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Timescales of exhumation and cooling inferred by kinetic modelling: An example using a lamellar garnet pyroxenite from the Variscan Granulitgebirge, E Germany

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Abstract

We present a numerical modeling approach to infer timescales of the exhumation and cooling history recorded in the chemical composition of minerals in a garnet pyroxenite from the Granulitgebirge, Saxony/Germany. The studied sample contains remarkable exsolution textures from former megacrysts that produced up to mm-wide, alternating lamellae of garnet (grt) and clinopyroxene (cpx). Compositional profiles of major and minor elements measured with the electron microprobe perpendicular to the grt-cpx interfaces reveal systematic zoning patterns for Fe, Mg, Al, Si, Cr, Ti in clinopyroxene and Ca, Fe, Mg, Mn in garnet, respectively. In addition to simple thermal modelling that is used to constrain the conditions of emplacement of the Granulitgebirge Massif at shallow crustal levels, we combine thermodynamic data with a numerical finite difference scheme that simulates growth and simultaneous diffusive exchange between garnet and clinopyroxene along a virtual cooling path. The latter model assumes local equilibrium at the interface. Diffusive fluxes are constrained by mass balance. It is shown that zoning patterns such as Fe-Mg exchange between garnet and clinopyroxene can be used to extract cooling rates and thus timescales of exhumation, while the profiles for the minor elements are provisionally related to the growth history of the lamellae. Furthermore, zoning profiles in the lamellae can only be reproduced with ultrahigh cooling rates similar to contact metamorphic conditions. This in turn, suggests that the massif was emplaced at temperatures above 900°C in agreement with the observed spatial extent of a contact aureole within low-grade metasedimentary rocks surrounding the granulite massif as predicted by thermal modeling. Exhumation of the massif without cooling below 900°C requires an exhumation rate of several cm/yr. Thus, we propose an almost

isothermal exhumation period of ~1Ma followed by isobaric cooling from 900 to 600°C within less than 10 ka.

Introduction

Metamorphic textures and mineral compositions are records of complex geodynamic processes such as subduction, orogenesis or exhumation. Determination of pressure and temperature conditions at various stages is one of the key tools to constrain the evolution of rock units on a larger scale. Commonly, thermodynamic calculations are used to infer P-T conditions based on observed phase assemblages and mineral compositions. The use of thermodynamic data is founded on the assumption that phases in a given sample are effectively able to adjust their composition up to a certain point in time and remain perfectly closed afterwards, i.e. without any further exchange reaction on the retrograde path. Especially in medium to high grade metamorphic rocks this assumption is questionable as virtually every system, evolving along a T-t path, is subject to diffusive re-equilibration to different extents. In the last decade, an increasing number of studies investigated non-equilibrium aspects with regard to textural and compositional records in rocks on various scales (e.g., Roselle et al., 1997; Mueller et al., 2004; Gaidies et al., 2008a; Gaidies et al., 2008b; Mueller et al., 2008; Caddick et al., 2010; Mueller et al., 2010; Gaidies et al., 2011). Rather than a limitation, the incomplete readjustment of mineral compositions during metamorphism should be regarded as an additional source of information on the mechanism and rates of processes, such as element / isotope exchange during large scale geodynamic processes with significantly changing P-T conditions (see also review by Mueller et al., 2010). Lasaga (1983) published a landmark paper in which he used the temperature dependent ability of diffusive compositional adjustment to infer exhumation rates based on the cooling history recorded in diffusion profiles of elements in minerals which led to the concept of “geospeedometry”. While the original focus of this approach was on exhumation rates, i.e. the determination of speed in mm/year, it has also often been misleadingly used to estimate timescales of igneous and metamorphic processes (for a detailed description see review by Costa et al., 2008). However, the concept of the determination of rates and durations of processes for isothermal and non-isothermal histories can successfully be applied if the relevant transport parameters, e.g. diffusion coefficients and information on other factors controlling the diffusive flux (e.g. grain size, modal abundance) are available. As a consequence, cooling histories of metamorphic terrains have been determined using this kinetic modeling approach (Lasaga et al., 1977; Spear and Florence, 1992; Ducea et al., 2003; Trepmann et al., 2004; Hauzenberger et al., 2005). Element exchange driven by diffusion is largely dependent on temperature, which directly relates the applicability of geospeedometry and geothermobarometry to the concept of diffusive closure of a mineral (Dodson, 1973; Dodson, 1986; Ganguly and Tirone, 1999). However, a complete description of the dynamic system governing the geochemical fluxes, in turn, allows evaluating whether mineral compositions are reset during heating, cooling and/or decompression and if so, to which extent. For example, the effect of mixed-volatile reaction, volume diffusion, and exsolution has been studied to successfully reproduce variations in measured calcite-dolomite thermometric data in contact metamorphic settings (Mueller et al., 2008). Recently, the Fe-Mg interdiffusion data for various ferromagnesian minerals such as garnet (Borinski et al., 2012), spinel (Liermann and Ganguly, 2002), clinopyroxene (Mueller et al., 2013), and orthopyroxene (Ganguly and Tazzoli, 1994) have been determined. Knowledge of these kinetic parameters in turn was used to evaluate the effect on the element distribution and thus on apparent thermometric data for typical cosmochemical and geological settings (Ganguly et al., 2013; Mueller et al., 2013).

In this paper, we use numerical models of kinetically controlled element exchange between co-existing garnet (grt) and clinopyroxene (cpx) exsolution lamellae to study the effect and timescales of diffusive compositional adjustment during a cooling and exhumation event. Such lamellae occur in an ultrabasic rock intercalated within a complex of high pressure granulite in the Variscan Granulitgebirge (Saxony/Germany). This metamorphic complex is a suitable example for two reasons: (1) the geological setting is simple enough to place solid constraints on the geometry, different lithologies, and tectonic setting (Fig. 1 and Reinhardt and Kleemann, 1994) and (2) there are a large number of studies which focused on the P-T evolution using exchange reactions and thermodynamic calculations (Roetzler and Romer, 2001; Massonne and Bautsch, 2002; Roetzler et al., 2004; Hagen et al., 2008; Roetzler et al., 2008; Schmaedicke et al., 2010) in addition to geochronological data that provide independent estimates for the timescale of the exhumation process (von Quadt, 1993; Kroener et al., 1998; Romer and Roetzler, 2001; Roetzler and Romer, 2010). It is shown here that a combination of equilibrium phase petrology and modeling of mass and heat transport can improve the reconstructed P-T-t exhumation path. Finally, the new results are discussed in the context of a large scale geodynamic exhumation model comparing previous petrological findings.

Geological settings and previously derived P-T-t evolution of the Granulitgebirge

The Variscan orogen of Europe formed by collision of the palaeocontinents Laurussia and Gondwana in the Late Palaeozoic. Many researchers assume that Gondwana-derived terrains collided with Laurussia first before Gondwana came in contact with Laurussia (e.g., Kroner and Romer, 2013). The eastern part of this orogen is represented by the Bohemian Massif, a collage of diverse basement blocks, which include units of high temperature, high to ultrahigh pressure metamorphic rocks from the root of the collisional orogen. These rock assemblages include garnet peridotite, eclogite, high pressure mafic and felsic granulite as well as related quartzofeldspathic rocks with a wide range of maximum P-T estimates [700° to 1100°C, 0.4 to 4.5 GPa (for summary see Massonne, 2011)]. The ages of high-pressure metamorphism in the Bohemian Massif are bimodal (Kroener and Willner, 1998): 400-380

Ma in the Gory Sowie, Tepla Barrandian Unit, and Münchberg Complex and 350-335 Ma in the Erzgebirge, Granulitgebirge, Snieznik, and Gföhl Unit (Fig. 1a). Evolution and mechanism of exhumation of these high pressure rocks are still a matter of debate (e.g., Willner et al., 2002; Kroner and Goerz, 2010).

The Granulitgebirge in Saxony (Germany) in the northern part of the Bohemian Massif represents a key unit for the younger high-pressure event, where geodynamic processes were studied in detail within a rather small area. The Granulitgebirge forms an oval-shaped dome structure composed of high-pressure felsic granulite including lenses of mafic granulite and garnet peridotite (Werner, 1987; Roetzler et al., 1992; Reinhardt and Kleemann, 1994; Roetzler and Romer, 2010). Protoliths of the granulites are Cambro-Ordovician igneous rocks with calcalkaline and tholeiitic affinities (Werner, 1987; Kroener et al., 1998). The contact of the Granulitgebirge to the surrounding rocks, which are low-pressure siliciclastic metasediments of early Palaeozoic to late Devonian age, is represented by a major extensional detachment zone. This shear zone comprises (1) the rim of the granulite complex, (2) dismembered slivers of medium-pressure garnet-cordierite gneiss and ophiolitic rocks, and (3) the lower part of the metasedimentary cover, and it shows a top-to-SE tectonic transport (Roetzler et al., 1992; Reinhardt and Kleemann, 1994). Various peak P-T conditions were estimated for the felsic and mafic granulites: >1 GPa, >800 °C (Grew, 1986; Roetzler et al., 1992), 2.2-2.3 GPa, >1000 °C (Roetzler and Romer, 2001; Roetzler et al., 2004; Hagen et al., 2008; Roetzler et al., 2008; Roetzler and Romer, 2010) and 1.4 GPa, > 800 °C (Massonne, 2006). The P-T estimates for the garnet peridotite and associated garnet pyroxenite and eclogite are in the range 1.9-3.3 GPa, 1000-1070 °C (Roetzler and Romer, 2001; Massonne and Bautsch, 2002; Schmaedicke et al., 2010). Later equilibration stages in the granulite during the exhumation were estimated to 0.9-0.95 GPa, 890-940 °C (Roetzler and Romer, 2001), 1.0-1.05 GPa, 940-980 °C [symplectite stage (Roetzler et al., 2008)] and 0.25 GPa, 740 °C [final emplacement stage (Roetzler et al., 2004)]. The age of the peak pressure conditions was constrained by dating of zircon (341.5±0.8 Ma) and titanite (342±0.8 Ma) with the U/Pb system (Romer and Roetzler, 2001). The obtained data agree with earlier zircon ages derived by von Quadt (1993) and Kroener et al. (1998). From the study of the garnet-cordierite gneiss, a decompression-heating path of 0.65 GPa, 730 °C to 0.5 GPa, 790°C was invoked by Roetzler & Romer (2010). These authors interpreted this partial P-T path as being due to heat transfer from the rising granulite.

The low-pressure metasediments (phyllite) surrounding the granulites show a progressive metamorphic zonation from very low grade metamorphic conditions towards incipient migmatization near the contact to the granulites at a depth corresponding to 0.2-0.3 GPa (Roetzler et al., 1992; Reinhardt and Kleemann, 1994). Subsequent growth of chlorite, andalusite, staurolite, cordierite, garnet, and sillimanite is observed in these metasediments (schist mantle). This ~1-3 km wide halo around the granulite complex is interpreted as the result of heating after emplacement of this complex during exhumation (Roetzler et al., 1992; Reinhardt and Kleemann, 1994; Roetzler and Romer, 2010). Rb/Sr ages of white mica in the low-pressure metasediments can be grouped into three categories according to Roetzler & Romer (2010): (1) ages of 348.6±3.5 Ma and 349.4±3.5 Ma at more than 600 m from the contact reflect the age of regional metamorphism of the sediments prior to emplacement of the granulites; (2) an age of 337.6±3.6 in the garnet-cordierite gneiss at the contact overlaps with the age of the peak of metamorphism in the granulite complex and is interpreted as the age of its juxtaposition with the granulite complex; (3) an age of 333.6±4.2 Ma in the schists at the contact is consistent with Ar-Ar ages of white mica of 334.2±1.9 Ma and 332.6±4 Ma (Werner and Reich, 1997) in these schists and a Pb-Pb single-zircon evaporation age of 333.1±1.0 Ma for a concordant granite intrusion into the schists (Kroener et al., 1998). The latter ages are interpreted as the time of the arrival of the granulite complex at shallow crustal depth and the formation of the contact metamorphic halo (Roetzler and Romer, 2010). The determined time interval for the exhumation of ~7 Myrs results in an exhumation rate of 7-13 mm/yr and a cooling rate of 40-70 °C/Myr (Roetzler and Romer, 2010). This very rapid extensional unroofing of the granulite complex from the root of a thickened crust (Reinhardt and Kleemann, 1994) is matched by comparable exhumation rates and mechanisms of high-pressure rocks in the Erzgebirge in the south (Willner et al., 2000; Willner et al., 2002; Massonne et al., 2007). Extensional unroofing in an "exhumation channel" is thought to be balanced by concomitant stacking at depth during ongoing convergence. Delamination of the lithospheric mantle was envisaged as primary cause for the rapid exhumation of the 350-335 Ma high-pressure rocks from the crustal root throughout the Bohemian Massif, where a thickened crust was likely maintained since the time of collision at 400-380 Ma (Massonne and O'Brien, 2003; Massonne, 2006), when the older high-pressure units of the Bohemian Massif originated. Other geodynamic models invoke intracontinental subduction (Kroner and Goerz, 2010; Kroner and Romer, 2013) or considerable crustal stacking after deep crustal subduction (O'Brien, 2008).

Sample description, mineral composition and origin of lamellar megacrysts

We studied a garnet pyroxenite from the abandoned serpentinite quarry at the village of Reinsdorf, Saxony (Germany). The garnet pyroxenite, which was first described by Hentschel (1937) and originally named as "Eklogit von Gilsberg", forms several centimeter to decimeter thick, boudinaged layers in the serpentinite body. These layers are parallel to each other. In some instances, alternating lamellae of garnet and clinopyroxene are discernable in the garnet pyroxenite (Fig. 2). Such domains of lamellar fabric are surrounded by more or less equigranular domains, which consist of mm-sized grains of garnet and clinopyroxene representing an equilibrium texture (Fig. 2). Both types of fabric can occur in homogeneous domains of several cm^3 in our sample. The equilibrium texture was the result of recrystallization of the lamellae proven by intermediate stages (e.g. curved and partially recrystallized lamellae as the result of deformation) between both types of fabric (Massonne and Bautsch, 2002). The garnet lamellae are topotaxially intergrown with clinopyroxene [cpx: (100)cpx//(110)grt and [001]cpx//[100]grt as well as (100)cpx//(100)grt and [001]cpx//[110]grt (Reiche and Bautsch, 1984; Jekosch and Bautsch, 1991)]. Therefore, the lamellar texture was interpreted to be the result of exsolution of garnet from clinopyroxene (Reiche and Bautsch, 1985) because of the dominance of clinopyroxene lamellae [vol.% cpx/grt = 7:3, (Massonne and Bautsch, 2002)]. As the lamellae can extend parallel over several cm, the invoked clinopyroxene originally occurred as megacrysts up to 10 cm in size forming once monomineralic layers in the exposed, now serpentinized mantle fragment.

Especially thick garnet lamellae without visible symplectites [composed of orthopyroxene, spinel, clinopyroxene and anorthite-rich plagioclase (Massonne and Bautsch, 2002)] were selected for detailed compositional profiles perpendicular to the interface between lamellae. Electron microprobe measurements have been performed using a Cameca SX 100 at Universität Stuttgart. Garnet and clinopyroxene composition have been analyzed at 15 kV and a beam current of 30 or 40 nA. A total of ten profiles for adjacent grt-cpx lamellae have been measured at different positions within the limits of a former megacryst. No significant difference can be observed and representative compositional profiles are shown in figure 3. Measured profiles reveal almost flat, but often slightly zoned patterns with increasing pyrope and almandine and decreasing grossular component from the garnet center towards the interface (Fig. 3), and almost no zoning of any major element from core to rim can be observed in the adjacent clinopyroxene (Fig. 3; see also Massonne and Bautsch, 2002). Spatially resolved minor element compositions show an increase in concentration of Cr, V and Ti towards the clinopyroxene rim. In contrast, no zoning for Cr and V can be observed in the garnet, which is also nearly free of titanium (Fig. 3).

In a previous study, Massonne and Bautsch (2002) determined the original megacryst composition on the basis of the compositions of the slightly chemically zoned clinopyroxene and garnet and their abundance. They concluded that the megacrysts were either Al-rich clinopyroxenes formed at about 1.7 GPa and 1400°C or Ca-majoritic garnets from an upper portion of the mantle transition zone. The question of the original host phase, i.e. whether garnet exsolved from clinopyroxene or vice versa, has important consequences for the reconstruction of the P-T evolution as argued by Massonne and Bautsch (2002). These authors used bulk rock trace element compositions to argue for a majoritic garnet to be the former host phase. In contrast, Reiche and Bautsch (1985) proposed cpx as the original phase based on the higher abundance of cpx compared to garnet. Roetzler and Romer (2010) argued that Al-rich spinel inclusions measured in garnet crystals of the matrix support the case of a cpx host. In fact, it is not essential to the purposes of this paper to determine the original host phase, but the spatially resolved compositional trace element profiles potentially contain the information needed to answer this question. For example, the virtually Ti-free garnet and the visible Ti-zoning in clinopyroxene (Fig. 3) could be interpreted as the consequence of titanium accumulation in clinopyroxene during the growth of the garnet lamella in which Ti is rather incompatible. Consequently, back diffusion of Ti into the residual clinopyroxene lamellae would then lead to the observed compositional profile as observed in other studies for Nb in rutile after reaction to titanite (Lucassen et al., 2011; Cruz-Uribe et al., 2014).

Numerical modeling

Peak metamorphic conditions are typically determined with geothermobarometers, for example the temperature dependent exchange of elements between two minerals (e.g. Fe-Mg between garnet and biotite). Based on thermodynamics, corresponding calculations constrain equilibrium between minerals that is the direct record of intrinsic, external variables such as temperature, pressure or a partition coefficient. A very important assumption for the interpretation of this concept to metamorphic rocks is that minerals are thought to adjust their composition infinitely fast according to the external conditions at least during prograde metamorphism, which includes formation of new minerals by net transfer reaction, recrystallization and/or fast diffusive homogenization at elevated temperatures. In contrast, retrograde adjustment of mineral compositions during cooling is often interpreted to be sluggish which has led many researchers to the erroneous interpretation that only mineral rim compositions are affected by retrograde element exchange whereas core compositions are likely to reflect peak metamorphic conditions. The later assumption has been shown to depend on a number of parameters such as cooling rate, grain size, modal abundances, which all determine the transport properties of elements along grain boundaries and within crystals and thus the effective flux of elements (Fisher, 1978; Ganguly and Tirone, 1999; Dohmen and Chakraborty, 2003; Mueller et al., 2010). Thus, it is necessary to evaluate which part of the thermal history is recorded in the chemical zoning pattern for a given mineral pair and set of parameters given above. Dodson (1973) developed a formulation to compute the so-called "closure temperature" being the mean temperature at which declining diffusion rates preclude significant exchange of elements by diffusion at a given cooling rate and grain size under the assumption of a simple mineral geometry and effectively infinite reservoir to exchange with. Later, some modifications allowed the spatial resolution of the closure temperature for different parts of a crystal (e.g., Dodson, 1986; Ganguly and Tirone, 1999). However, in the present case, interdiffusion rates of Fe-Mg in clinopyroxene (Mueller et al., 2013) and garnet (Borinski et al., 2012) are very similar, i.e. the assumption of an effectively infinite reservoir and thus the above formulation cannot be used to evaluate the compositional resetting of a cpx-grt pair during cooling. In recent studies, Ganguly et al. (2013) and Mueller et al. (2013) stated that there is no analytical solution for this problem and they developed a 1-D numerical model for a polythermal diffusive element exchange between two phases without net mass transfer under isobaric conditions using a temperature dependent partition coefficient. The model of Mueller et al. (2013), specifically focused on the Fe-Mg exchange between ferromagnesian mineral pairs (spinel, garnet, olivine, ortho- and clinopyroxene). Modeling results revealed that for most geologically relevant conditions the mineral pairs efficiently adjust their chemical composition above 1000-1100 °C independent of the cooling rate.

In this study, we extended the simple polythermal diffusive element exchange model to incorporate the effect of exhumation (i.e., decompression) and mineral growth (i.e., net mass transfer) and applied this to the grt-cpx lamellae in our sample. The length of the modeled compositional profiles perpendicular to the interface between the lamellae are negligible compared to the extent of the lamellae parallel to the interface which justifies the application of the 1-D model geometry excluding additional element fluxes in a second or even third dimension. For both adjacent lamellae we solved the diffusion equation:

$$\left(\frac{\partial C_{Fe/Mg}}{\partial t}\right)^{\alpha} = \frac{\partial}{\partial X}\left(D_{Fe-Mg}^{\alpha}\left(\frac{\partial C_{Fe/Mg}}{\partial X}\right)^{\alpha}\right) \qquad (1)$$

using a finite difference scheme where α denotes the mineral phase. In this equation, the actual change in concentrations of Fe and Mg ($C_{\mathrm{Fe/Mg}}$) are calculated for each node (with node spacing X) within the crystal for a given time interval t and the effective diffusion coefficient $D_{\mathrm{Fe\text{-}Mg}}$ that is re-calculated after every time step according to the current temperature. Based on the results by Mueller et al. (2013), an efficient adjustment of mineral compositions in both phases above 1000 °C was assumed leading to initially flat concentration profiles. Temperature dependent diffusion coefficients are calculated using the experimental data for Fe-Mg interdiffusion in garnet (Borinski et al., 2012) and clinopyroxene (Mueller et al., 2013). Fe and Mg concentrations for both phases at the interface are set to be in local equilibrium, i.e. these concentrations followed a pressure and temperature dependent partitioning:

$$K_D^{grt-cpx} = \frac{\left(Fe/Mg\right)^{grt}}{\left(Fe/Mg\right)^{cpx}} = f(P,T) \quad (2)$$

For this study, we used the partition coefficient derived by Ganguly et al. (1996). It is important to bear in mind that the subtle differences in the transport properties of Fe and Mg in clinopyroxene and garnet require an additional constraint to calculate the element fluxes correctly. This becomes especially important in the case of simulated lamellae growth. Consequently, mass balance is maintained for fluxes across the interface by:

$$D_{Fe-Mg}^{grt}\left(\frac{\partial C_{Fe/Mg}}{\partial X}\right)^{grt} = D_{Fe-Mg}^{cpx}\left(\frac{\partial C_{Fe/Mg}}{\partial X}\right)^{cpx} \quad (3)$$

Diffusion and partition coefficients are updated to the pressure and temperature corresponding to the conditions attained at the time along a predefined exhumation and cooling path. Resulting concentration profiles are calculated iteratively and final, frozen compositional profiles are presented ranging from the center of the garnet lamella over the interface to the center of the clinopyroxene lamella.

In the following, we explore three different model scenarios in order to separate and evaluate the effects of cooling, exhumation and lamellae growth on the resulting recorded chemical profile and compare the model results with the measured X_{Fe} distribution in the natural sample. Final half-lamella dimensions of 80 µm for the garnet and 150 µm for the clinopyroxene have been chosen to allow direct comparison of model results and natural samples. The initial concentration in the garnet lamella has arbitrarily been set to X_{Fe}=0.21 and the corresponding clinopyroxene composition has been calculated to be in equilibrium with the garnet at the P-T-conditions at the start of the model run using equation 2. For simplicity, we selected a simple linear cooling and exhumation path for model runs with a total duration of $2x10^3$, $2x10^4$, and $2x10^5$ years, which corresponds to cooling rates of $2x10^5$, $2x10^4$, and 2000 °C/Ma, respectively.

Case 1 – isobaric cooling / no lamellae growth

A first set of models evaluate the effect of cooling on the compositional profiles recorded in both the garnet and the clinopyroxene lamellae. Based on the results of Mueller et al. (2013) which suggested complete (instantaneous) adjustment of compositions above 1000-1100 °C and an apparent closure between 600 and 700 °C, we modeled a linear cooling from 1000 to 600 °C with different cooling rates. The pressure was chosen to 0.2 GPa which corresponds to the final depth of emplacement of the massif. Our initial garnet composition of X_{Fe}=0.21 results in an initial X_{Fe} of 0.1 in the clinopyroxene. We note that these values closely correspond to the measured core compositions of both lamellae.

Modeling results for the case 1 scenario are shown in figure 4 (case 1). The recorded profiles reveal a general increase in Fe in the garnet coupled to decrease of X_{Fe} in the clinopyroxene, which is in agreement with the partition coefficient reflecting that Fe is more compatible in garnet than in clinopyroxene with decreasing temperatures. Remarkably, both lamellae exhibit a different Fe-zoning pattern with a slight increase from the center of the garnet lamella towards the interface and a steep decrease of Fe concentration in clinopyroxene towards the interface. The observed difference for the zoning pattern is the consequence of two factors: (1) the smaller size of the garnet lamella results in a more efficient homogenization. In addition, there is a Fe influx from the opposite grt-cpx interface which is further promoted by (2) the higher diffusivity of Fe-Mg in garnet compared to clinopyroxene. The slower transport of Fe and Mg through the clinopyroxene lattice causes an apparent "depletion" of Fe near the interface. In other words, the limited supply of Fe from the lamella interior produces a Fe-concentration gradient towards the interface. Sluggish diffusion within the clinopyroxene also results in the preservation of the initial concentration for cooling histories below $2x10^4$ years, i.e. cooling rates above $2x10^4$ °C/Ma. In addition, we noted that the original clinopyroxene composition is completely reset at slower cooling rates. In contrast, the smaller lamella size combined with faster diffusion erases the original garnet composition for all cooling histories lasting longer than ~10,000 years, i.e. only extremely high cooling rates of > $4x10^4$ °C/Ma, typical of contact metamorphism, will preserve the initial element distribution in the center of the garnet lamella.

Comparison of the measured concentrations reveal that very short cooling histories with very high cooling rates are necessary to produce modeled element distributions that are in agreement with the observed ones. Slower cooling rates allowing more diffusive exchange inevitably result in a stronger Fe-zoning in the clinopyroxene lamella which is not observed in the natural sample. In the case of garnet, the model predicts the zoning profile, but much higher Fe-concentrations would be expected.

Case 2 – polybaric cooling / no lamellae growth

In the second set of models we have explored the modification of the preserved cooling profile due to the different temporal evolution of the partition coefficient if exhumation, i.e. changes in the confining pressure, is taken into account. In theory, diffusive migration of elements through the crystal lattice is also affected by changes in pressure, but to our knowledge, no pressure dependent Fe-Mg interdiffusion data exist for clinopyroxene and garnet. However, in most cases this pressure effect on diffusion becomes only significant at very high pressures (Watson and Baxter, 2007; Mueller et al., 2010). Thus, we neglect a possible minor pressure dependence of Fe-Mg interdiffusion for the purpose of this study. Modeling results of this scenario are shown in figure 4 (case 2).

For the same initial garnet composition (X_{Fe} = 0.21) a starting composition for the clinopyroxene of X_{Fe} = 0.09 results, which is slightly below the measured natural concentration. We applied the same thermal histories as in case 1. The modeling results exhibit similar features, i.e. formation of zoning patterns in both lamellae and a comparable extent of increasing X_{Fe} in garnet countered by a decrease of X_{Fe} in clinopyroxene. Nevertheless, subtle differences can be observed in both lamellae that are a direct consequence of the partition coefficient being a function of pressure and temperature. Here, decreasing pressure favors Fe incorporation into pyroxene, whereas decreasing temperatures act in the opposite direction. As a consequence, the effective influx of iron into the garnet is somewhat smaller which reduces the total increase in Fe-content. Nevertheless, cooling timescales greater than 10^4 years for the cooling from 1000 °C to 600 °C modify the entire initial lamellae compositions and produce a slight zoning pattern with increasing X_{Fe} towards the interface. For the clinopyroxene, the model predicts an extended depletion of Fe near the interface even for a short period of time of 2,000 years, but the initial composition is still preserved in the center for cooling histories shorter than 10^5 years. Longer cooling times yield flatter Fe-zoning compared to the case 1 scenario. In addition, the zoning significantly extends into the lamella interior, which is in clear disagreement with the measured data.

Case 3 – isobaric cooling / lamellae growth

The effect of lamella growth on the developing concentration profile is the focus of the third set of models. Given the minor impact of pressure changes on the recorded profiles in case 2 scenarios and to separate each parameter, we decided to run this set of models at a constant pressure of 0.2 GPa. Thus, all model parameters are the same as in case 1 models. The garnet lamella with an initial thickness of 40 μm (cpx = 190 μm) grows linearly with time by 40 μm to a final thickness of 80 μm over the duration of the calculation. The same amount of clinopyroxene was consumed, ignoring any volume change induced by this reaction. Figure 4 (case 3) shows the modeling results for the case of isobaric cooling from 1000 °C to 600 °C accompanied by the final growth stage of the garnet lamella at the expense of clinopyroxene.

The calculated final concentration profiles are generally similar to all previous model scenarios. Again, spatial variations in the zoning pattern and differences in total Fe-content of garnet can be observed. In the present case, the original garnet lamella composition is completely modified even for short run durations of only 2,000 years. This is a direct consequence of the small initial lamella size, which allows diffusion to efficiently transport Fe to the center of the lamella. Interestingly, the model predicts only a very narrow Fe-zoning in clinopyroxene near the interface. The reason for this is that the growing garnet basically “consumes” the developing depletion in the clinopyroxene lamella progressively. Retention of the original clinopyroxene composition in the center of the lamella corresponds exactly to the case 1 models, i.e. preservation for thermal histories with cooling rates above $2x10^4$ °C/Ma.

Discussion

The crystallization history of co-existing mineral phases is typically recorded in their chemical compositions, the basic concept of geothermobarometry. Many metamorphic studies have applied this concept to decipher the P-T evolution of a metamorphic rock and placed the results into a larger geodynamic context. For example, a number of studies reconstructed P-T-paths for rocks from the Bohemian Massif, particularly for those of higher metamorphic grade. Such rocks occur in the Granulitgebirge (e.g., Roetzler and Romer, 2001; Massonne and Bautsch, 2002; Roetzler et al., 2004; Roetzler et al., 2008; Schmaedicke et al., 2010). While there is a general agreement over a clockwise P-T-path, it is often based on exchange reactions applied to mineral pairs which are subject to retrograde, diffusive modification. In addition, information on the timescales of geodynamic processes is mostly restricted to geochronological data obtained on different minerals. To both ends, kinetic modeling allows the placing of time constraints and evaluates if a mineral composition is reset and if so, to what extent. In the following sections, we consider both equilibrium phase petrology and kinetic modeling to determine timescales of different stages in the P-T evolution of rocks from the Granulitgebirge in Saxony and compare our findings with previous studies.

Reconstruction of the P-T-t path

Decompression during exhumation, cooling and net mass transfer reactions are recorded in the concentration profiles of the studied garnet and clinopyroxene lamellae exsolved from a former megacryst. Mueller et al. (2013) presented convincing evidence that mineral compositions rapidly adjust at temperatures above 1000 °C for most geological settings. Therefore, modeling of the element distribution in the studied lamellae will only give information on the thermal history below this temperature. The predicted profiles of all model scenarios clearly suggest that cooling from 900-1000 °C was very fast (<< 10,000 years) indicated by the absence of pronounced zoning patterns, which are predicted for slower cooling rates (Fig. 4). This short period of time, which is typical for contact metamorphic aureoles such as that around the Adamello Batholith (Berger and Herwegh, 2004), and Ubehebe Peak (Roselle et al., 1999; Mueller et al., 2008), is the first key observation that result from the diffusion modeling presented here.

The first model of isobaric cooling at shallow crustal levels (mimicking simple contact metamorphism) produced concentration profiles that do not exactly match the observed, measured profiles (Fig. 4 – case 1). On the one hand, the concentration in the center of the clinopyroxene lamella is in agreement with the measured data and represents the original composition. On the other hand, the central garnet composition increased slightly, but not sufficiently to exactly match the observed data for the 2,000 year cooling episode. Surprisingly, the addition of continuously changing pressure conditions during cooling to account for the exhumation of the massif does not improve the fittings (Fig. 4 – case 2). In this case, the short time scales necessary to limit the spatial extent of the zoning patterns will also preserve the initial clinopyroxene lamella composition in the center. Using the pressure and temperature dependent partition coefficient we calculated an initial Fe-content which is slightly below the observed data. As this calculation is a direct consequence of the arbitrarily defined starting composition in garnet, this difference could be minimized by an increase of the Fe-content in initial garnet. However, the pressure effect on the partition coefficient leads to a flatter and broader zoning pattern in the clinopyroxene lamella in apparent contrast to the measured profile (Fig. 4 – case 2). Hence, we interpret the apparent deviation of the predicted profiles as an indication that the vast majority of the cooling history below 1000 °C took place at or near the final depth of emplacement, i.e. at a pressure of about 0.2 GPa.

The effect of lamella growth on the final profiles is not substantial, but is discernable in the final shape of the zoning pattern (Fig. 4 – case 3). Based on thermodynamic constraints we assume that the garnet lamella grew about 50 % of its final size during cooling. The garnet growth, in turn, results in a more efficient homogenization of the garnet leading to an increase in the Fe-content up to the center of the lamella, which is in perfect agreement with the measured data. At the same time, the progressive growth of garnet will consume the depletion of Fe in clinopyroxene, resulting in a very narrow and steep zoning profile (Fig. 4 – case 3). In conclusion of the diffusion modeling we interpret the observed Fe-Mg profiles in adjacent grt-cpx lamellae to be the result of isobaric cooling from at least 900 – 600 °C within ~10,000 years at shallow crustal levels (~6 km depth).

The high cooling rates (> $2\text{x}10^5$ °C/Ma) predicted by the diffusion modeling are common for contact aureoles as mentioned above. The presence of the schist mantle surrounding the tectonically separated granulite complex of the Granulitgebirge (Fig. 1c) is the consequence of contact metamorphism during the emplacement (Roetzler and Romer, 2010), which is in agreement with increasing metamorphic grade towards the tectonic contact and has already been suggested by Frech (1917). The spatial extent of the contact metamorphic halo in the schist mantle provides an excellent opportunity to independently constrain the temperature of the Massif during emplacement of the granulite complex with a simple thermal model. To that end, we modeled the T-t evolution of the granulite complex and surrounding country rocks. The model assumes a tabular shape of the granulite complex with a radius of 10 km. Figure 5 presents the temporal evolution of the thermal history in rocks surrounding the Massif. Metamorphic temperatures necessary to form the exposed phyllite from pelitic sediments are around 350 °C. Reported migmatites near the tectonic contact require temperatures near 700 °C. Inspection of figure 5 reveals a maximum dimension of about 1-3 km for the contact aureole in the western part. The spatial extension in the eastern area is less, but this may be a cut effect of the current topography or the exact 3-D position of the granulite complex. In addition, we monitor the cooling history of a rock located about 1 km away from the contact within the granulite complex. This position is approximately the location of the investigated lamellar garnet pyroxenite. Calculated thermal histories are shown in figure 5. It can be seen that both, the spatial extent of the predicted contact-metamorphic halo (Fig. 5) and cooling rates corresponding to those determined by the diffusion modeling (Fig. 5 - inset), can well be estimated with this simplified thermal model for a contact aureole assuming an initial temperature of ≥ 950 °C for the granulite complex. A more detailed and sophisticated thermal model would be necessary to really constrain exact initial temperatures, which is beyond the scope of this study. We note, however, that a simplified thermal model is an independent second line of arguments supporting the results of our diffusion modeling, i.e. the major cooling history that took place at almost isobaric conditions after emplacement.

One major goal of this study is to place time constraints on different stages of the P-T-t path. The heat and diffusion modeling provided two solid constraints. First, the major portion of the cooling history from ~1000-600 °C took place at almost isobaric conditions and secondly this cooling episode occurred at a short timescale of several thousand years only. Thus, the exhumation of the granulite complex is likely to follow an almost isothermal decompression path (Fig. 6). Several studies have estimated the peak P-T conditions for most rocks from the granulite complex to be around 2.2-2.3 GPa and ≥1000°C (Roetzler and Romer, 2001; Massonne and Bautsch, 2002; Roetzler et al., 2004; Roetzler et al., 2008; Schmaedicke et al., 2010) ignoring the higher temperatures for the magmatic formation of the megacrysts preceding the garnet pyroxenite from Reinsdorf. It is important to keep in mind that determination of the above P-T conditions are based on geothermobarometry using the core compositions of co-existing mineral pairs (e.g. grt-cpx). The modeling results of the diffusive element exchange during cooling indicate that in the present case only the central clinopyroxene composition remained unchanged. The garnet composition, in contrast, was completely reset during cooling as a consequence of the smaller lamella size and faster diffusion. Under these circumstances, conventional thermometry using core-core compositions of co-existing mineral phases will either overestimate the pressure or underestimate the temperature if the P-T dependent partition coefficient of Ganguly et al. (1996) is applied. However, the results generally suggest a very limited cooling during the exhumation process. While the exact reaction history remains unclear as discussed above, the presence of a nearly isothermal decompression path sets some thermal constraints on the timescale of exhumation. To that end, one can again use a very simplified thermal model to evaluate the minimum exhumation rate for a block that cooled progressively inwards during exhumation due to the decreasing temperature of the surrounding rocks within an “exhumation channel”. Figure 7 shows the predicted temperature distribution after 1, 3 and 7 Ma for the block with the same geometry and heat transport properties as in the previous calculation. In this model the contact temperature decreases linearly from 1200 °C representing the original root zone to 350 °C mimicking the temperature of the sediments at the final depth of emplacement at 0.2 GPa. It is important to keep in mind that the results of the diffusive element exchange as well as the modeling of the thermal history of the aureole revealed a minimum temperature of 900 °C for the garnet-pyroxenite sample located about 1 km away from the contact. The simplified thermal model for the exhumation event of the granulite complex suggests a maximum integrated time of exhumation to be less than 1 Ma, which translates into an average exhumation rate of 4-5 cm/year. Slower exhumation rates are likely to cool the outermost kilometer of the granulite complex to temperatures significantly below 900 °C which is incompatible with the finding of the diffusion model. We note, that our model has many simplifying assumptions, e.g. that there is no friction, latent heat of crystallization, etc., and thus the extracted exhumation rates could be somewhat overestimated. Again, we emphasize that a much more detailed thermal model is required to constrain exact information of the thermal evolution of the granulite complex during exhumation and cooling in order to verify our conclusions. However, our simple thermal model calculations provide at least rough, but independent estimates which all point to the same P-T-t evolution of the studied sample.

Comparison with previous P-T-t estimates

We combined our modeling results to construct a P-T-t path presented as path A in figure 6. For comparison we added the reported P-T evolution of Roetzler and Romer (2001), Roetzler et al. (2004, 2008) Schmaedicke et al. (2010), Massonne and Bautsch (2002), Massonne (2006), and O'Brien (2008). The latter author studied the P-T path of co-existing garnet and clinopyroxene in rocks from the southern Bohemian Massif which belongs to the same overall geological setting, but has a different final depth of emplacement (0.8 GPa). The P-T-path of Roetzler and Romer (2001), and Roetzler et al. (2004, 2008) derived by a series of studies summarized in Roetzler and Romer (2010) and the geological settings of the current study, is based on conventional thermobarometry and multivariant reactions (path C in figure 6). For example, peak P-T conditions are estimated on felsic and mafic granulite using the Fe-Mg exchange thermometry between co-existing garnet and clinopyroxene, re-integrated feldspar composition and equilibrium oxygen isotope fractionations. All approaches, including the geothermobarometry data of Massonne and Bautsch (2002) and Schmaedicke

(2010), yield a very narrow range of apparent peak temperatures around 1000 °C. However, in the light of this study it could be that this coincidence is an artefact of efficient element and isotope exchange leading to an effective preservation of the compositional record at temperatures below 1000 °C. This is certainly true for element and isotope exchange processes which are kinetically controlled, i.e. Fe-Mg exchange and oxygen isotope thermometry. Re-integration of feldspar composition might give more robust information. Roetzler & Romer (2001) and Roetzler et al. (2004, 2008) applied the commonly used GASP barometer to estimate the peak pressure conditions. Again, caution is necessary when applying this barometer using the possibly modified garnet composition. To account for this we expanded the P-T pressure range extracted by Roetzler and Romer (2001), Roetzler et al. (2004, 2008), Massonne and Bautsch (2002) and Schmaedicke (2010) to include lower and higher temperatures.

P-T estimates for the garnet-cordierite-gneiss were used as a second constraint for the P-T-path by Romer and Rötzler (2010) who proposed a decompression-heating path for the rocks that have been incorporated into the ascending granulite complex. Several models exist for the exhumation mechanism of the Varisican HP-HT rocks (Franke and Stein, 2000; Willner et al., 2002; Massonne, 2006; Kroner et al., 2007). For the purpose of this study it is not necessary to discriminate between the many existing models as only the time response of mineral compositions on the exhumation process is considered here. A schematic model for the ascent of the granulite core in an “exhumation channel” (Fig. 8) illustrates the consequences of the P-T conditions determined for the garnet-cordierite gneiss (Fig. 8) on the P-T-t path of the studied garnet-pyroxenite sample. There is general agreement that the garnet-cordierite gneiss became attached on the granulite complex during exhumation. During this uptake, this rock was heated by the rising granulite complex which is documented by the decompression-heating path proposed by Romer and Roetzler (2001). These authors concluded that the granulite complex had the same temperature as the surrounding gneiss which is represented by the cooling path in figure 6 (path C3 and C). Again, transport of heat is not instantaneous and thus the heating of the uptaken rock portion can be imagined as a contact metamorphic event along the short-lived exhumation process. In other words, while there is no doubt that the metamorphic garnet-cordierite gneiss experienced the proposed decompression-heating path, there is no direct evidence of similar low temperatures for the central part of the granulite complex. In contrast, sluggish heat transfer is likely to decouple the thermal history for the different lithologies leaving the thermal evolution of the original block near its isothermal behavior due to adiabatic cooling only in agreement with our modeling results (Fig. 8).

In a recent study, Schmaedicke et al. (2010) presented a series of thermometric data of the garnet peridotites and garnet pyroxenites exhibiting kelyphitic reaction textures surrounding garnet crystals of the same locality. Thermometry data based on Fe-Mg exchange revealed the same P-T estimates for grt-cpx and grt-olivine pairs (~2.4 GPa, ~1000 °C). However, co-existing opx-cpx pairs in the kelyphitic reaction rims yield systematically lower temperatures ranging from 890-940 °C for the garnet peridotite (at 2.0 GPa) and 840 °C at 1.5 GPa for the garnet pyroxenite, respectively. We note that the symplectites observed in our sample replacing garnet have to be formed after the formation of the grt-cpx lamellae, i.e. after exhumation to approximately 0.2 GPa. However, the lower temperature estimates have led Schmaedicke (2010) to shift the reconstructed P-T-path to be located around 100 °C lower, but parallel to previous estimates (path E in Fig. 6). This interpretation favors the opx-cpx data and neglects the results of the grt-cpx and feldspar thermometry. In the light of our modeling results, however, it is likely that the opx-cpx pairs have experienced a more efficient element exchange, which results in a larger reset of the preserved, i.e. measured temperatures. While the diffusion coefficients of Fe-Mg interdiffusion in grt and opx are similar at the relevant temperature range (Mueller et al., 2013), this interpretation is supported by the mostly pressure sensitive, continuous reaction forming the opx-cpx-spinel kelyphite texture at pressures below 2.0 GPa. Modeling results of our case 3 scenarios revealed that mineral growth leads to more efficient homogenization and thus the progressive cooling would be preferentially recorded in cpx-opx pairs while already existing grt-cpx pairs experience more sluggish adjustment of central compositions. Hence, we attribute the lower temperatures extracted by opx-cpx thermometry in kelyphitic reaction rims to diffusive closure of element exchange at lower temperatures and thus at a later stage during cooling on the retrograde path. Excluding the opx-cpx thermometric data in the study of Schmaedicke et al. (2010) would shift the resulting P-T path towards higher temperatures and thus perfectly fit the data of Roetzler and Romer (2008).

In a very thorough study of rocks from the southwestern part of the Bohemian Massif, O'Brien (2008) presented convincing evidence for a very similar isothermal decompression path around 1000 °C using thermodynamic phase equilibria calculations on whole rock chemistry and element zoning in grt-cpx pairs (path G in figure 6). In this case, the isothermal exhumation is followed by an almost isobaric cooling episode at approximately 0.8 GPa. Here, the metamorphic block is supposed to have not been exhumed to the same extent as in the granulite complex. Given the greater depth of emplacement, the reconstructed P-T evolution of O'Brien (2008) is in good agreement with our findings. We thus interpret all of these rocks to have been exhumed by the same, although unknown mechanism and most likely the same rates, but to different final depths. This interpretation highlights the potential of combining equilibrium phase petrology with kinetic modeling to decipher rates and mechanisms of large-scale geodynamic processes.

Implications

We applied kinetic modeling to decipher the effect of changing external parameters, i.e. pressure and temperature, on the evolution of concentration profiles in minerals which are direct recorders of geochemical fluxes in metamorphic rocks. The fact, that minerals adjust their compositions according to external parameters, is typically used to reconstruct the P-T-evolution of a rock using a combination of available geothermobarmeters. In this study, we demonstrate that care has to be taken by using geothermobarometric data to reconstruct P-T-paths without constraining the kinetically controlled efficiency of geochemical fluxes. While there is no doubt that geochemical exchange records the change of external temperatures and pressures, it often remains the question by how much. In other words, the temperatures determined by rim-rim and core-core compositions may not necessarily reflect peak metamorphic or any other assigned conditions as previously suggested by Dohmen and Chakraborty (2003) and Faryad and Chakraborty (2005). Additional information is necessary to place these data into a larger context within a petrogenetic grid. Modeling of the diffusive element exchange during cooling provides a solid estimate for the extent of reset allowing the temperature data to be interpreted as dynamically evolving parameter. Moreover, this study highlights the potential of assigning timescales not only to geological settings with large P-T changes over short time-intervals such as contact aureoles, but also on large scale geodynamical processes in regional metamorphic settings.

The diffusive exchange model was used to extract the major cooling episode at shallow crustal levels which is in agreement with the thermal modeling that requires the emplacement of the granulite block at temperatures above 900 °C in order to produce the observed contact metamorphism in the schist mantle and the phyllite zone. This in turn requires an almost isothermal exhumation from great depth at rates comparable to active plate movements of several cm per year. While modeling of the mineral zoning in grt-cpx pairs places narrow limits on the timescales of the final cooling episode, the evaluation of timescales for the exhumation is much more complex. Our very simplified thermal model for the exhumation process only suggests a very rapid exhumation and consequently has to be regarded as an end-member model. The other extreme would be a slow adiabatic exhumation in which case no time-related information is recorded. Hence, much more detailed thermal modeling within the context of geodynamical transport processes is necessary to extract more detailed information on the exhumation rate of the Granulitgebirge. We close this section by emphasizing that every conceptual model explaining a large scale exhumation process needs to fit the geochemical record preserved in the spatial element distribution within minerals.

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Figure captions

Figure 1: (a) Location of the Granulitgebirge within the Variscan Bohemian Massif of Central Europe with the distribution of high-pressure rocks (redrawn after Willner et al., 2000). (b) Geological Map of the Granulitgebirge modified after Reinhardt and Kleemann (1994) with the location of the garnet pyroxenite sample. (c) Simplified cross section of the Granulitgebirge after Reinhardt and Kleemann (1994). Note that the black units shown in panels (b) and (c) contain both, garnet peridotite and garnet pyroxenite.

Figure 2: Thin section image of garnet-pyroxenite sample under crossed polarized light. (A) Image showing the dimensions of the former cm-sized megacryst within a matrix of recrystallized garnet and clinopyroxene. (B) Alternating lamellae of garnet and clinopyroxene with a final volume ratio of 3:7 are formed within the megacryst during exhumation and cooling.

Figure 3: Representative compositional profiles of major and minor elements within adjacent garnet and clinopyroxene lamellae measured with an electron microprobe. Line profiles reveal almost flat, but weakly zoned patterns with increasing X_{Fe} from the garnet center towards the interface. Almost no zoning for X_{Fe} can be observed in the cpx lamella. Minor elements show an increase in concentration for Cr and Ti within the clinopyroxene towards the interface. In contrast, no zoning is visible in the garnet. Note, that the garnet lamella is nearly free of Ti.

Figure 4: Modeling results using a finite difference scheme that simulates diffusive exchange of Fe-Mg between garnet and clinopyroxene along a virtual cooling and exhumation path. The model assumes local equilibrium at the interface and diffusive fluxes are constrained by mass balance. Three different scenarios are modeled to investigate the effect of cooling (case 1), exhumation (case 2) and growth (case 3) on the developing concentration profiles. Progressively evolving concentration profiles are shown ranging from the initial step profile up to 0.2 Ma. Note that only a combination of cooling on very short timescales of several thousands of years in combination with growth of the garnet lamella is in agreement with the measured data.

Figure 5: Thermal modeling of the contact metamorphic aureole producing the schist mantle and the phyllite surrounding the granulite block. The numerical 1-D model assumes a tabular shaped geometry of the granulite block and a general thermal diffusivity of 1×10^{-6} m^2/s.

Temperature profiles are shown for different times ranging from 2k to 200k years. Note, that temperatures necessary to match the spatial extent of the schist mantle and the surrounding phyllite require an emplacement temperature of more than 900 °C for the granulite complex. The black box represents the temperature estimates of the mantle schist as summarized in Roetzler and Romer (2010). *Inset:* Modeled temperature-time path for the approximate position of the garnet peridotite sample of this study as well as selected locations for rocks of the mantle schist and the phyllite zone. Note that the major cooling episode (950-780 ° C) of the garnet peridotite takes place in less than 2,000 years, which is in agreement with the short modeled time scales for the Fe-Mg concentration profiles presented in figure 4.

Figure 6: Synopsis of modelled and determined P-T paths in the Granulitgebirge. A - modelled P-T path of the granulite complex of this work; B - observed progressive contact metamorphism in the schist mantle after Roetzler et al. (1992), Reinhardt and Kleemann (1994) and Roetzler and Romer (2010); C - observed P-T-path of the granulite complex after Roetzler & Romer (2001; 2010); C1 - observed peak conditions (Roetzler and Romer, 2001; Roetzler et al. 2004, 2008; Hagen et al. 2008); C2 - symplectite stage (Roetzler et al. 2008); C3- observed decompression-heating path of the garnet-cordierite gneiss (Rötzler & Romer 2010); D – observed late exhumation path of garnet pyroxenite after Massonne and Bautsch (2002); E - observed late exhumation path of garnet peridotite after Schmaedicke et al. (2010); E1, 2- observed conditions of two symplectite stages (Schmaedicke et al., 2010); F - observed local early stage metamorphic conditions (Massonne, 2006); G - observed P-T path of a high-pressure granulite from the southwestern Bohemian Massif emplaced at mid-crustal conditions (O'Brien, 2008).

Figure 7: Simplified numerical model simulating the cooling of the granulite block upon exhumation in contact with an infinite reservoir of country rock with a linear geotherm. The

original temperature of the block and the surrounding was set to 1200 °C according to the assumption of clinopyroxene as original host phase. The country rock is assumed to geothermally equilibrate with depth forming a linear gradient that is opposed to the interface of the exhumed tabular shaped block. Modeled thermal profiles are shown for exhumation times ranging from 1-7 Ma. No external heat source (e.g. friction, latent heat of crystallization, etc.) within an "exhumation channel" was taken into account by this simplified model, which means that the determined timescales have to be regarded as minimum timescales, i.e. maximum rates of exhumation. Nevertheless, the results emphasize the fast exhumation rates in the order of several cm per year are necessary to preserve temperatures higher than 900 °C. Such temperatures are required to match the spatial dimensions of the formed contact aureole.

Figure 8: Mechanistic model explaining the observed temperature-time evolution of three rock units between A - the position before the ascent of the granulite complex in extensional detachment zones within an "exhumation channel" (a), i.e. during concomitant convergence - and B - after emplacement of the granulite complex within the schist mantle at shallow crustal conditions. Temperature-time evolution of (b) the schist mantle near the contact to the granulite complex, (c) the mid-crustal garnet-cordierite gneiss emplaced during coupled motion at the contact, (d) the granulite complex.

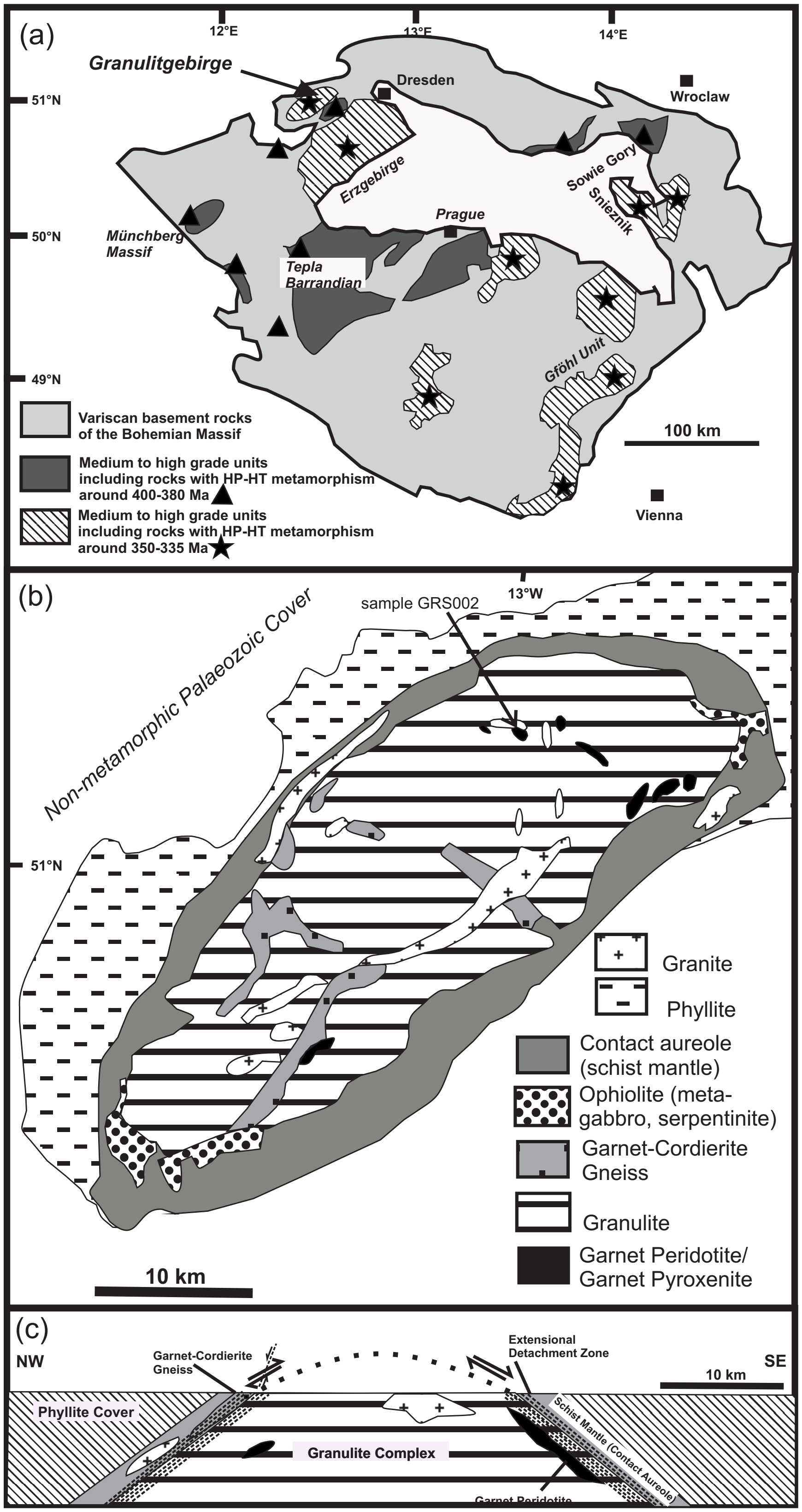

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Figure 1

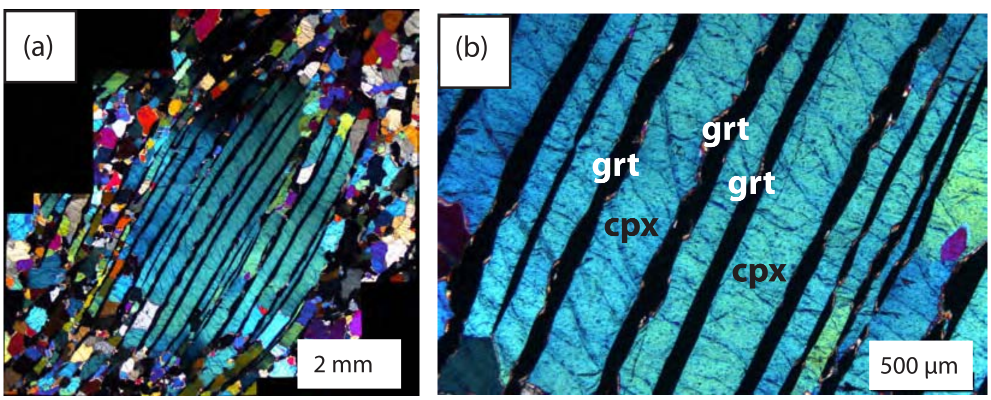

Figure 2
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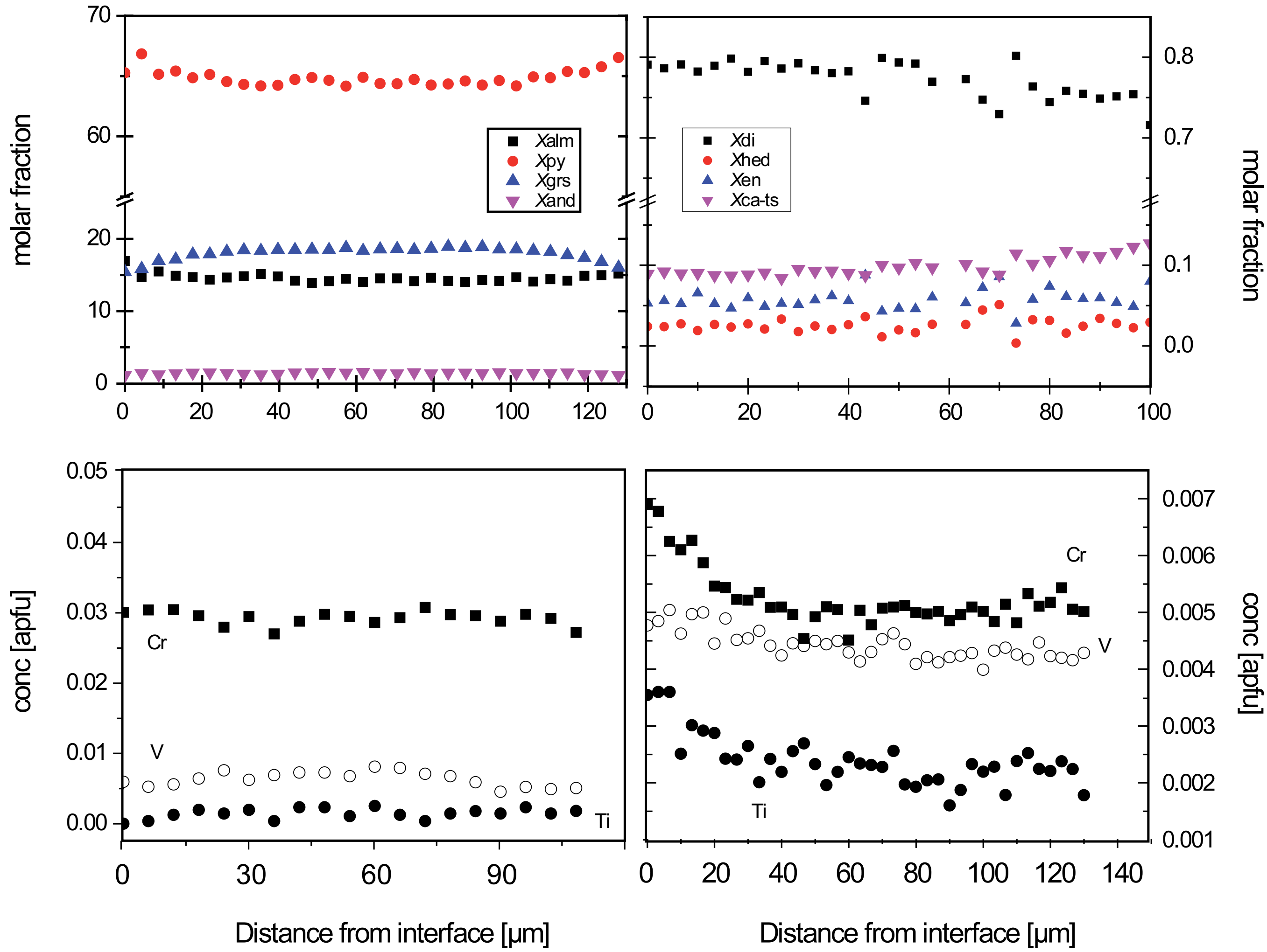

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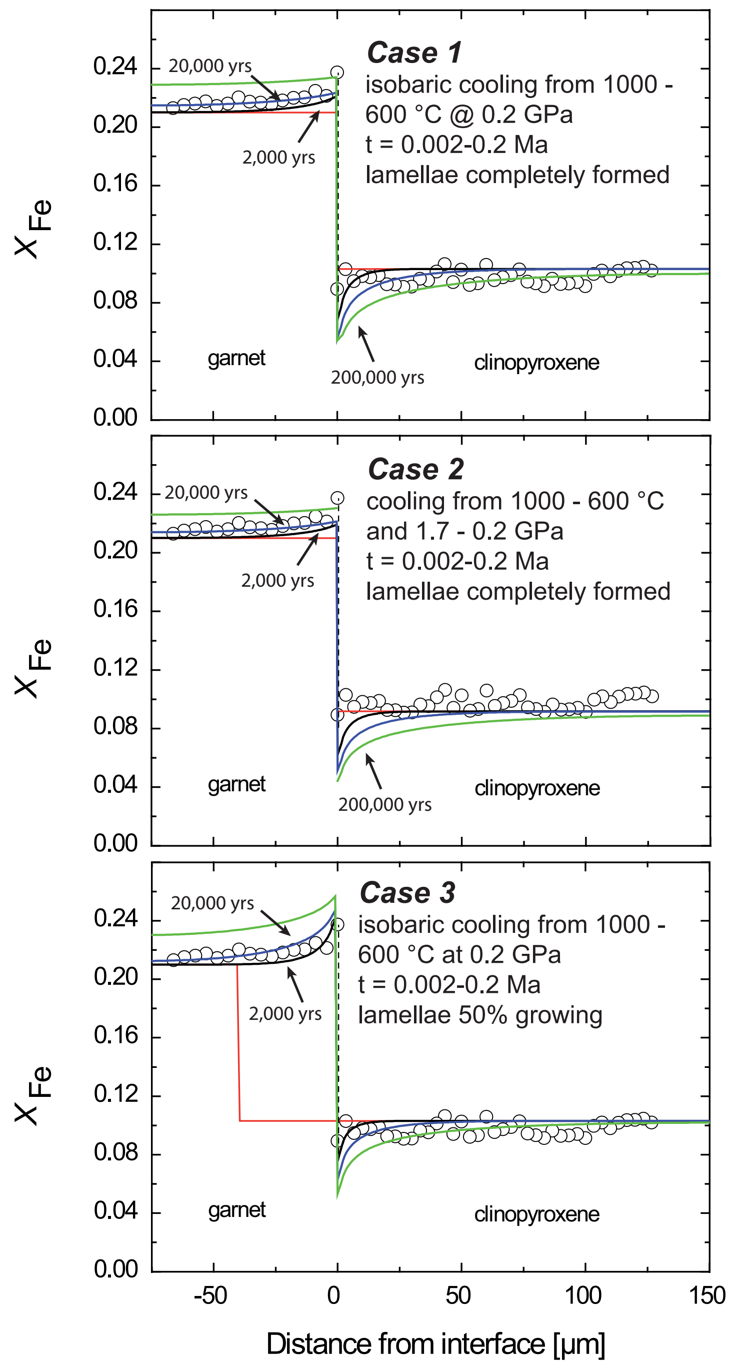

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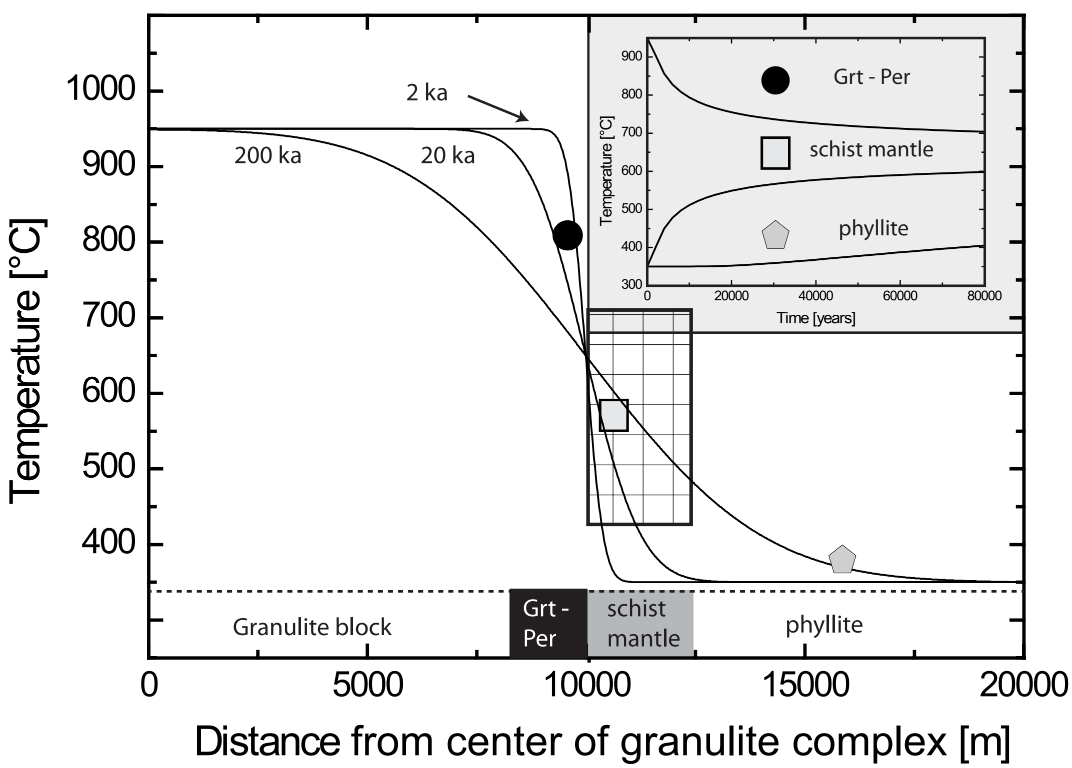

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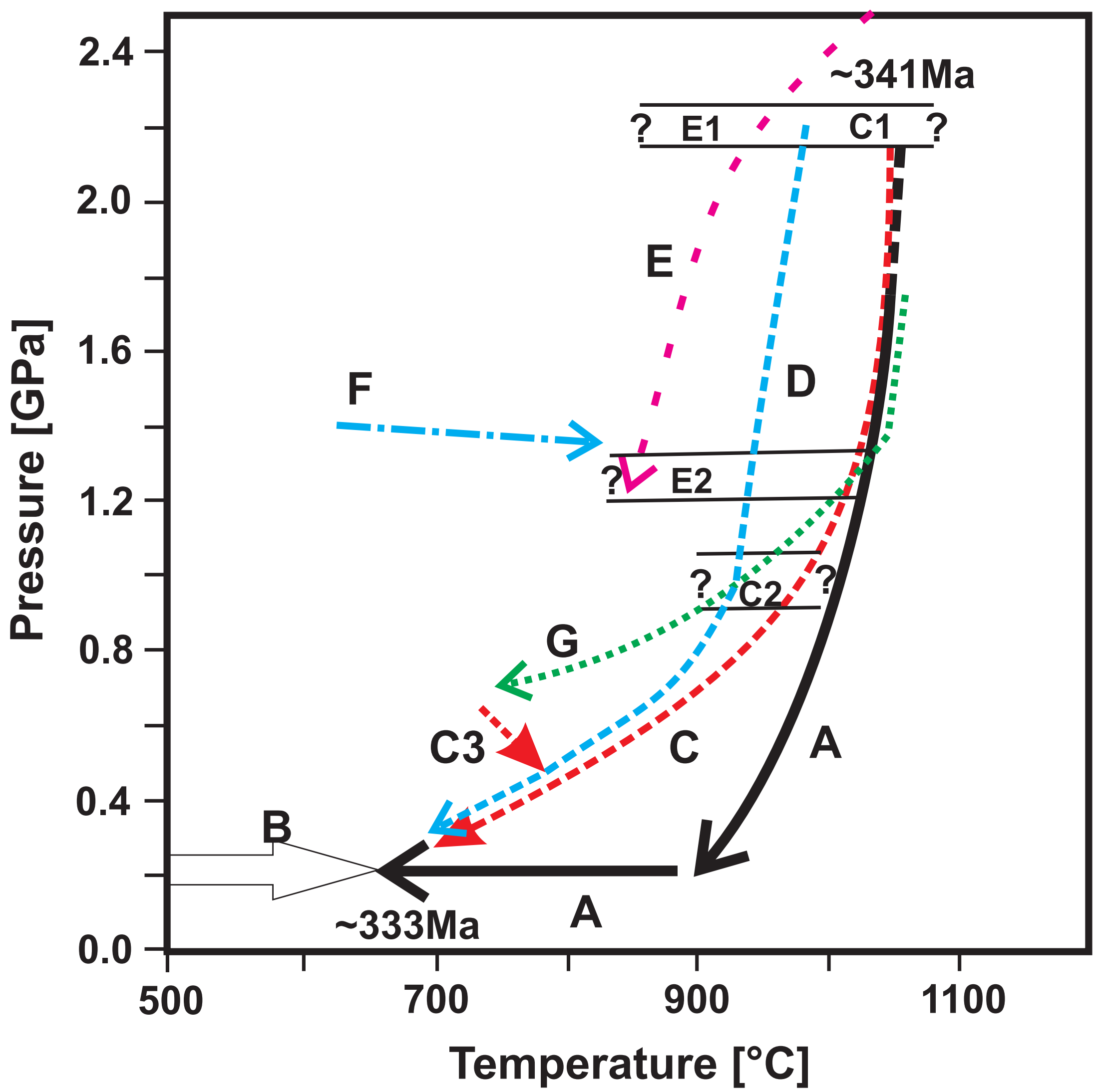

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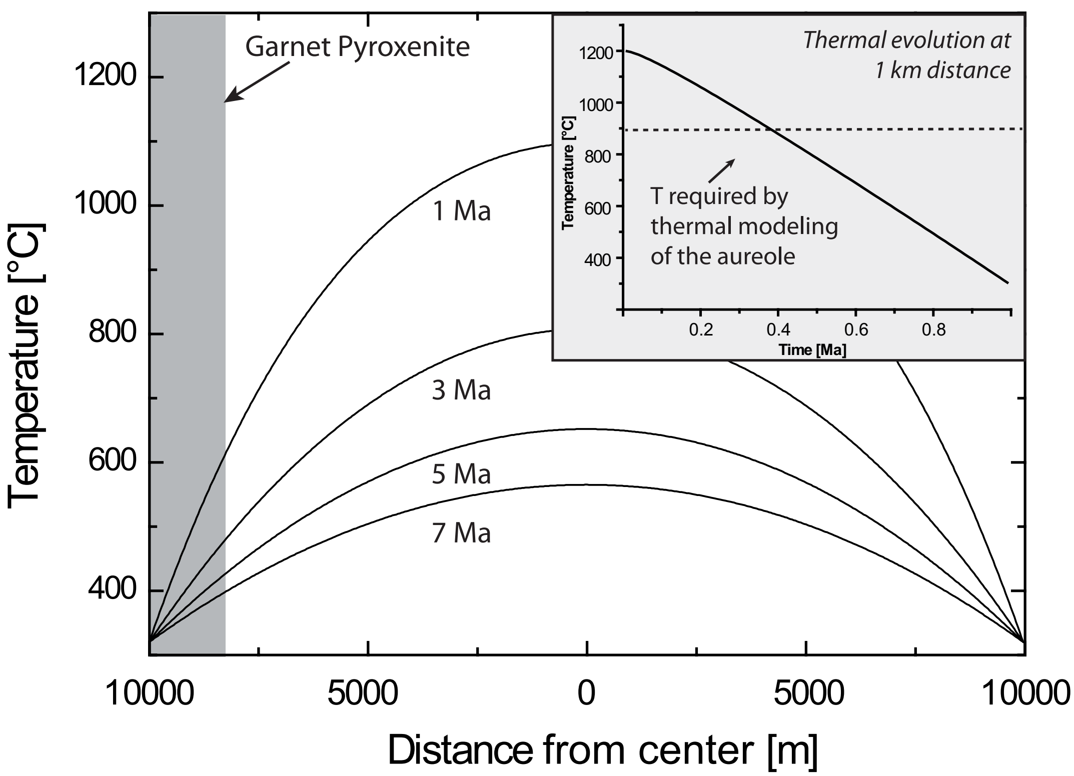
Figure 6



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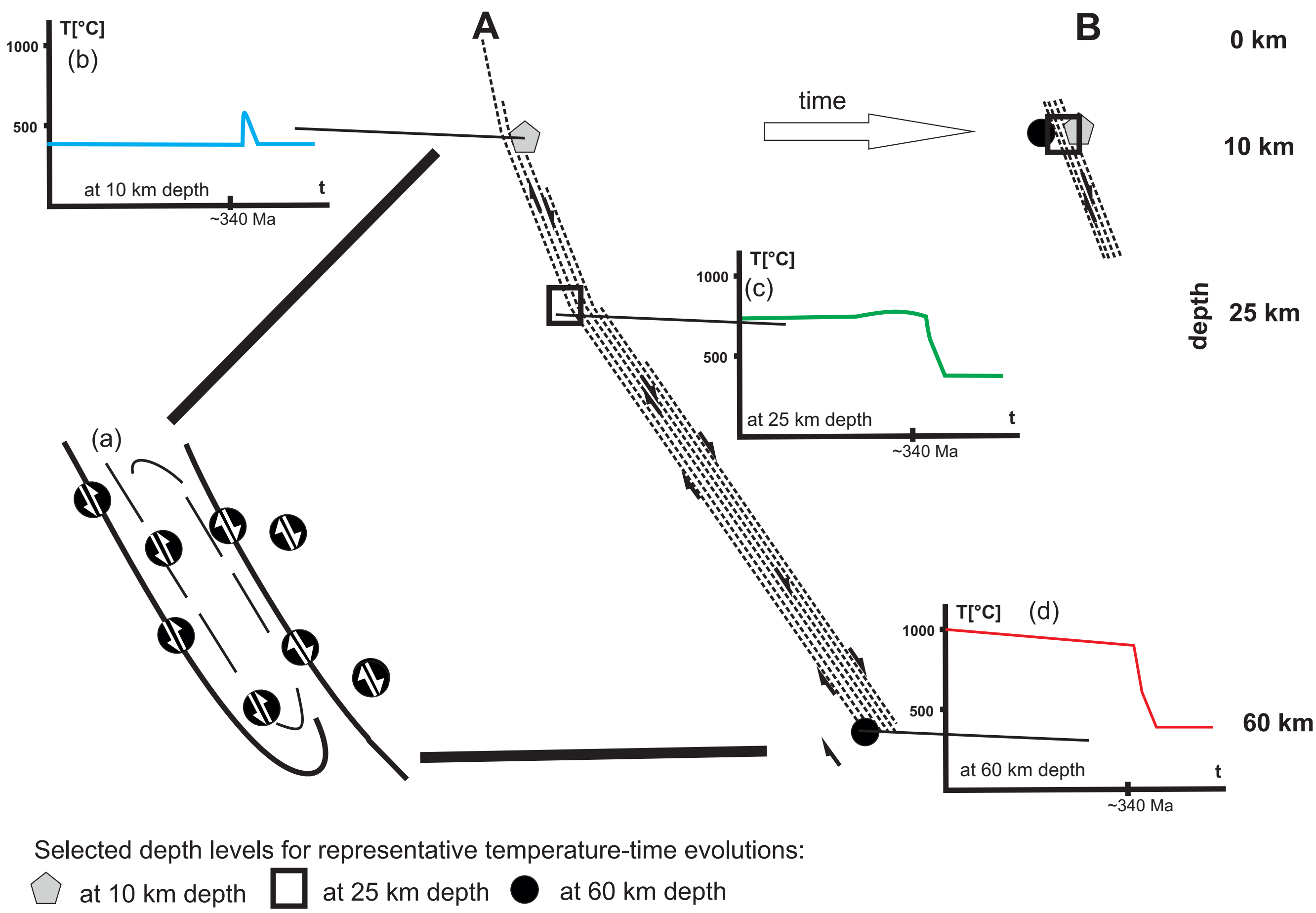

Figure 8
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