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Two contrasted *P–T*–time paths of coronitic metanorites of the French Massif Central: are reaction textures reliable guides to metamorphic histories?

C. NICOLLET[1] AND P. GONCALVES[2]
[1]*Laboratoire Magmas et Volcans, OPGC – UBP – CNRS, 5, rue Kessler, 63 038 Clermont-Ferrand Cedex, France (c.nicollet@opgc.univ-bpclermont.fr)*
[2]*Département de Géosciences, Université de Franche-Comté, 16, route de Gray, 25 030 Besançon Cedex, France*

ABSTRACT Metanorites from two eclogitized metagabbros of the Hercynian French Massif Central preserve coronitic textures of hornblende, garnet, quartz and/or kyanite produced at the expense of the primary magmatic assemblage orthopyroxene and plagioclase. Using a petrogenetic grid in the CFMASH system, two possible *P–T* evolutions for the origin of the coronas are evaluated. The sequence of reactions involving the formation of Hbl (–Ky) ± Grt and Qtz coronitic assemblages is consistent with an isobaric cooling at high pressure (*c*. 1–2 GPa) under hydrated conditions. However, this *P–T* path, inferred by using only petrographical observations, is inconsistent with the geochronological constraints: emplacement of the gabbro at 490 Ma and high-pressure metamorphism at 410 Ma. In order to reconcile petrographical observations with geochronological constraints, we propose a discontinuous two-stage evolution involving a change in water activity with time. (1) Emplacement and cooling of the norite at low pressure under anhydrous conditions, at 490 Ma. (2) During the Hercynian orogeny, the norite experienced an increase in pressure and temperature under fluid-present conditions. Adding water to the system implies a dramatic change in the petrogenetic grid topology, restricting the orthopyroxene–plagioclase assemblage only to high temperatures. Therefore, the breakdown of the unstable magmatic assemblage, through apparent retrograde reactions, occurred along the prograde *P–T* path which never crossed the equilibrium boundaries of these reactions.

Key words: equilibrium boundaries; French Massif Central; metanorite; *P–T–t* paths; reaction textures.

INTRODUCTION

Determination of the *P–T–t* histories of metamorphic rocks provides critical constraints for the tectono-thermal modelling of the evolution of the lithosphere through time (e.g. Bohlen, 1987 and many others). A *P–T–t* path is commonly inferred by the study of a sequence of discontinuous petrographic steps observed in rocks as represented in mineral zoning, reactions textures and especially coronas. In the case of a single thermal event, a set of reaction textures is assumed to have formed along a simple *P–T–t* path which agrees with the *P–T* evolution followed by the rock. However, if such reaction textures resulted from the superposition of many thermal events, then, they cannot be directly used to construct a *P–T–t* path. The interpolation of different portions of discontinuous *P–T* paths would result in an apparent single-event *P–T–t* path, but without geological significance, while more complicated *P–T–t* paths might result from the combination of separate *P–T–t* paths (Vernon, 1996). The validity of a *P–T–t* path is best tested by combining petrological with structural and geochronological studies (Hensen *et al*., 1995; Hand *et al*., 1997; Buick *et al*., 1998; Goncalves *et al*., 2004).

A classic example of derivation of erroneous *P–T–t* paths is given by the interpretation of coronitic metagabbros. The partial conversion of gabbroic rocks through garnet-bearing coronitic assemblages was initially interpreted as the result of isobaric cooling at high pressure (Griffin & Heier, 1973). Later, however, geochronological constraints demonstrated that the high-*P* metamorphism occurred a long time after the gabbro intrusion and must be considered as prograde, which implies that the garnet-bearing coronas were produced along a prograde *P–T* path (Mork & Mearns, 1986; Griffin, 1987).

RELATIONS BETWEEN EQUILIBRIUM REACTIONS AND *P–T–t* path

The question of whether coronitic textures originate by a simple thermal event or successive metamorphic overprinting events has been addressed many times before and is usually solved by geochronology. Figure 1 illustrates three of different *P–T* paths that could give rise to a coronitic assemblage. If the coronitic texture representative of metamorphic conditions M2 is produced during a single event, it could be interpreted to be the result of isothermal decompres-

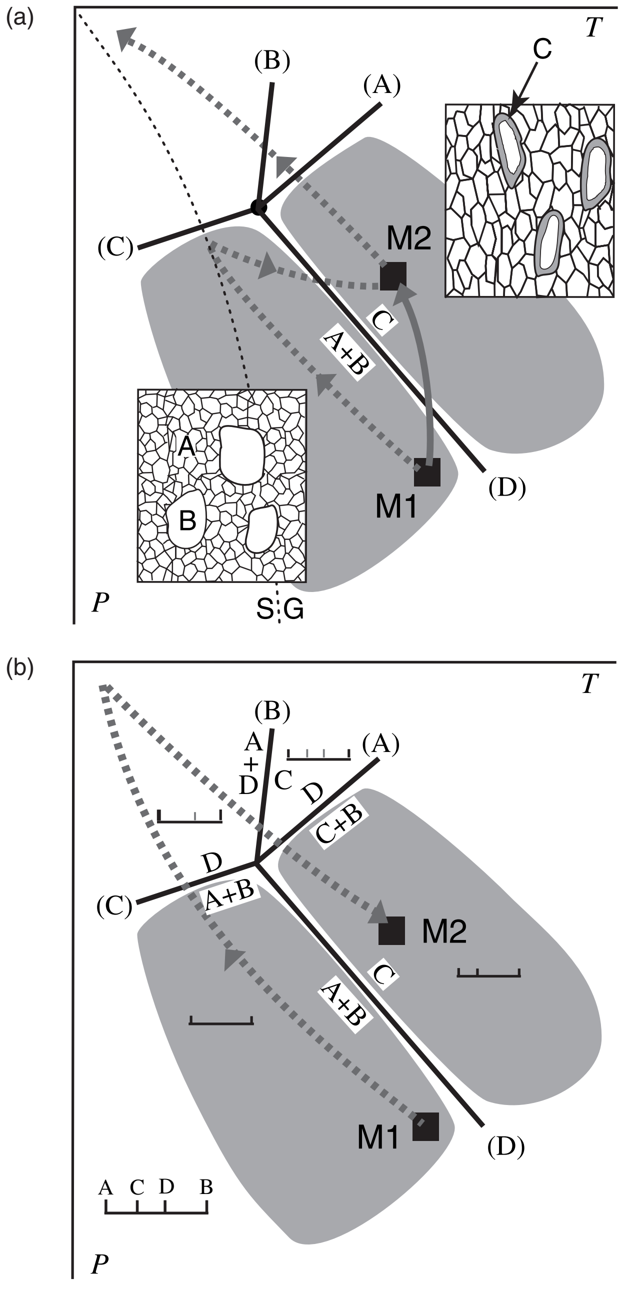

Fig. 1. Coronitic textures and different possible *P–T–t* paths for a rock with an assemblage A + B affected by one thermal (metamorphic) event (plain arrow) or two distinct thermal events M1 and M2 (dashed arrows). (a) The coronic assemblage is formed after crossing the equilibrium boundary of the reaction A + B = C. (b) For kinetic reasons, the assemblage A + B could be temporarily metastably preserved out of its stability field, at low *P*/*T*, between M1 and M2; during the M2 event, the coronic assemblage is formed without crossing the equilibrium boundary of the reaction A + B = C in the stability field of the produced phases C + A/B. The binary composition diagrams show the compositions of the phases used in the invariant point and the divariant stable assemblages. The end of *P–T–t* path of (b) is omitted for clarity. The dotted line (SG) in (b) is the stable geotherm.

sion (ITD: solid arrow in Fig. 1a). Alternatively, if the texture is produced during two thermal events that are separated in time and at different pressure conditions, a phase of cooling to the stable geotherm is required before the second event. This would result in a discontinuous *P–T* path shown by the dashed arrow in Fig. 1(a), as illustrated by Nicollet *et al.* (1993), Vernon (1996), Buick *et al.* (1998), Pattison *et al.* (1999) and Goncalves *et al.* (2004). In such a case, the continuous *P–T* path (i.e. the ITD path) would represent an incorrect path.

The two paths illustrated in Fig. 1(a) suggest implicitly that the reaction boundary A + B = C is crossed during the *P–T* evolution. Figure 1(b) shows a further *P–T* path, which should give rise to the same coronitic texture as in Fig. 1(a). During cooling and exhumation following M1, the assemblage A + B could be preserved metastably at low pressure and temperature. This case occurs when the rock, for kinetic reasons, fails to react when the reaction A + B = D is crossed, and so the phase D does not appear. As the rock undergoes later burial and metamorphism, the metastable assemblage A–B enters the stability field of B–C and so develops the coronitic assemblage A–B–C, but without crossing the reaction boundary (D) A + B = C (Fig. 1b).

In an even more extreme case, due to an abnormally large amount of overstep, the metastable reaction A + B = C occurs outside the stability field of the reactants A–C or B–C (Rubie, 1986; Droop, 1989). Thermometamorphism of xenoliths in volcanic rocks is a common example of these extreme disequilibrium textures.

In this paper, examples of classical 'cooling' textures are reported resulting apparently from retrograde reactions in two metanorites from the Hercynian 'complexe leptyno-amphibolique' (CLA) of the French Massif Central. We demonstrate that (1) these coronitic textures are formed during a prograde metamorphic event at high pressure and (2) equilibrium boundaries of the reactions resulting in these coronitic textures have never been crossed.

THE EUROPEAN VARISCAN BELT AND THE 'CLA'

The European Variscan belt results from the convergence of Baltica and Africa blocks after closing of several oceanic domains (e.g. Matte, 1991). The allochtonous CLA is a major unit in the Hercynian belt occurring as fragments found in the entire European Variscan belt. It consists of quartzofeldspathic gneisses (the so-called 'leptynites') and metamorphosed mafic rocks. Geochemical studies performed on the mafic rocks suggest that they represent fragments of oceanic crust, back arc basins or transition zone of the passive margin incorporated into the continental crust during continental collision. Some of these mafic rocks preserve relics of *HP–HT* metamorphism (eclogites, garnet-bearing metaperidotites) with near-peak conditions ranging from 1.0 to 2.0 GPa at *c*. 700–750 °C, followed by mid-amphibolite facies conditions resulting in partial resetting of the high-pressure assemblages. These *HP–HT* mafic rocks record the end of oceanic subduction and the early stage of Hercynian collision. The emplacement of the mafic protolith during an oceanic expansion occurred at 500–480 Ma, whereas the *HP–HT* metamorphism, which is interpreted as the consequence of the beginning of the continental collision, is dated between 440 and 390 Ma (e.g. Pin & Peucat, 1986; Santallier *et al*., 1988; Pin, 1990).

THE Hbl–Grt AND/OR Ky-BEARING METANORITES AND RELATED HP RELICS IN THE FRENCH MASSIF CENTRAL

The metanorite of Arvieu in the dome of Lévezou

The Arvieu area, west of the CLA of the Lévezou dome (South Massif Central) consists of a large metagabbro body (A in Fig. 2). In the mafic rocks, the magmatic texture is well preserved, although clinopyroxene is replaced by green hornblende. Relics of coronitic metatroctolite, Mg–hornblende–kyanite-bearing eclogite and metanorite, of tens to hundreds of metres in size, preserve evidence of *HP* metamorphism. The ages of magmatism and metamorphism of this massif are unknown. However, geochronological investigations on metatrondhjemites associated with eclogites from the southern part of the Lévezou dome document a magmatic age of 485 Ma and an *HP* metamorphism at 415 Ma (Nicollet *et al*., 1979; Pin & Lancelot, 1982; Pin & Piboule, 1988).

The magmatic assemblage preserved in the Arvieu metanorite is dominated by centimetric orthopyroxene, clinopyroxene and plagioclase (Pl1) with minor quartz and opaque minerals (Fig. 3). The secondary metamorphic assemblages are millimetre-sized minerals and occur usually as coronas around the magmatic minerals. They consist of hornblende, garnet, kyanite, plagioclase (Pl2), anthophyllite and quartz (Figs 3 & 4). Garnet is also present as centimetric porphyroblasts. The corona separating plagioclase from pyroxene is made of hornblende only, when orthopyroxene and clinopyroxene are involved in the reaction (Fig. 3a). This suggests the reaction

$$\mathrm{Opx} + \mathrm{Cpx} + \mathrm{Pl} + \mathrm{V} = \mathrm{Hbl}. \quad (1)$$

In the absence of clinopyroxene, the assemblage orthopyroxene–plagioclase 1 is destabilized into a complex coronitic texture of hornblende–kyanite (Fig. 3a) or hornblende–garnet–kyanite and occasionally quartz (Figs 3b & 4a,b). The amphibole is systematically located against the orthopyroxene, whereas the coronitic garnet is juxtaposed to plagioclase. Kyanite forms needles either at the contact between amphibole and plagioclase, or at the crystal boundaries of the secondary plagioclase (Pl2) (Figs 3 & 4), and it is never in direct contact with orthopyroxene. Garnet contains inclusions of hornblende and kyanite (Fig. 4b). These coronas are interpreted as the result of the following reactions:

$$\mathrm{Opx} + \mathrm{Pl} + \mathrm{V} = \mathrm{Hbl} + \mathrm{Ky} \quad (2)$$

and

$$\mathrm{Opx} + \mathrm{Pl} + \mathrm{V} = \mathrm{Hbl} + \mathrm{Grt} + \mathrm{Ky} + \mathrm{Qtz}. \quad (3)$$

Pyroxene and garnet do not show significant compositional variation. X_{Mg} [Mg/(Mg + Fe) in atoms] of orthopyroxene and clinopyroxene are 0.77 and 0.87, respectively, while garnet is a solid-solution alm43-py44gr13. Garnet porphyroblasts are slightly enriched in almandine (alm50py34gr13sp3). The magmatic plagioclase (Pl1) is a labradorite (An_{60}), while in metamorphic plagioclase (Pl2), anorthite varies between 0.60 and 0.25 from core to rim (Fig. 4c). This zoning of Pl2 probably results from the partial reaction: 2 anorthite + 3 Si + 2 Na = 2 albite + kyanite + 2 Ca. The amphibole is a magnesio-hornblende with X_{Mg} varying from 77 to 81. In the corona, the amphibole shows zoning related to a pargasitic substitution, with the Al/Si ratio, and, to a lesser extent, the Na increasing from the Opx (Ath)–Hbl boundary towards the Hbl–Pl boundary, whereas the X_{Mg} ratio decreases. These variations in plagioclase and hornblende compositions suggest a strong chemical gradient through the corona. Such a gradient reflects the relative immobility of Al_2O_3 due to its slow diffusion rate (e.g. Ashworth *et al*., 1998; Carlson, 2002), and suggests that in this sample, chemical equilibrium was not achieved at the thin-section scale.

P–T conditions were estimated using the TWEEQU software (Berman, 1991). In a coronitic texture, such estimation is not straightforward due to the strong

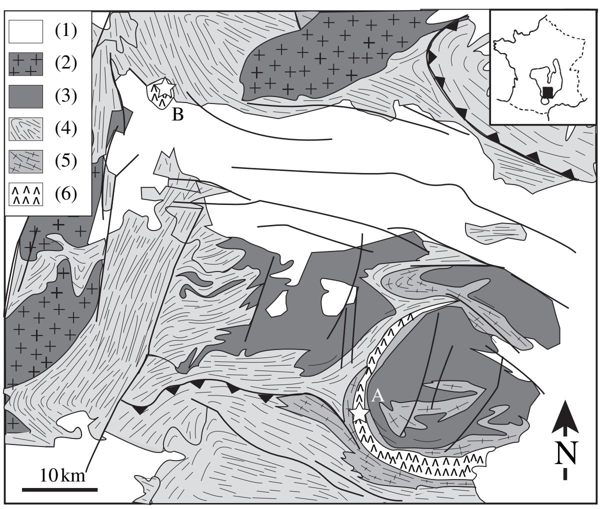

Fig. 2. Location of the metanorites (stars) from Arvieu (A) and Bessenoits (B) in the 'complexe leptyno-amphibolique' (French Massif Central). 1 – post Hercynian cover; 2 – Hercynian granites; 3 – metapelites and paragneiss; 4 – migmatites; 5 – orthogneiss; 6 – 'Complexe leptyno-amphibolique'.

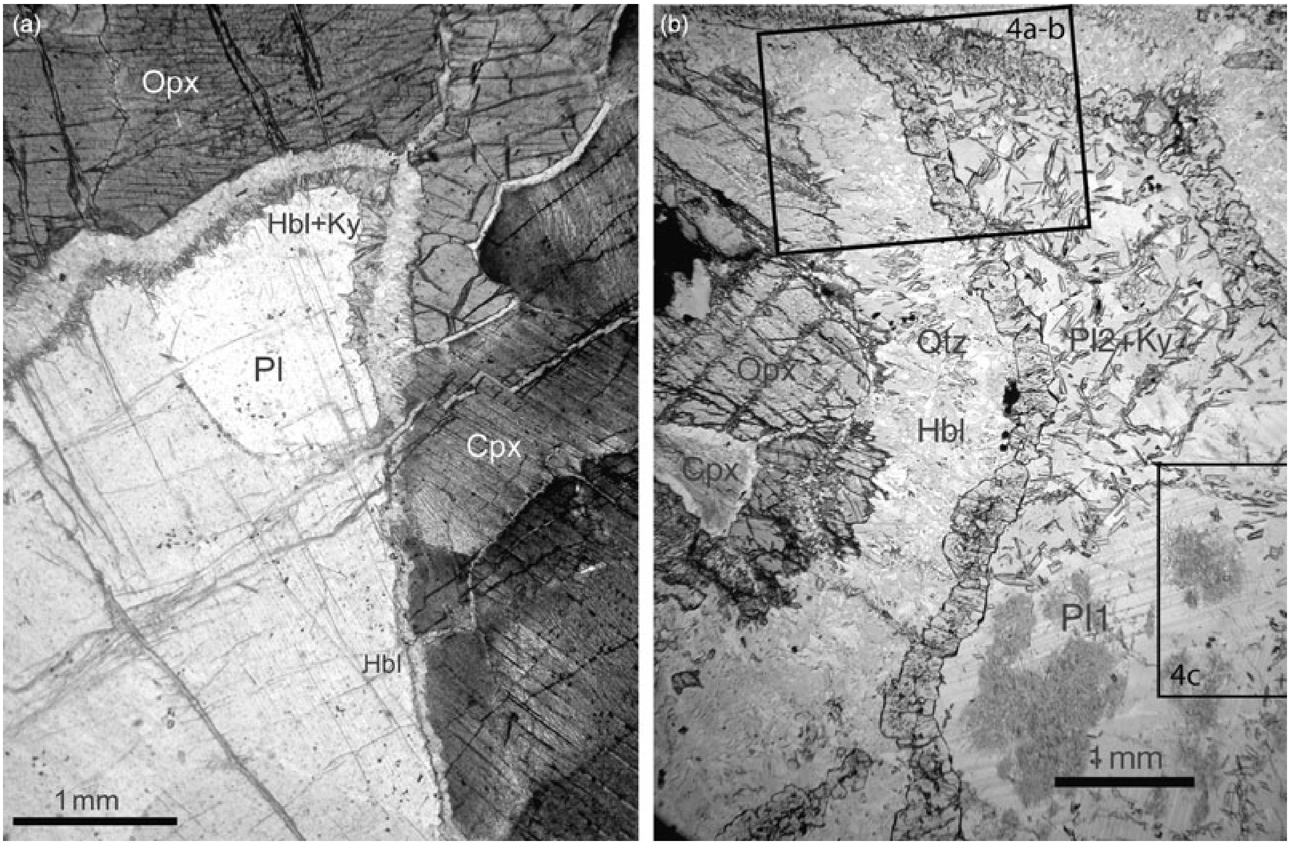

Fig. 3. Coronitic assemblages in the metanorite of Arvieu. (a) Coronitic hornblende between clinopyroxene and plagioclase, and hornblende + kyanite between orthopyroxene and plagioclase. (b) Coronitic assemblages consist of hornblende, garnet, quartz and kyanite between the magmatic minerals orthopyroxene and plagioclase 1 (altered in the core). The needles of kyanite are located at the grains boundaries of the zoned plagioclase 2. Plane polarized light. Rectangles: enlarged areas shown in Fig. 4.

chemical disequilibrium through the corona (e.g. Ashworth *et al.*, 2001). Here, it is assumed that minerals in contact are in local equilibrium, at millimetre scale. Temperatures calculated vary according to the Fe–Mg exchange reaction thermometer used: Cpx–Opx (850–900 °C), Opx–Grt and Cpx–Grt: 650–700°, Hbl–Grt: 600–650°. Pressures estimated with the Grt–Ky–Pl–Qtz barometer in micro domains where minerals are in contact ranges from 1.0 to 1.2 GPa at 650–700 °C. *P–T* conditions calculated on the Hbl–Ky-bearing eclogite associated with the metanorite yield equivalent results. In both lithologies, amphibole belongs to the high-pressure paragenesis, which is in good agreement with the high contents of Al^{VI} for its Si^{IV} and Al^{IV} (Leake, 1987).

The metanorite of the Bessenoits Klippe

One hundred kilometres to the NW, the Bessenoits massif (B in Fig. 2) is an orthogneissic klippe derived from the CLA (Paquette *et al.*, 1995). The orthogneisses contain ultramafic bodies as well as amphibolites. In these amphibolites, metanorites and metagabbros show a progressive transition towards Ky-eclogites, with several steps of corona development (Monchoux & Couturier, 1987). A multi-method geochronological investigation applied to several metanorites and eclogites indicates an age of 481 Ma for the mafic magmatism and an age of 408 Ma for the *HP* prograde metamorphism (Paquette *et al.*, 1995) in good agreement with data obtained on the metatrondhjemites from South Lévezou.

Metanorites of the Bessenoits Massif display a fine-grained (1–5 mm) doleritic texture. The igneous assemblage consists of plagioclase, hypersthene, diopside, minor amount of biotite, quartz, apatite, zircon and oxides. Two types of coronas are observed: (1) Anhydrous coronas of garnet, clinopyroxene and quartz surrounding the magmatic orthopyroxene in agreement with the reaction

$$\mathrm{Opx + Pl = Cpx + Grt + Qtz.} \quad (4)$$

(2) Hydrous coronas with hornblende or hornblende + garnet suggesting reaction (1) and the following reaction:

$$\mathrm{Opx(+Cpx) + Pl + V = Hbl + Grt + Qtz.} \quad (5)$$

Metamorphic conditions were not estimated on the metanorite of the Bessenoits Klippe. However,

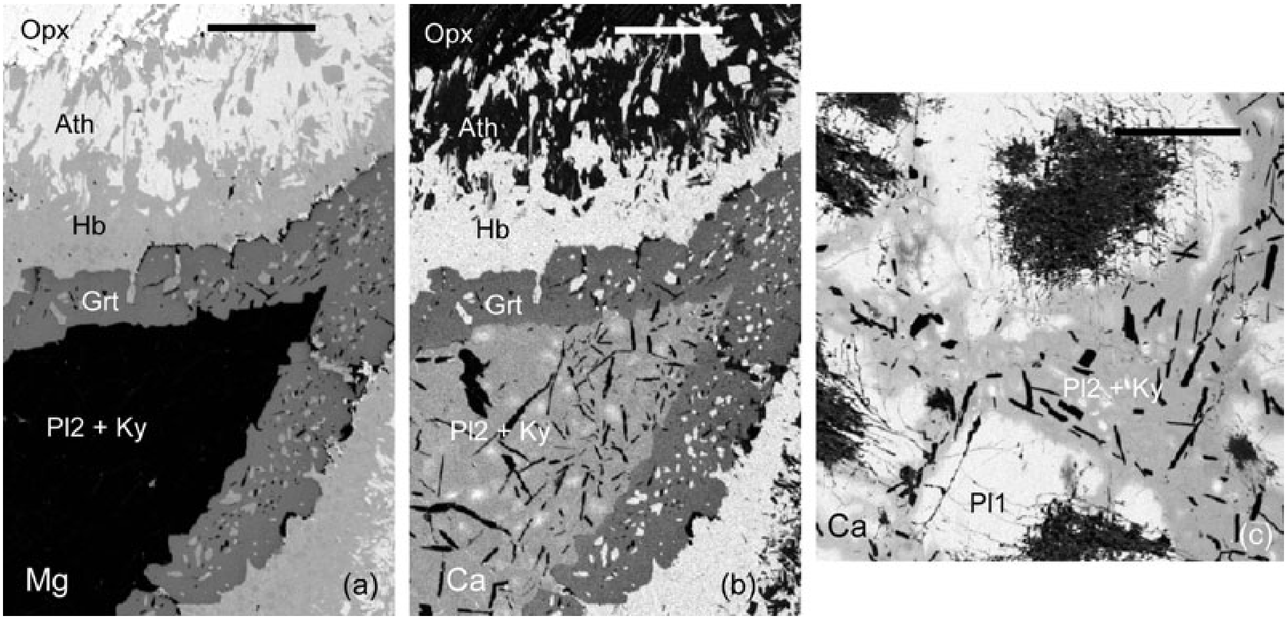

Fig. 4. X-ray compositional maps showing Mg and Ca of areas located in Fig. 3. (a) The Mg map shows that the amphibole corona consists of anthophyllite and hornblende. Quartz (black rims) occurs sporadically at the interface between Grt and Hbl. The coronitic garnet is characterized by the occurrence of hornblende (grey) and kyanite inclusions (black); (b) Ca map of the same area as (a). Note the zoning of Pl2; (c) partially altered (black) labradorite (white), which is recrystallized at its grain boundaries into more albitic Pl2 (grey) and Ky (black). The bars measure 0.5 mm.

previous thermobarometric estimates obtained on eclogites located a few kilometres north of the Bessenoits massif suggest conditions of about 1.9 GPa and 710 °C (Monchoux & Couturier, 1987).

PHASE RELATIONS IN THE CFMASH SYSTEM

The mineralogical assemblages of the metanorites are interpreted using a *P–T* projection (i.e. petrogenetic grid: Figs 5 & 6) and a phase diagram section (Fig. 7)

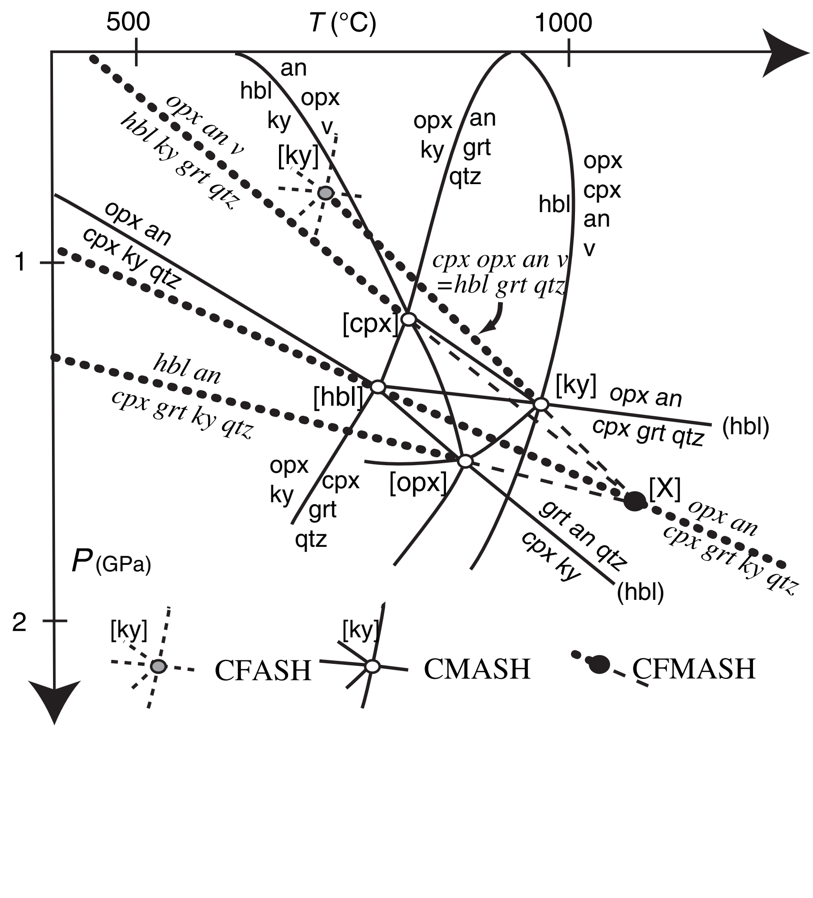

Fig. 5. Semi-quantitative petrogenetic grid in the CFMASH system. The stable invariant points of the Mg end-member system (CMASH) are [Opx], [Ky], [Cpx] and [Hbl] (open circles); the only stable invariant point of the Fe end-member system (CFASH) is [Ky] (grey circle). The univariant reactions in the CFMASH system linked these end-member invariant points (dotted lines; dashed lines: metastable portions of these CFMASH reactions; filled circle: CFMASH invariant point). Univariant CMASH reactions: (Opx, Ky) An + Hbl = Cpx + Grt + Qtz + V; (Cpx, Opx) An + Grt + Qtz + V = Hbl + Ky; (Cpx, Ky) An + Opx + V = Hbl + Grt + Qtz. The CFASH reactions around the Fe [Ky] point are not represented. Grids drawn by Nicollet (1988) using the thermodynamic database of Berman (1991). Abbreviations used from Kretz (1983).

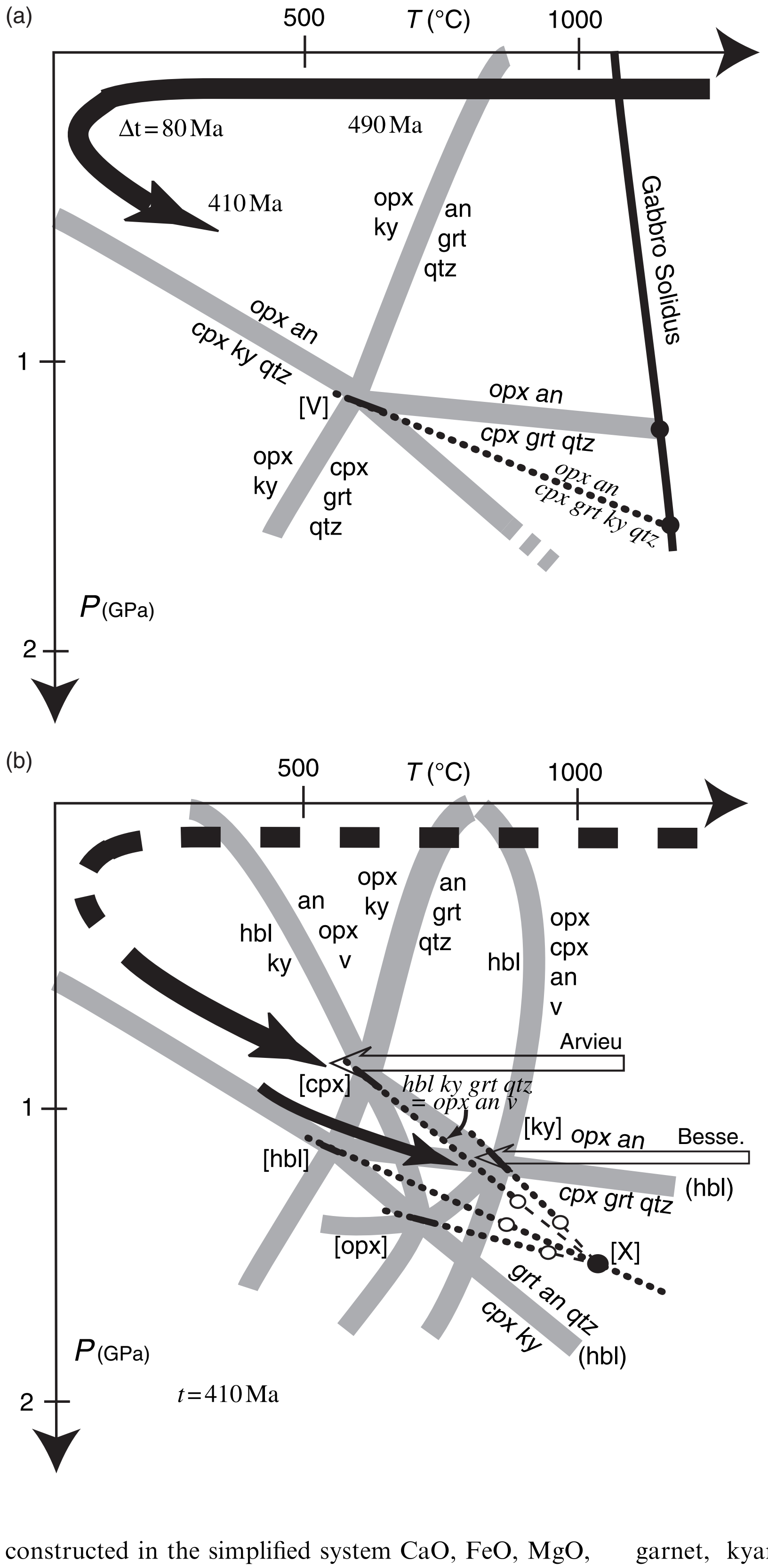

Fig. 6. Semi-quantitative petrogenetic grids in CFMAS(H) system for a fixed X_{Mg} ratio. Dotted lines, open and filled circles as in Fig. 5. For a fixed bulk X_{Mg}, only a restricted portion of the CFMASH univariant reactions is stable (heavy black lines: we call them 'pseudo-invariant points'). Around these stable CFMASH pseudo-invariant points, all the possible divariant Fe–Mg reactions are represented by thick grey lines (the thickness of the line qualitatively schematizes the divariant field of these reactions). (a) Fluid-absent conditions (CFMAS). The pseudo-invariant point [V] is the only one stable. The black arrow is the first stage of the proposed *P–T–t* path: intrusion and isobaric cooling of the norites at low pressure at 490 Ma followed by the beginning of the Hercynian prograde *HP* metamorphism after a time gap of 80 Myr, in anhydrous conditions. (b) Fluid-present conditions (CFMASH). The two black arrows show the end, at 410 Myr, of the *P–T–t* paths of the metanorite of Arvieu (large arrow) and, at higher *P*, of the metanorite of Bessenoits (narrow arrow). The open arrows illustrate the apparent isobaric cooling paths at a pressure of *c.* 1 GPa (metanorite of Arvieu; see also Fig. 7) and around 1.5 GPa (metanorite of Bessenoits: Besse.).

constructed in the simplified system CaO, FeO, MgO, Al_2O_3, SiO_2 and H_2O (CFMASH). The phases involved are orthopyroxene, clinopyroxene, anorthite, garnet, kyanite, hornblende, quartz and water. In Fig. 5, the invariant points [Cpx], [Opx], [Ky] and [Hbl] are stable in the end-member system CMASH

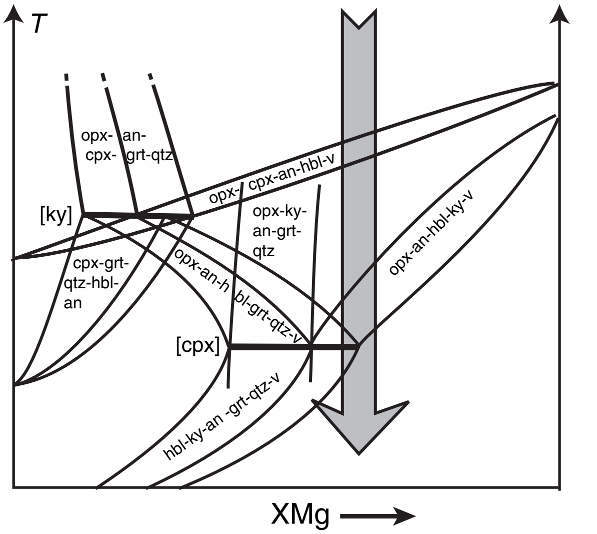

Fig. 7. Qualitative pseudo-section T–X_{Mg} at constant pressure of *c.* 1 GPa. An isobaric cooling path at an appropriate X_{Mg} ratio crosses the pseudo-invariant reaction [Cpx] and divariant reactions that explain the coronitic texture of the Arvieu metanorite.

(open circles) and CFASH (grey circle), while invariant points [An], [Grt], [V] and [Qtz] are metastable (they are not represented in Fig. 5). The invariant points [Hbl] and [V] overlap, as hornblende is the only hydrous phase in the system. However, none of these end-member grids are stable in nature. In the CFASH system, except for [Ky] (grey circle), all the other invariant points would be located at negative pressure and they are not represented in Fig. 5. The four stable points of the end-member grid in the CMASH system (open circles) are located at pressures ranging from 1.2 to 1.5 Ga at temperature of 850–950 °C: therefore, they would be metastable with respect to partial melting.

The stable CMASH invariant points (open circles) generate univariant reactions (dotted lines) in the CFMASH system (Fig. 5). These univariant reactions connect the invariant points of the two end-member systems CMASH and CFASH and converge to a virtual CFMASH invariant point [X] of upper order (filled circle). The CMASH univariant lines (thin lines in Fig. 5) slide along these CFMASH univariant lines and become divariant Fe–Mg bands in the CFMASH system (Fig. 6). For a fixed X_{Mg}, only portions of the CFMASH univariant reactions are stable, represented by black segments on the dotted lines in Fig. 6. Around these portions of stable CFMASH univariant reactions, called 'pseudo-invariant point', the divariant Fe–Mg reactions are represented by thick grey lines. Fe–Mg divariant reactions around the (Ky) pseudo-invariant point show the classic and key phase relations for metabasites under granulite and amphibolite facies conditions (e.g. fig. 3 in Wells, 1979).

Plagioclase, amphibole and, at high pressure, clinopyroxene (omphacite) are affected by several cationic substitutions involving Na, Al, Ca, Si. Including them in the grid calculation does not influence qualitatively the phase diagram topology. Therefore, they will not be taken into account here.

The petrogenetic grid in Figs 5 and 6(b) is calculated assuming fluid saturated conditions (CFMASH system). In contrast, Fig. 6(a) is calculated under anhydrous conditions (CFMAS system). Consequently, the pseudo-invariant point [V] is the only stable point. The stabilization of this pseudo-invariant point has the critical effect of increasing the stability field of the assemblage orthopyroxene–plagioclase to low temperatures.

TWO POSSIBLE *P–T–t* PATHS FOR THE METANORITES: THE ISOBARIC COOLING PATH AND THE TWO-STEP *P–T–t* PATH

Isobaric cooling paths

The coronitic textures of both metanorites can be described using the petrogenetic grid of Fig. 6(b) with H_2O-present conditions and the X_{Mg}–T pseudo-section of Fig. 7. Indeed, isobaric cooling at a pressure close to that of the pseudo-invariant point [Cpx] (*P*, *c.* 1 GPa: open 'Arvieu' arrow in Fig. 6b) implies the following sequence of reactions in the metanorite of Arvieu:

$$\mathrm{Opx + Cpx + An + V = Hbl} \qquad (1)$$

and

$$\mathrm{Opx + An + V = Hbl + Ky} \qquad (2)$$

or

$$\mathrm{Opx + An + V = Hbl + Grt + Qtz} \qquad (5)$$

for Mg-rich and Fe-rich whole-rock compositions, respectively (Figs 6b & 7). For a specific bulk composition (arrow in Fig. 7), the assemblage Opx–An breaks down via the CFMASH pseudo-invariant reaction

$$\mathrm{[Cpx]Opx + An + V = Hbl + Ky + Grt + Qtz} \quad (3).$$

In the same way, isobaric cooling at a pressure close to that of the pseudo-invariant point [Ky] may explain the sequence of reactions in the metanorite of Bessenoits (see open 'Besse' arrow in Fig. 6b)

$$\mathrm{Opx + An = Cpx + Grt + Qtz} \qquad (4)$$

or

$$\mathrm{Opx + Cpx + An + V = Hbl} \qquad (1)$$

$$\mathrm{Opx + Cpx + An + V = Hbl + Grt + Qtz} \qquad (6)$$

and

$$\mathrm{Opx + An + V = Hbl + Grt + Qtz.} \qquad (5)$$

A near-isobaric cooling at high pressure, illustrated by the open arrows in Fig. 6(b), represents the simplest solution to explain the mineralogy of the metanorites. These P–T evolutions have crucial geodynamic implications, because they suggest that the *HP–HT* metamorphism follows 'immediately' the emplacement of the gabbro during its cooling, such that, magmatism and metamorphism are related to the same geodynamic event. These P–T paths are inferred only by petrographical observations and do not take into account geochronological and thermodynamic constraints. In this particular case, the ages of 490–480 Ma for the mafic magmatism and 410 Ma for the *HP* metamorphism, means that the gabbro cooling at high pressures required at least 70–80 Ma, suggesting unrealistically slow cooling! For comparison, a straightforward thermal modelling predicts that a 2-km-thick sill would cool by conduction to 700 °C in about 3 Myr. Therefore, these isobaric cooling paths have no geological meaning and cannot be interpreted as the real P–T–t paths.

The most probable P–T–t paths do not cross the reaction boundaries

To take into account the geochronological constraints, we propose a model consisting of a first stage without a vapour phase and a second stage with an H_2O vapour phase. The graphical interpretation of the formation of the coronitic assemblage is done first with the grid under anhydrous conditions (Fig. 6a) and then, using one constructed under fluid-present conditions (Fig. 6b). The first stage involves an isobaric cooling at low pressure (< 0.3 GPa) under anhydrous conditions. Under these conditions, the magmatic assemblage orthopyroxene–plagioclase ± clinopyroxene is stable to < 300 °C at 0.3 GPa. The second stage involves a fully hydrated prograde metamorphism up to near-peak conditions estimated by thermobarometry to be *c.* 700 °C at 1 GPa. The fluid influx implies a 'switch' from the fluid-absent (Fig. 6a) to the fluid-present grid (Fig. 6b). Under fully hydrated conditions, the orthopyroxene–plagioclase stability field is restricted to high temperatures, whereas the field of the hydrated assemblage (Ky–) Hbl–An ± Grt is expanded. Consequently, during the prograde P–T path (see the plain black arrow which reaches a pressure of *c.* 1 GPa in Fig. 6b), the magmatic orthopyroxene–plagioclase assemblage of the metanorite of Arvieu is metastable and breaks down to a (Ky–)Hbl–An ± Grt stable assemblage to produce coronitic textures shown in Fig. 3 through the sequence of reactions (1)–(3). In the same way, the magmatic orthopyroxene–plagioclase assemblage of the metanorite of Bessenoits breaks down via reactions (4) or (1), (5), (6) to produce the Cpx–Grt and Grt–Hbl coronitic assemblages (black arrow at around 1.5 GPa in Fig. 6b).

These apparently retrograde reactions are produced during the prograde path, and it implies that these P–T–t paths never crossed the equilibrium boundaries of the reactions that produce the coronitic minerals in P–T space.

CONCLUDING REMARKS

The two-stage P–T–t paths proposed in Fig. 6(b) (black arrows) are consistent with the geodynamic constraints from the Hercynian belt of the French Massif Central. Indeed, the retrograde stage is related to the emplacement of the gabbroic complexes in an oceanic crust at 490 Ma, followed by 'rapid' isobaric cooling at low pressure to greenschist facies conditions. The anhydrous character of the gabbroic rocks favours preservation of magmatic textures and assemblages (Opx–Cpx–An), whereas the hydrous-surrounding rocks are transformed to low-grade actinolite, chlorite, epidote, albite-bearing rocks. These complexes are then involved in the eo-Hercynian subduction and collision at about 410 Ma. We suggest that, during subduction, the surrounding rocks are dehydrated, as proposed by Heinrich (1982), providing a source of fluids for the partial hydration of the gabbro and its *HP* metamorphism. The extent of the arrested reactions may have been controlled by the limited deviation of fluid-present conditions (Rubie, 1986).

This example demonstrates, as previously suggested (Hensen *et al.*, 1995; Vernon, 1996; Carlson, 2002), that the use of reactional textures to infer a continuous P–T path must be done with caution. As P–T vary in time, a rock should evolve continuously towards the equilibrium state by minimizing the free-energy configuration of its mineral assemblage. However, thermodynamic constraints are not the only factor controlling the evolution of mineral assemblages. Indeed, reaction kinetics also control how close a rock is to the equilibrium state. In the absence of deformation, fluid influxes are critical, because they favour the kinetics of reactions, even if the mineral transformations only involve anhydrous phases (Rubie, 1986). A change in fluid conditions (amount and composition) during a P–T evolution generally has a strong effect on phase diagram topology. Therefore, the thermal evolution of a rock can rarely be interpreted using a grid assuming constant fluid conditions. This problem is also enhanced by the fact that hydration can affect the whole rock or be restricted to channels, and fluid events occur as pulses, whereas P–T evolution is temporally more continuous.

The metanorites of the French Massif Central illustrate very well what Rubie (1990) emphasized: 'the timing of mineral reactions will not necessarily depend on when equilibrium boundaries are crossed in P–T space, but rather on when fluid becomes available at reaction sites'. In the same way, the triggering of a reaction does not occur exactly when the conditions of equilibrium (*TE* and *PE*) are reached. It requires a significant overstep of the P–T conditions ($TE + T$ and $PE + P$), which can be reached by different ways.

In our case, the equilibrium boundary of the reaction has never been crossed (Figs 1b & 6b).

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