y., Cherniak, D. J., 2010. Diffusion in minerals and melts. Reviews in Mineralogy and Geochemistry 72, 1-4.
Zirakparvar, N.A., Baldwin, S.L., Vervoort, J.D., 2011. Lu-Hf garnet geochronology applied to plate boundary zones: Insights from the (U)HP terrane exhumed within the Woodlark Rift. Earth and Planetary Science Letters 309, 56-66.
Zheng, Y-F., Zhao, Z-F., Chen, R-X. 2018. Ultrahigh-pressure metamorphic rocks in the Dabie-Sulu orogenic belt: compositional inheritance and metamorphic modification. HP-

UHP Metamorphism and Tectonic Evolution of Orogenic Belts. Geological Society, London, London, Special Publications, 474, https://doi.org/10.1144/SP474.9