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Prograde and retrograde $P$–$T$ evolution of a Variscan high-temperature eclogite, French Massif Central, Haut-Allier

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Abstract – The $P$–$T$ evolution of a mafic eclogite sample from the Haut-Allier was studied in order to constrain the dynamic of the Variscan subduction in the eastern French Massif Central. Three successive metamorphic stages M1, M2 and M3, are characterized by assemblages comprising garnet1-omphacite-kyanite, garnet2-plagioclase, and amphibole-plagioclase, respectively, and define a clockwise $P$–$T$ path. These events occurred at the conditions of eclogite (M1; $\sim$ 20 kbar, 650 °C to $\sim$ 22.5 kbar, 850 °C), high-pressure granulite (M2; 19.5 kbar and 875 °C) and high-temperature amphibolite facies (M3; $< 9$ kbar, 750–850 °C), respectively. Pseudosection modelling of garnet growth zoning and mineralogy of the inclusions reveal a prograde M1 stage, first dominated by burial and then by near isobaric heating. Subsequent garnet1 resorption, prior to a renewed growth of garnet2 is interpreted in terms of a decompression during M2. High-pressure partial melting is predicted for both the M1 temperature peak and M2. M3 testifies to further strong decompression associated with limited cooling. The preservation of garnet growth zoning indicates the short-lived character of the temperature increase, decompression and cooling cycle. We argue that such $P$–$T$ evolution is compatible with the juxtaposition of the asthenosphere against the subducted crust prior to exhumation driven by slab rollback.

Keywords: French Massif Central / eclogite / HP granulite / subduction / $P$–$T$ pseudosection / isobaric heating

Résumé – Évolution $P$–$T$ prograde et rétrograde des éclogites varisques du Haut-Allier, Massif Central (France). Cette étude a pour but d’apporter des contraintes sur la dynamique de la zone de subduction varisque de l’est du Massif Central Français à travers l’étude de l’évolution $P$–$T$, notamment du trajet prograde, d’un échantillon d’éclogite mafique du Haut-Allier. Trois événements métamorphiques, M1, M2 et M3, respectivement définis par des assemblages comprenant garnet1-omphacite-disthène, garnet2-clinopyroxène-plagioclase et amphibole-plagioclase, définissent une évolution $P$–$T$ horaire. Ces événements métamorphiques traduisent la succession des conditions du faciès des éclogites (M1; $\sim$ 20 kbar, 650 °C à $\sim$ 22.5 kbar, 850 °C), des granulites de haute pression (M2; 19.5 kbar, 875 °C), puis des amphibolites de haute température (M3; $< 9$ kbar, 750–850 °C). L’étude pétrologique de cet échantillon par l’analyse de la zonation du garnet, de la minéralogie des inclusions qu’il contient et de la modélisation des équilibres de phases (pseudosections), suggère que le premier événement métamorphique (M1) est prograde et traduit un enfouissement, puis un réchauffement isobare. La résorption du garnet1 à laquelle succède la croissance du garnet2 est interprétée comme le résultat d’une décompression isotherme lors du métamorphisme M2. Il est suggéré que ces roches ont subi une fusion partielle lors du pic thermique du stade M1 et lors du stade M2. Le dernier événement métamorphique traduit une forte décompression associée à un refroidissement limité. La préservation d’une importante zonation de croissance du garnet à de telles conditions de température traduit la brièveté de l’ensemble de l’évolution métamorphique et par conséquent, du réchauffement, de la décompression puis du refroidissement qui s’ensuit. Cette évolution des conditions $P$–$T$ est compatible avec un modèle géodynamique invoquant la juxtaposition du manteau asthénosphérique chaud contre les roches de la croûte subductée à laquelle succède une exhumation dominée par le retrait du panneau plongeant (slab rollback).

Mots clés : Massif Central Français / éclogites / granulites HP / subduction / pseudosection / réchauffement isobare

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1 Introduction

Eucrites exhumed in the core of orogens are commonly considered to evidence ancient subduction zones (e.g. Miyashiro, 1961, 1972; Godard, 2001; Ernst and Liou, 2008). As such, the pressure-temperature (P–T) paths of Variscan eucrites in the French Massif Central place fundamental constraints on the earliest tectonometamorphic evolution of the orogen. Pioneering works on eucrites in the Massif Central revealed the shape of the retrograde P–T path (either associated with cooling or heating in the western and eastern Massif Central, respectively) but the inferred maximum pressures were surprisingly low for a subduction environment (mostly 13–15 kbar; Mercier et al., 1991 and references therein). The discovery of coesite in the Monts du Lyonnais area that typifies UHP metamorphism (Lardeaux et al., 2001) showed that the rocks may record significantly higher pressure. This was confirmed by recent studies based on the use of thermodynamic modelling (Berger et al., 2010; Lotout et al., 2018; Lotout et al., 2020). Despite these advances, the prograde part of the P–T path remains unknown and the dynamic of the subduction is therefore largely unconstrained.

The prograde part of a P–T path may be recorded by the chemical zoning of crystals grown during the prograde metamorphism, typically garnet, as well as their inclusion patterns (e.g. Thompson et al., 1977; Spear et al., 1984; Carlson and Schwarze, 1997; Stipská et al., 2006; Tual et al., 2017). Additionally, multi-stage garnet may record a complex crystallization and resorption sequence that can be used to unveil complex P–T paths (e.g. Karabinos, 1984; de Hoomy de Marien et al., 2019).

One eucrite from the Haut-Allier, sampled at La Borie, was the target of one of the first U-Pb datings of the eucrite-facies metamorphism in the Massif Central (Ducrot et al., 1983) and the obtained Silurian age of c. 430 Ma had a great influence on a number of geodynamic interpretations of the Variscan evolution of the Massif Central. The method used (dissolution of a zircon population) is now known to yield erroneous results (Paquette et al., 2017; Lotout et al., 2018) and our work in progress aims at determining the age of the eucrite-facies metamorphism in this locality with modern methods. Our focus on this locality for specifying with precision the metamorphic evolution of the eucrite was guided by both the historical importance and the position of the eucrite in the Variscan nappe-stack of the EMC. In this contribution, we present the results of a petrologic study using P–T pseudosections in order to constrain the P–T path of a Variscan eucrite sample of the Haut-Allier region in the Massif Central. We take advantage of complex growth/resorption sequence of porphyroblasts (e.g. garnet, omphacite and amphibole) to decipher rarely identified prograde evolution showing a pressure and temperature increase before an isobaric heating of about 150 °C at peak pressure conditions.

2 Geological setting

The formation of the Variscan belt in western Europe results from the amalgamation of several continental blocks during the convergence of Laurussia and Gondwana in the Palaeozoic (Matte, 1986; Kroner and Romer, 2013; Stampfli et al., 2013), which led to the formation of Pangea. The French Massif Central belongs to the internal zones of the orogen (e.g. Lardeaux, 2014) and is recognized as a nappe stack of different crustal units (e.g. Burg and Matte, 1978; Burg et al., 1984; Ledru et al., 1989; Faure et al., 2009). However, the Western and the Eastern Massif Central (EMC), located on either side of the lithospheric-scale “Sillon Houiller” fault (Burg et al., 1990) show significant differences. Several eucrite-bearing units are recognized in the Western Massif Central (Girardeau et al., 1986), while only one has been reported from the EMC (Burg and Matte, 1978; Burg et al., 1984). Available petrological and geochronological data on the eucrites from the EMC are equivocal, and their tectonic setting is a matter of debate.

2.1 Petrological and chronological framework

Most of the eucrites occur as lenses in the so-called Leptyno-Amphibolite Complex (LAC) (e.g. Santallier et al., 1988), interpreted as a tectonic melange of mafic (amphibolite, gabbros), ultramafic (garnet peridotites), felsic (granitoid orthogneisses, commonly fine-grained, called leptynites) and metasedimentary rocks (e.g. Forestier, 1961; Forestier and Lasnier, 1969; Forestier et al., 1973; Lasnier, 1977; Gardien et al., 1988, 1990). The LAC in the EMC has been variably interpreted in terms of 1) a dismembered continental passive margin, 2) ocean floor tholeiites or 3) a back-arc basin (Piboule, 1977; Giraud et al., 1984; Piboule and Briand, 1985; Bodinier et al., 1988; Briand et al., 1988; Lardeaux, 2014). Regardless of the setting of the protoliths, the LAC is interpreted as a marker of subduction (e.g. Santallier et al., 1988; Ledru et al., 1989; Lardeaux, 2014).

The eucrites from the EMC record a HP, eucrite-facies metamorphism and a subsequent retrogression in the HT amphibolite or granulite facies (e.g. Mercier et al., 1991). Recent petrological works improved the estimation of peak P–T conditions with estimations between 15–20 kbar at ∼600 °C in the Najac area (Lotout et al., 2018) and 18–23 kbar at ∼750 °C in the Lévézou massif (Lotout et al., 2020). Coesite in the Monts du Lyonnais typifies UHP conditions of >28 kbar at ∼750 °C (Lardeaux et al., 2001). Subsequent decompression down to 8–10 kbar is inferred isothermal in the Monts du Lyonnais (Lardeaux et al., 2001) or associated with moderate cooling in the Lévézou (600 °C; Lotout et al., 2020). The eucrites from the LAC thus indicate (U)HP metamorphism and subsequent exhumation at high temperature.

The age of the high-pressure event in the LAC, and thus the subduction event, is not well known. Data suggesting an early-Variscan, Silurian age (Pin and Lancelot, 1982; Ducrot et al., 1983; Paquette et al., 1995) have been discredited because of the methods used (dissolution of zircon population; Paquette et al., 2017; Lotout et al., 2018). Rare recent works suggest a younger, Devonian age for the eucrite-facies metamorphism in the southern EMC (c. 380 Ma for Najac – Lotout et al., 2018; c. 360 Ma in the Lévézou; Lotout et al., 2020), compatible with ages from other parts of the Variscan belt (Lotout et al., 2018).

2.2 The Haut-Allier

The Haut-Allier (HA) belongs to the core of the EMC, where Variscan high-grade metamorphic rocks are exposed.
These rocks were intruded by Carboniferous granitoids (ca. 330 Ma; Gardien et al., 2011; Laurent et al., 2017) and subsequently overlain by Upper Carboniferous sediments and lavas (Fig. 1). The high-grade rocks are subdivided into two superposed units, the Lower Gneiss Unit (LGU) and the Upper Gneiss Unit (UGU). In the studied area, the LGU is mostly composed of orthogneisses as well as biotite-sillimanite and staurolite-kyanite micaschists that record a prograde MP metamorphism. The LGU underwent a heterogeneous partial melting. The UGU is composed of metapelitic biotite-sillimanite(-cordierite) migmatites hosting remnants of kyanite-bearing granulate lenses, metabasites (garnet-pyroxene granulites, amphibolites) and orthogneisses (Forestier and Lasnier, 1969; Marchand, 1974; Lasnier, 1968, 1977; Forestier et al., 1973). The superposition of the UGU over the LGU is interpreted as the result of crustal nappe stacking during the exhumation of the UGU (e.g. Burg and Matte, 1978).

Although crustal nappe stacking can occur in different contexts (e.g. Vanderhaeghe, 2012), crustal nappe stacking during continental collision is typically associated with a medium-pressure metamorphism (e.g. England and Thompson, 1984; Le Fort, 1986; Spear, 1993; Jamieson et al., 1998). Surprisingly, available conventional thermobarometry data on the biotite-sillimanite micaschists and the staurolite-kyanite micaschists from the LGU as well as the kyanite-bearing granulites from the UGU indicate peak pressure conditions of ~13 kbar at 700°C for both units (Schulz et al., 1996; Schulz, 2014). Prograde metamorphism and partial melting of the LGU, inferred to be coeval with the decompression and melting of the UGU, is interpreted in terms of inverted metamorphism during thrusting (Burg et al., 1984). A 360 Ma age for the crustal nappe stacking is inferred from two EPMA U-Th-Pb studies on monazite in an UGU granulite (Gardien et al., 2011; Schulz, 2014). The kyanite-bearing granulite from the UGU underwent a poly-stage decompression, typified by the replacement of kyanite by sillimanite (Marchand, 1974) either associated with cooling or heating with peak temperature close to 700–800°C between 5–10 kbar (Gardien et al., 2011; Schulz, 2014). A late heating is also possibly recorded in metabasites from the LAC (Nicollet et al., 1993). The decompression is constrained between ca. 330 Ma by U-Th-Pb on monazite from the granulate (Schulz, 2014) and ca. 315 Ma by U-Pb on zircon from S/C granites (Gardien et al., 2011). Subsequent cooling is estimated at ca. 275 Ma by 40Ar/39Ar on K-feldspar (Gardien et al., 2011).

Nappe stacking was preceded by an earlier subduction event recorded by granulite- and eclogite-facies metamorphism in metabasites from the LAC (Matte and Burg, 1981). The metabasites in the HA share geochemical affinities with either ocean-floor tholeiites or back-arc basalts (Giraud et al., 1984). Conventional thermobarometry applied on the HA garnet-pyroxene granulites resulted in peak P–T conditions of about 20 kbar for a temperature fixed at 800°C (Pin and Vielzeuf, 1988) and the P–T evolution of the eclogites was never studied in detail. The age of this eclogite facies metamorphism has been estimated at ca. 430 Ma by U/Pb on dissolved zircon population (Ducret et al., 1983), but this method is known to yield erroneous results (Paquette et al., 2017) and the age of the eclogite-facies metamorphism must be determined with modern methods.

3 Petrography and mineral chemistry

Mineral analyses have been performed with a Cameca SX100 electron microprobe (Microsonde Ouest, IFREMER, Brest-Plouzané, France). Representative analyses of selected minerals are listed in Supplementary material (Tab S1). The mineral abbreviations are consistent with Holland and Powell (2011) and Green et al. (2016) — amp: amphibole, bi: biotite, chl: chloride, cpx: clinopyroxene, coe: coesite, ep: epidote, g: garnet, ilm: ilmenite, ksp: potassium feldspar, ky: kyanite, law: lawsonite, mu: muscovite, opx: orthopyroxene, pl: plagioclase, q: quartz, ru: rutile, sph: sphenite (titanite), sp: spinel, sul:
sulphide. Mineral endmembers (expressed in mole %) and compositional variables (mole fractions) are: 

- $X_{\text{Mg}} = \text{Mg}/(\text{Mg} + \text{Fe})$; $X_{\text{F}3} = \text{Fe}^{3+}/(\text{Fe}^{3+} + \text{Fe}^{2+})$; 
- almandine, alm = $\text{Fe}/(\text{Fe} + \text{Mg} + \text{Ca} + \text{Mn})$, pyrope, prp = $\text{Mg}/(\text{Fe} + \text{Mg} + \text{Ca} + \text{Mn})$; 
- grossular, grs = $\text{Ca}/(\text{Fe} + \text{Mg} + \text{Ca} + \text{Mn})$, spessartine, sps = $\text{Mn}/(\text{Fe} + \text{Mg} + \text{Ca} + \text{Mn})$; 
- jadeite, jd = $\text{Na}/(\text{Na} + \text{Ca})$; 
- albite, ab = $\text{Na}/(\text{Ca} + \text{Na} + \text{K})$, anorthite, an = $\text{Ca}/(\text{Ca} + \text{Na} + \text{K})$; 
- orthoclase, or = $\text{K}/(\text{Ca} + \text{Na} + \text{K})$; pistacite, ps = $\text{Fe}^{3+}/(\text{Fe}^{3+} + \text{Al} + 2)$; 
- geikielite, gk = $\text{Mg}/(\text{Fe}^{2+} + \text{Fe}^{3+} + \text{Mg} + \text{Mn})$; 

In addition, the amount of calcium on site B labelled Ca(B) and Na on site A labelled Na(A) in amphibole have been estimated following the procedure of Leake et al. (1997).

The studied eclogite was sampled west of the historical locality of La Borie (Fig. 1), from a hectometre lens of variously retrogressed eclogites surrounded by diatexites, in the lowermost part of the LAC. Under the microscope, the studied sample is a retrogressed eclogite composed of garnet porphyroblasts (up to 3 mm) and various fine-grained (< 25 μm) symplectites (Fig. 2a). It also contains minor rutile, ilmenite, sulphide, apatite and zircon. A fabric is marked by the ellipsoidal shape of the symplectites (Fig. 2a). The crystals that compose these aggregates are randomly oriented and lack signs of deformation, which suggests static replacement of primary crystals that had a preferred orientation.

Garnet contains abundant inclusions of amphibole, epidote, rutile, quartz as well as minor kyanite, clinopyroxene (Figs. 2b–2d), phengitic muscovite (μ1; Si = 3.7 pfu; $X_{\text{Mg}} = 0.6$) and zircon. The distribution of the inclusions defines an optical zoning (Figs. 3a and 3b). Garnet core and mantle contain numerous inclusions of epidote (ep1; ps = 0–40) and pargasitic amphibole (amp1; Ca(B) = 1.5–1.8; Na(A) = 0.4–0.6; Al = 2.7–3.1 pfu; Si = 6.0–6.1 pfu; $X_{\text{Mg}} = 0.64–0.71$). They are small (< 100 μm) in the core and significantly larger (up to 200 μm) in the mantle. Garnet rim is free of epidote and contains only scarce, more aluminous amphibole (Al = 3.5–3.6 pfu; $X_{\text{Mg}} = 0.62–0.66$) as well as rutile and zircon. Garnet core, mantle and rim are referred to as garnet1 (see below). An outer rim, referred to as garnet2, is characterized by the presence of more magnesian amphibole (Al = 3.5–3.6 pfu; $X_{\text{Mg}} = 0.62–0.66$) and anhedral omphacitic clinopyroxene (Fig. 2d; cpx1; Al = 0.42 pfu; $X_{\text{Mg}} = 0.85–0.90$).

The optical zoning of garnet defined by the inclusion pattern coincides with the chemical zoning (Fig. 3). Garnet1 is characterized by a decreasing grossular content and increasing pyrope content. The zoning is weak in the core with a roughly constant grossular (grs28–30) and spessartine (spss2) contents, slightly increasing pyrope (prp21–23) and decreasing almandine content (alm47–45). The mantle and the rim are characterized by a stronger zoning that involves further increase of pyrope (prp23–38–40) associated with a...
decrease of the almandine (alm 41–38–36), grossular (grs 28–30–23–21) and spessartine (sps 2–1–1) contents. The highest proportion of pyrope corresponds to the lowest grossular content. It is noteworthy that the slope of the pyrope, grossular and almandine zoning flattens from the outer part of the mantle rimward (transition marked by an arrow in Fig. 3c). The outer rim (garnet2) displays a striking inversion of the zoning trend of grossular (grs 21–26) and pyrope (prp 40–39). The discontinuity of the grossular content corresponds to an irregular boundary that marks the limit between garnet1 and garnet2 (Fig. 3a). Garnet is surrounded by a corona of amphibole and plagioclase symplectite, the composition of which is similar to the composition of amphibole and plagioclase of other symplectites in the matrix. The most abundant type of matrix symplectites comprises diopside (cpx2; Al = 0–0.1 pfu; XMg = 0.85–0.86), amphibole (amp3; pargasite to magnesiohomb lance, Ca(B) = 1.7–1.9; Na(A) = 0.2–0.6; Al = 3.2–3.5; Si = 6.0–7.2 pfu; XMg = 0.75–0.88), plagioclase (an = 18–35), and minor quartz (Fig. 2a). Another type of symplectites is distinctly Al-rich and corotic. Corundum is present in the inner corona, followed rimward by spinel (XMg = 0.44–0.52) and muscovite (Si = 3.1 pfu). These minerals are intergrown with plagioclase of a strongly variable composition from anorthite-rich in the inner symplectite to albite-rich in the rim (an = 91–20). Anhedral kyanite is locally observed in the core of these corotic structures. The third type of symplectite is K-rich and contains biotite, muscovite (Si = 3.0–3.1 pfu) associated with plagioclase (an 18–82) and minor epidote (ps0).

Fig. 3. Inclusion pattern and chemical zoning of garnet. X-ray maps for (a) Mg and (b) Ca contents in garnet. Notice the change of size and amount of inclusions from garnet core, mantle and rim. (c) Chemical zoning profile in garnet (location marked by black arrow in a). The outer rim (garnet2) displays a striking inversion of the zoning trend of grossular (grs 21–26) and pyrope (prp 40–39). The discontinuity of the grossular content corresponds to an irregular boundary that marks the limit between garnet1 and garnet2 (Fig. 3a).

Fig. 4. BSE image of an anhedral albite bleb surrounded by a corona of diopside (cpx2) in contact with the symplectites in the matrix.

type of symplectites is associated with anhedral rutile juxtaposed to ilmenite (geikielite up to 19%, pyrophannite < 1%), both of them being locally surrounded by a corona of sphene.

A key petrographic feature for the understanding of the sample are plagioclase crystals found as anhedral blebs of pure albite (100 μm) in the matrix (Fig. 4). The crystals are significantly smaller than garnet1 (mm-sized) but one to two orders of magnitude larger than crystals forming symplectites (1–10 μm). Additionally, the albite blebs are systematically isolated from the matrix symplectites by a corona of diopside. These observations suggest that the albite blebs belong to an intermediate stage of metamorphism, between the crystallization of the primary coarse-grained garnet-bearing assemblage and the retrogression of the sample associated with the development of the symplectites.

4 Interpretation of the petrographic observations

These observations are interpreted in terms of three metamorphic stages. The M1 assemblage is defined by coarse (mm-sized) garnet, its inclusion suite and the initial nature of the matrix crystals subsequently replaced by symplectites during M3. An intermediate M2 stage is subtle and characterized, among others, by small porphyroblasts of albite, and garnet2 overgrowths over garnet1.

The dominant M1 assemblage comprises garnet and three minerals now replaced by different symplectites. Diopside-amphibole-plagioclase-quartz symplectites are interpreted to replace omphacite, corundum/spinel-plagioclase (Al-rich) symplectites as former kyanite, and biotite-bearing symplectites as replacing a K-rich mineral, probably muscovite. This interpretation is strengthened by inclusions of omphacite, kyanite and muscovite in garnet. In addition, garnet also contains rutile and quartz as well as epidote and amphibole in its core. The garnet + omphacite-bearing but plagioclase-free assemblage M1 (garnet-omphacite-kyanite-muscovite-rutile-quartz with
epidote-amphibole in the core of garnet) typifies eclogite-facies conditions. In detail, the chemical and textural zoning of garnet marked by a decrease of spessartine and increase of pyrope as well as the disappearance of epidote and amphibole in garnet rim (g1, Fig. 3a) suggest that the M1 metamorphic event corresponds to a prograde evolution of the P–T conditions.

The irregular boundary between the rim (g1) and the outer rim of garnet (g2, Fig. 3a), is associated with the relatively abrupt increase of grossular, as well as the irregular garnet1 contour, commonly with convex faces, cutting across the concentric growth zoning. This suggests a period of partial resorption of garnet1, grown during M1, before the crystallization of garnet2 (outer rim – g2) during M2. M2 is also marked by the renewed growth of euhedral amphibole2 and by the resorption of omphacite, both preserved as inclusions in garnet2. Minor rutile and quartz, preserved as inclusions in garnet2, were also part of the assemblage. The albite blebs found in the matrix are inferred to belong to the M2 stage because 1) their grain-size (100 μm) is an order of magnitude smaller than the grain-size of the M1 assemblage (mm-sized) and 2) they are anhedral and isolated from the matrix symplectites grown during M3 by a corona of diopside (1–10 μm). These observations suggest that albite neither belongs to the M1 assemblage nor to the M3 symplectites but to an intermediate stage, M2. The equilibrium with clinopyroxene is suggested by the inclusion of omphacite (albite anhedral) in garnet2. The M2 assemblage contains at least garnet2-albite-amphibole2-rutile-quartz and probably omphacite in addition to a possible K-bearing mineral and/or kyanite.

The M3 event is characterized by the partial or complete replacement of the large M1 crystals by plagioclase-, amphibole-, diopside- and/or corundum-spinel-bearing symplectites. Such symplectites typically develop during decompression of high-pressure rocks, suggesting that M3 occurred at lower pressures. This agrees with the observed relations between rutile, ilmenite and sphene that suggest a sequential pressure (e.g. Zhang et al., 1995).

5 Phase diagram modelling

P–T pseudosections were calculated in the model system MnNCKFMA-SHTO and NCFMASHO using Theriaik/Dominov et al. (2015) and the thermodynamic data set 6.2 (Holland and Powell, 2011). The solution phases considered in the calculations and the activity-composition models used are amphibole, clinopyroxene, melt (Green et al., 2016); biotite, chlorite, garnet, muscovite (White et al., 2014b); epidote (Holland and Powell, 2011); ilmenite (White et al., 2000; White et al., 2014b); orthopyroxene (White et al., 2014a, b); plagioclase (Holland and Powell, 2003); spinel (White et al., 2002). The mixing models were converted for Theriaik/Domino by Doug Tinkham (http://dtinkham.net/peq.html).

Bulk compositions used for the calculations were obtained by the area-scan method at SEM-EDS (JSM-7100 F scanning electron microscope, CMEBA, University Rennes 1) on parts of thin sections estimated to approach an equilibrium volume, and the results were checked for robustness. FeO (vs. Fe₂O₃) was set so that the FeO/Fe₂O₃ ratio was equal to that of the bulk rock composition (analysed at the Geochemical and Petrographical Research Center, SARM laboratory, CNRS-CRPG, Nancy; FeO measured by wet titration) unless otherwise stated. The bulk compositions used are indicated as insets in the diagrams in mole per cent normalized to 100% with the exception of H₂O which is indicated as an additional component.

A first P–T pseudosection (Fig. 5) was computed in order to investigate the initial prograde metamorphism. This computation was achieved using a bulk composition measured on an area of a thin section comprising garnet with inclusions of epidote, amphibole, omphacite and a proportion of matrix with diopside-amphibole-plagioclase bearing symplectite, Al-rich symplectite, K-rich symplectite and albite blebs. The P–T pseudosection was contoured with compositional isopleths for garnet and amphibole. In this diagram, epidote is stable below 20–24.5 kbar and 750°C. Isopleths corresponding to the composition of garnet core (alm47; prp23; grs28) and the lowest observed Al content in amphibole (Al = 2.7 pfu) intersect in the field cpx-amp-g-ep-mu-q-ru around 650°C and 20 kbar. Decreasing grossular and almandine content together with an increasing pyrope content is compatible with increasing P–T conditions toward the stability field of kyanite and ultimately the epidote-absent field (cpx-amp-g-mu-ky-ru). This field is limited at higher pressures by the amphibole-out line between 650°C at 28 kbar and 750°C at 23 kbar. The flattening of the slope (in the chemical zoning profile, Fig. 3) of pyrope, almandine and grossular content in the outer mantle of garnet suggests that garnet continued to crystallize, but its composition evolved less rapidly. In the pseudosection this corresponds to a P–T evolution that crosses the compositional isopleths at lower angle. A curvature of the P–T path from crossing the isopleths initially at high angle to lower angle afterward indicates a roughly isobaric heating in the field cpx-amp-g-mu-ky-ru-fluid. This interpretation was checked for robustness by modelling the expected garnet zoning along a P–T path without curvature (i.e. straight from 650°C, 20 kbar to 750°C, 22.5 kbar) and a P–T path first dominated by a pressure and temperature increase (from 650°C, 20 kbar to 700°C, 22.5 kbar), and then by isobaric heating up to 750°C (see Supplementary Material Fig. S1 for details). Compositional isopleths for garnet1 rim (alm36; prp40; grs21) intersect in the field cpx-amp-g-mu-ky-ru, close to the melt-in line around 22.5 kbar and 750°C.

Lower pyrope and almandine as well as higher grossular contents suggest that garnet2 must have crystallized in the P–T domain where melt is stable (Fig. 5). Since melt incorporates a significant amount of H₂O, and the topology of the pseudosection beyond the solidus is expected to be dependent of the availability of water, another P–T pseudosection has been computed to investigate the evolution of the rock in the melt-present region (Fig. 6). Except for the H₂O content, the P–T pseudosection has been computed using the same bulk rock composition (this aspect is briefly discussed below).

The second P–T pseudosection (Fig. 6) is used to infer the P–T conditions of the M2 metamorphism. The amount of H₂O is set so that the rock is just H₂O-saturated at 750°C and 22.5 kbar, in the field cpx-amp-g-mu-ky-ru (i.e. contains about 1 volume % of free aqueous fluid accounting for interstitial space filled with fluids, as a result of progressive
dehydration-dominated subsolidus metamorphism). Calculat-
ed compositional isopleths corresponding to the composition of garnet2 (alm36; prp38; grs26) intersect in the field melt-
amp-cpx-g-pl-ky-q-ru-mu/ksp between 850 – 900 °C and 18.5 –
19.5 kbar in agreement with the inferred assemblage (garnet2-
albite-amphibole-rutile-quartz-clinopyroxene ± kyanite ± K-
bearing mineral). The composition of amphibole2 (Al = 3.2 –
3.5 pfu) is coherent with this estimation, but does not allow to
better constrain the P–T conditions. The resorption of garnet1
and crystallization of garnet2 is a first order constraint to
interpret this P–T pseudosection. Indeed, a straight P–T path
between the M1 peak conditions (750 °C and 22.5 kbar) and the
M2 conditions (ca. 875 °C and 19.5 kbar) could not account for
the observations since such P–T path would only result in
increasing the amount of garnet, therefore, the resorption of the
garnet1 would not be observed. However, heating from
22.5 kbar, 750 °C would result in garnet mode increase
(resulting in additional growth of garnet1) and a subsequent
pressure decrease to ~ 870 °C, 19.5 kbar would decrease garnet
mode in the field melt-cpx-g-pl-ky-q-ru (accounting for the
inferred resorption of garnet1) before a subsequent increase in
the plagioclase-bearing field (resulting in the growth of garnet2). Furthermore, the mode of garnet in the melt-amp-
cpx-g-pl-ky-q-ru-mu/ksp field must be higher than that
corresponding to the P–T conditions of the preserved garnet l
rim (34% of garnet at 750 °C, 22.5 kbar) to account for the
growth of garnet2, suggesting that the rock equilibrated at
temperature higher than 870 °C, in the field melt-amp-cpx-g-
pl-ky-q-ru. Clinopyroxene mode is very pressure-sensitive
and expected to decrease with decreasing pressure. This P–T
path would then also account for the anhedral shape of
clinopyroxene included in garnet2. Furthermore, this P–T path
would cross the amphibole-in line at 870 °C, 20 kbar and
account for the renewed growth of amphibole (included in
garnet2).

A final pseudosection (Fig. 7) has been calculated in order
to investigate the retrograde P–T path and the conditions of the
M3 stage using the bulk composition of a small area of
symplectite composed of diopside, amphibole, plagioclase and
a small amount of quartz, inferred to mostly be the product of
retrogression of former M1 omphacite. The H2O amount was
arbitrarily fixed as equivalent to the previous P–T pseudo-
section and the Xf3 ratio set in agreement with the ferric iron
incorporated in omphacite at 19.5 kbar and 875 °C (Xf3 =
0.40). In the resulting diagram, the field corresponding to the
observed assemblage (amp-cpx-pl-q) extends from 750 °C to
875 °C and 3 kbar to 15 kbar. The observed composition range
for Al in amphibole (Al = 1.1–2.4 pfu) from the matrix is
consistent with an equilibration pressure below 9 kbar
delimiting the temperature range between 750 °C and
850 °C. Though less constraining, this is also in agreement
with the observed Si content of amphibole (Si = 6.0–7.2 pfu),
Al in clinopyroxene (Al = 0–0.1 pfu) and anorthite content of
plagioclase (an = 18–35).

**Fig. 5.** P–T pseudosection and selected compositional isopleths calculated in the model system MnNCKFMASHTO for a local bulk composition of a part of the sample measured by SEM. Coloured fields highlight the stability of the M1 assemblage with epidote, epidote-kyanite and kyanite. The arbitrary large amount of H2O ensures that all the subsolidus assemblages are saturated in aqueous fluid.
6 Discussion

6.1 Considering garnet fractionation

Although garnet fractionation may affect the $P-T$ pseudosection results (e.g. Zuluaga et al., 2005), this effect on the general pseudosection topology is commonly limited, beyond the garnet-in line. Furthermore, in the sample studied, garnet contains abundant inclusions in the core. These inclusions represent to a certain degree the matrix of the rock. Consequently, the growing garnet did not only fractionate its own composition, but also the composition of the matrix, and the resulting modification of the effective bulk composition of the rock is therefore negligible. A $P-T$ pseudosection using the bulk rock composition with the garnet cores removed (without considering the inclusions) has been calculated, nevertheless, and the interested reader is referred to the Supplementary material for details (Fig. S2).

6.2 Partial melting and $H_2O$-content of the rock

The $P-T$ path determined in this contribution suggests that the studied sample equilibrated above the hydrated solidus. Yet, neither leucosomes nor melt inclusions, also referred to as "nanogranites" in the literature (e.g. Cesare et al., 2009) were observed. Hydrated partial melting may occur in a rock given that such rock contained a free aqueous fluid and reached temperatures high enough to cross the hydrated solidus. In this section we argue that these conditions were fulfilled and point out that the inferred equilibration of the rock above the solidus during M2 offers the advantage to explain several first-order petrographic observations, a posteriori supporting the results of the pseudosections modelling.

In the studied sample, garnet cores contain numerous inclusions of epidote and amphibole, whereas garnet1 rims are strikingly free of such inclusions. Given the dehydrating nature of most prograde metamorphic reactions, the disappearance of epidote and amphibole is interpreted, with the support of $P-T$ pseudosection, in terms of epidote and amphibole breakdown coeval with garnet growth during increasing pressure and temperature at sub-solidus conditions. Epidote and amphibole breakdown released a free aqueous fluid, filling the inter-crystalline space of the rock, even in the improbable case that the rock was not fluid-saturated before. Such space is thought to be equivalent to 1% of the rock volume (e.g. Thompson and Connolly, 1990). During the prograde M1 stage, the rock reached $P-T$ conditions of at least about 750°C, 22.5 kbar during an isobaric heating, flirting with the modelled hydrated solidus. Therefore, the basic requirement for the studied sample to undergo hydrated melting are satisfied and there are no a priori reasons to exclude this possibility.
The mineral composition of the M2 minerals, in particular garnet2, suggests P–T conditions beyond the hydrated solidus and we explored the possibility that the rock recorded partial melting during M2. Pseudosection modelling for the M2 stage successfully reproduces several first-order petrographic constraints in the melt-present domain such as 1) garnet1 resorption and garnet2 overgrowth, 2) garnet2 composition, 3) clinopyroxene resorption, and 4) the renewed growth of amphibole 2. The absence of unquestionable evidence of melt may be explained either by the possibility of melt to flow along strain gradients toward another location, preventing the formation of in-situ leucosomes, by the low proportion of melt produced and by the small probability to observe trapped melt inclusions in the tiny garnet2 overgrowths. Consequently, despite the absence of direct evidence of partial melting, the general fit between P–T pseudosection modelling, several petrographic observations and mineral compositions, supports the results of the modelling and may be taken as indirect evidence of partial melting of the eclogite at the peak of M1 and during M2.

It is noteworthy that quartz-plagioclase-kyanite-garnet-zoisite-bearing layers in eclogites from the southern Lévézou and Marvejols massifs in the EMC have been interpreted as high-pressure trondhjemites recording the partial melting of their host rocks (Nicollet and Leyreloup, 1978). Consequently, our results may be taken as a first step for further research of evidence of partial melting, and its consequences, in the eclogites in the EMC. Indeed, partial melting of high-pressure rocks has implications on the rheology of subducted lithospheres (e.g. Labrousse et al., 2011, 2015; Wang et al., 2014), metasomatism of the overlying mantle and related contribution to arc magmatism (e.g. Prouteau et al., 1999, 2001; Borghini et al., 2019; Hernández-Uribe et al., 2020).

6.3 P–T evolution

The metamorphic evolution of the studied sample is recorded by three metamorphic stages. During the M1 stage, the rock underwent the crystallization of a garnet- and omphacite-bearing assemblage typical for eclogite-facies metamorphism. The development of the eclogite assemblage was coeval with a ductile deformation (materialised by the preferential orientation of the now pseudomorphed kyanite crystals). The inferred M2 assemblage includes garnet2 and albite. The presence of omphacite, albeit anhedral, in garnet2 and the results of the P–T pseudosections suggest that clinopyroxene was also present in the assemblage, and M2 may then represent a high-pressure granulite-facies metamorphism. During the M3 stage, former porphyroblasts were partially or fully replaced by diopside-amphibole-plagioclase- and corundum/spinel-plagioclase-bearing symplectites, suggesting an equilibration under HT amphibolite- to LP granulite-facies conditions. Taken together these three stages characterize a clockwise P–T path.

The M1 metamorphic stage can be traced through the inclusion suite in garnet. The disappearance of hydrated phases...
– amphibole and epidote – from the core to the rim of garnet typifies prograde metamorphism from ~20 kbar – 650°C to ~22.5 kbar – 750°C, quantified using the compositional zoning of garnet. Further analysis of the garnet growth zoning suggests that such prograde metamorphism was initially dominated by burial (pressure increase), followed by isobaric heating (temperature increase).

Petrographic observations indicate that a portion of garnet grown during the M1 metamorphism was subsequently partly resorbed (Fig. 8a). This leaves an incertitude on the peak P–T conditions for this metamorphic event. However, two observations can be used to tentatively infer the trend of the missing portion of the P–T path: 1) the preserved garnet1 growth zoning indicates an isobaric heating during M1 (Fig. 5a), and 2) the growth of garnet2 requires either isothermal decompression or heating in the field melt-amp-cpx-g-pl-ksp-ky-q-ru (Fig. 6a). It must be emphasized that garnet2 could not have grown during cooling. Therefore, unless the rock underwent an unusual P–T evolution, it can be deduced that the peak P–T conditions for the M1 stage did not significantly exceed 22.5 kbar and 880°C (Fig. 8b).

Based on textural features supported by thermodynamic modelling, it is inferred that the M2 assemblage comprised garnet2, albite, amphibole, quartz, rutile, clinopyroxene, kyanite and a K-rich mineral. Pseudosection modelling indicates that garnet mode decreases in the plagioclase-free fields but increases in a small region with plagioclase, amphibole and kyanite (light blue fields in Fig. 6a) through a decrease of pressure, possibly associated with an increase of temperature. This path also accounts for the renewed growth of amphibole and the anhedral shape of clinopyroxene, both observed in garnet2. The transition from the eclogite to the high-pressure granulite facies therefore results from a decompression associated or not with heating toward 19 kbar, 875°C following the significant temperature increase, under eclogite-facies conditions, during M1 (Fig. 6a).

The M3 metamorphic stage is evidenced by the pervasive replacement of the former high-pressure minerals by symplectites. Pseudosection modelling indicates a strong decompression to P < 9 kbar along a steep retrograde P–T path associated with a slight to moderate cooling to 750–850°C (Fig. 8b).

6.4 Geodynamic implications

The peak P–T conditions reported in this study indicate a high-pressure metamorphism, consistent with the discovery of coesite in the Monts-du-Lyonnais area (28 kbar; Lardéaux et al., 2001) and recent petrological works in the EMC (Najac massif, 15–20 kbar, Lotout et al., 2018; Lévézou massif, 18–23 kbar, Lotout et al., 2020). The initial prograde metamorphism shows a high dP/dT gradient compatible with burial in a subduction zone in agreement with the accepted interpretation of the eclogites in the EMC (Nicollet, 1978; Matte and Burg, 1981; Mercier et al., 1991; Lardéaux et al., 2001; Faure et al., 2014; Lotout et al., 2018). Furthermore, the decompression path associated with limited cooling agrees with the P–T path reported by Lotout et al. (2020) in the Lévézou. The most interesting aspect of the inferred P–T path is to unveil an isobaric heating of ~150°C during the prograde metamorphism. Such heating may be accomplished by either thermal equilibration, shear heating, or a “contact” metamorphism.

The achievement of conductive thermal reequilibration may take several tens Myr (England and Thompson, 1984).
This could a priori reconcile the 430 Ma age inferred for the eclogite facies metamorphism in the LAC of the HA (Ducrot et al., 1983) and subsequent exhumation during crustal nappe stacking at 360 Ma (Gardien et al., 2011). However, this interpretation is unlikely for several reasons. As previously mentioned, the zircon population dissolution method used by Ducrot et al. (1983) has been shown to produce incorrect results especially if zircons are zoned (Paquette et al., 2017). Furthermore, there is growing evidence of a Devonian rather than Silurian age for the Variscan subduction in France (Bosse et al., 2000, 2005; Paquette et al., 2017) and in the EMC in particular (Lotout et al., 2018, 2020). Paquette et al. (2017) proposed that the Silurian ages obtained by dissolution of zircon population resulted from an over-interpretation of the U-Pb data. Finally, several studies argued that the preservation of garnet growth zoning implies a short-time residence at high temperature (e.g. Rötzler and Rötzler, 2003; Caddick et al., 2010) difficult to reconcile with the hypothesis of conductive thermal reequilibration. As a consequence, our data do not support this hypothesis.

Deciphering the possible influence of shear heating, or a “contact” metamorphism (e.g. by the juxtaposition of a hot mantle) may be harder. In the classic form, shear heating may explain a temperature rise of up to ~200 °C on a hectometre to kilometre scale along shear zones (e.g. Camacho et al., 2001; Duprat-Oualid et al., 2013; Duretz et al., 2014; Schmalholz and Duretz, 2015). However, deformation-generated viscous dissipation on the lithospheric scale (also termed “viscous heating”) is comparable to or even exceeds bulk radiogenic heat production within the crust and may affect the thermicity of a subduction zone and explain regional-scale HT metamorphism (Burg and Gerya, 2005; Gerya et al., 2008). Alternatively, an alternative interpretation for similar heating involves the juxtaposition of a hot mantle with the studied samples (e.g. Dragovic et al., 2015; Massonne, 2006; Liu et al., 2019) that may apply to a regional scale HT metamorphism.

In the EMC, the LAC and the UGU display striking similarities regarding the shape of their P–T path (i.e. HT decomposition from HP conditions). Indeed, the eclogites from the LAC record a retrogression under HT amphibolite to granulites facies (e.g. Mercier et al., 1991 and references therein) confirmed by recent petrological data (Monts du Lyonnais: ~750 °C – ~10 kbar, Lardeaux et al., 2001; Lévézou: ~600 °C, 9 kbar, Lotout et al., 2020; HA: 750–850 °C, < 9 kbar, this study) and the HP ky-thom-bearing granulites of the UGU underwent partial melting during decomposition (Burg, 1977) at temperatures between 700–800 °C (Gardien et al., 2011; Schulz, 2014). The similar shape of the P–T path in the UGU and the LAC led numerous authors to envisage a common decomposition history of both units under high-temperature conditions (e.g. Burg et al., 1984; Faure et al., 2009; Lardeaux, 2014). This HT character of the decomposition path remains valid despite the apparent pressure difference between the eclogite-devoid portion of the UGU (~13 kbar; Schulz, 2014) and the LAC (~22.5 kbar; this study).

Although the lack of reliable geochronological data for the eclogite facies metamorphism and the subsequent HT decomposition in the HA prevents a regional-scale correlation and therefore a definitive interpretation, regional-scale HT metamorphism appears to be a more probable option than a scale-limited shear heating. In the models presented in Gerya et al. (2008) only rocks that underwent UHP metamorphism (P > 35 kbar) record an isobaric heating and temperatures comparable with those obtained in this study (~900 °C) suggesting that the studied sample was not dragged deep enough in the mantle to undergo a viscous heating of the expected magnitude. Alternatively, the delamination of the lithospheric mantle from the subducted crust may trigger asthenosphere flow (Brun and Facecenna, 2008) that would in turn cause the retreat of the subducting slab and provoke the exhumation of the subducted rocks. Such process may be invoked to explain the isobaric heating up to high temperature and subsequent subisothermal, supposedly rapid exhumation of the studied sample facilitated by the development of a regional scale partial melting (e.g. Labrousse et al., 2011) followed by cooling. The high temperature (~800 °C) recorded by some granulites of the UGU (Gardien et al., 2011) and the late temperature increase recorded by coronitic gabbros (Niccol et al., 1993) may also be explained by such heat input from the mantle. This interpretation is in line with the mantle delamination and slab rollback mechanism proposed to explain the HT exhumation of the eclogites in the EMC by Matte (2007).

7 Conclusions

The studied sample recorded three metamorphic stages. M1 is characterized by an assemblage dominated by garnet, omphacite and kyanite, without plagioclase, indicating eclogite-facies metamorphic conditions. The rimward disappearance of epidote inclusions and the decreasing proportion of primary amphibole in garnet1 indicates a prograde metamorphism from 20 kbar and 650 °C to, at least, 22.5 kbar and 750 °C. The trend of garnet growth zoning is interpreted in terms of a prograde path first dominated by burial and then by heating. It is inferred to peak at ~875 °C, 22.5 kbar. M2 is characterized by an association of garnet2 and plagioclase together with clinopyroxene, typical for the HP granulate-facies metamorphism, that crystallized around 19.5 kbar and 875 °C.

Both the M1 temperature peak and M2 are inferred to occur at conditions where the rock is predicted to be partially molten. Although no direct evidence for partial melting has been found in the rock studied, HP melts have been described independently in other locations of the EMC. Given the possible geodynamic importance of eclogite-facies partial melting, this aspect would merit to be looked for specifically in other localities of the orogen.

The M3 stage is characterized by the replacement of former HP minerals by symplectites at < 9 kbar and 750–850 °C. This overall evolution defines a clockwise P–T path initially dominated by a pressure increase, then significant isobaric heating and finally by a strong decompression at high temperature. The relatively short duration of this P–T evolution and the probable subsequent fast cooling are suggested by the preservation of garnet growth zoning. Although an orogen cannot be reinterpreted from one sample, the proposed P–T evolution is compatible with a geodynamic environment dominated by subduction, lithospheric mantle delamination and subsequent slab rollback – a scenario that should be tested elsewhere in the Variscan belt.
Supplementary Material

Figure S1. The expected garnet zoning for two P–T paths over 50 points using the drive-file function of Theriak-Domino.

Figure S2. The P–T pseudosection below has been computed with the effect of 95% garnet fractionation considered.

Table S1. Representative analyses of selected minerals.

The Supplementary Material is available at http://www.bsgf.fr/10.1051/bsgf/2020016/olm.

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