Periodico di Mineralogia (2011), 80, 2, 267-285 DOI: 10.2451/2011PM0020

PERIODICO di MINERALOGIA
established in 1930

An International Journal of
MINERALOGY, CRYSTALLOGRAPHY, GEOCHEMISTRY,
ORE DEPOSITS, PETROLOGY, VOLCANOLOGY
and applied topics on *Environment*, *Archeometry* and *Cultural Heritage*

Cumulative cordieritite formation as a result of anatexis and melt expulsion. An example from the Chavanon sequence, Variscan French Massif Central

Vincent Thiéry

EM Douai, LGCgE-MPE-GCE, 59508 DOUAI, France
vincent.thiery@mines-douai.fr

Abstract

In the upper part of the Chavanon sequence (Variscan French Massif Central), a widespread, high temperature, Devonian regional anatexis led to the genesis of a complex imbrication of cordierite-rich rocks. One striking type is characterised by a high modal (~ 60-70%) amount of euhedral cordierite and its cumulative texture. The cordierite crystals contains inclusions of sillimanite needles that outlines the successive stages of cordierite growth in a melt. The estimated temperature range for the cordierite formation is 725-781 °C. The textural analysis of the rock, coupled with a crystal size distribution (CSD) diagram of cordierite, reveals crystallisation in equilibrium with melt. The complex imbrications between different migmatites types reveal several stages of melt expulsion and crystallisation. The different possibilities for the formation of this peculiar type of rock are also discussed.

Key words: Anatexis; Variscan French Massif Central; Cordierite; texture; Crystal Size Distribution.

Introduction

"Cordieritite" is not a common term in the geological literature since it is used both to describe orbicular, cordierite-rich intrusions (e.g. Rapela et al., 2002), restites following the removal of leucogranite melts (Ugidos et al., 2008) and cordierite-rich (> 60 % modal) hornfelses (Droop et al., 2003). It is more commonly used to describe corundum-bearing, cordierite-rich rocks, that resulted from high temperature metamorphism (Giuliani et al., 2007; Rakotondrazafy et al., 2008). Clarke (1995) uses this term to describe "rocks predominantly consisting of cordierite" as "an important subset of the monomineralic rock problem in igneous petrology". In the present paper, "cordieritite" is used to describe pods of cordierite-rich, cumulative rocks that are associated with migmatites and are migmatitic themselves.

Migmatites are strikingly complex rocks and are a keystone in the understanding of the nature and the processes involved in the genesis and the evolution of the continental crust. Their peculiar nature (e.g. partially melted rocks) leads to the different ways of studying them. On a sample scale, their microtextures unambiguously argue for their partially molten origin (Brown, 2002;

Holness, 2008; Holness and Sawyer, 2008; Sawyer, 1999; Vernon and Collins, 1988). Widely, their behaviour in orogens is investigated since they may flow on a large scale and originate wide scale melt-residuum processes (Godin et al., 2006; Guernina and Sawyer, 2003; Vanderhaeghe, 2009; Vanderhaeghe and Teyssier, 2001).

As noted by Solar (2008), it is difficult to distinguish at the outcrop scale what is purely petrographic from what is purely tectonic in migmatites. It is of first importance to unravel the successive stages of melting events and melt segregation to recognise what has melted and has been extracted (i.e. the leucosomes), what has not melted (the paleosome) and what has been left after melting (the residuum). For a comprehensive review of those phenomena, see Sawyer (2008).

The present paper aims at a comprehensive description of cordierite cumulates (the so-called "cordieritites") in an inner zone of the Variscan French Massif Central. The emphasis is put on the petrogenetical features.

Geological context

The Variscan French Massif Central

The French Massif Central corresponds to the northern margin of Gondwana, which is the southern continent involved in the Variscan orogeny, and its overall structure is characterized by collision tectonics and nappe stacking (Burg and Matte, 1978; Burg et al., 1984; Faure et al., 2009; Ledru et al., 1989; Matte, 1986; 1991; Matte and Burg, 1981). It is a part of the so-called Moldanubian domain of the belt, which represents the inner units (Figure 1A). The scheme for the final nappe stacking is a succession of three main nappes (Figure 1B). The uppermost nappe (so-called "upper gneissic unit") is characterized by a high-grade metamorphism locally reaching the eclogite facies (e.g. Lardeaux et al., 2001; Mercier et al., 1989). The middle nappe (so-called "lower gneissic unit") is characterized by a widespread anatexis (Faure et al., 2008) with no ultra-high pressure relics. Finally, the lowermost nappe (so-called "parautochtonous unit") is characterised by a low to middle-grade metamorphism without anatexis (Ledru et al., 1989).

Several models have been proposed, invoking either a monocyclic (Lardeaux et al., 2001; Matte, 1986) or a polycyclic (Faure et al., 2009; Faure et al., 1997) evolution for the belt. During Namuro-Westphalian times, a NW-SE to E-W trending extension is recorded by granitoid magmatic foliations (Burg et al., 1994; Faure and Becq-Giraudon, 1993). During the Stephanian, the NNE-SSW post-orogenic collapse guides the opening of coal basins along normal or wrench faults, and also the emplacement of granite-migmatite domes (Echtler and Malavieille, 1990; Faure, 1995; Faure and Becq-Giraudon, 1993; Malavieille et al., 1990).

The Chavanon sequence

This metamorphic sequence consists of the basement in which the Guéret magmatic complex was emplaced (Cartannaz, 2006). It is bound to the west and to the south by the right-lateral La Courtine shear zone, which is the eastern continuation of the Southern Armorican Shear Zone (Figure 1A). It is a wide ductile shear zone, intruded by granitoids (Cartannaz, 2006; Gébelin, 2004; Rolin, 1987), that affected the metamorphic sequence. To the east, the Chavanon sequence is bound by the Sillon Houiller fault. This main feature of the Massif Central is a left-lateral wrench fault with an estimated offset of ca. 70 km (Grolier and Letourneur, 1968; Joly, 2007; Thiéry et al., 2009). Finally, to the north, the Chavanon sequence migmatites are in contact with the Guéret magmatic complex (Rolin et al., 2008).

The Chavanon sequence (Martin, 1980) is made of para- and ortho- derived rocks, mainly metagraywackes with marble intercalations and probable metavolcanics. The whole sequence experienced an amphibolite facies metamorphism. Migmatites are widespread and locally contain kyanite-garnet granulite relics. The sequence shows an inverted metamorphism since the micaschists are structurally under the migmatites. The detailed mapping of the sequence (Rolin et al., 2008; Thiéry et al., in press) led to the recognition of complex imbrications between migmatites, in particular a close association of metatexites and diatexites from outcrop scale to map scale (Thiéry, 2010).

The so-called "cordieritites" of the present study crop out on the very upper part of the sequence, near a small hamlet called "Ribièras"

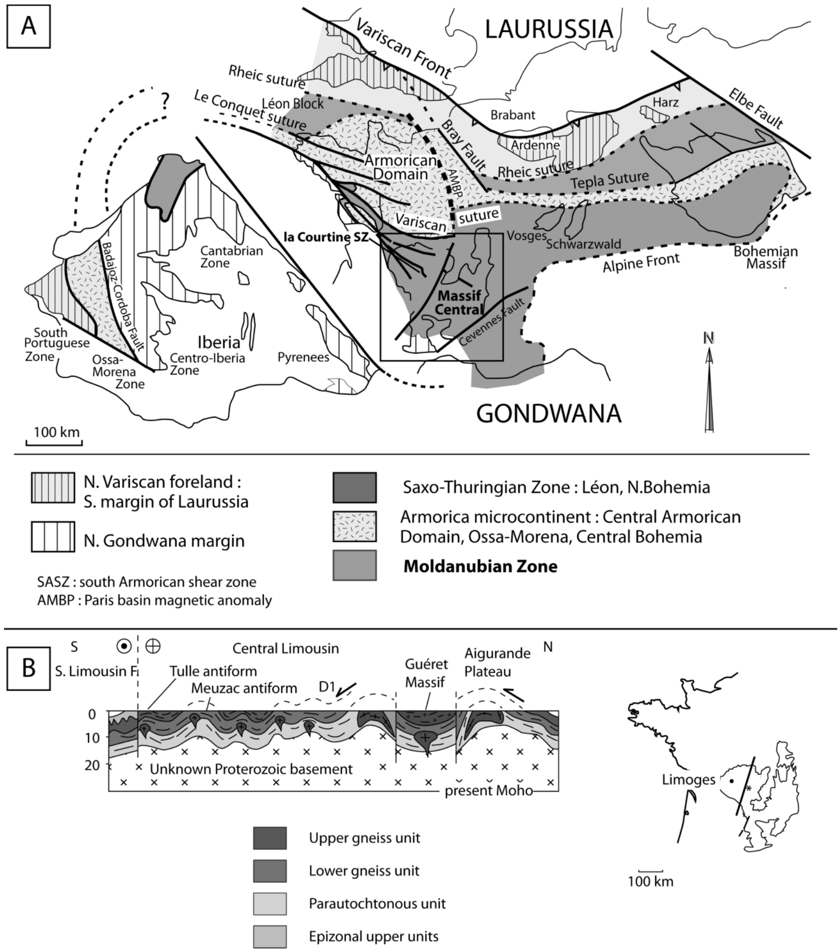

Figure 1. A) general map of the Variscan domain in western Europe (Faure et al., 2005); B) cross-section at the scale of the French Variscan Massif Central (Faure et al., 2009) showing the stack of nappes. The outcrop area of the Variscan French Massif Central is precised on the map; the full line represents the cross-section line, the small star locates the working area.

(Figure 2). The characteristic migmatites of this part of the sequence are medium-grained heterogeneous cordierite nodules bearing diatexites known as "Aubussonites" for the French town of Aubusson where they have been described (Grolier and Lacour, 1982; Le Breton et al., 1986). Textures vary a lot within those migmatites, whose texture is similar to a coarse-

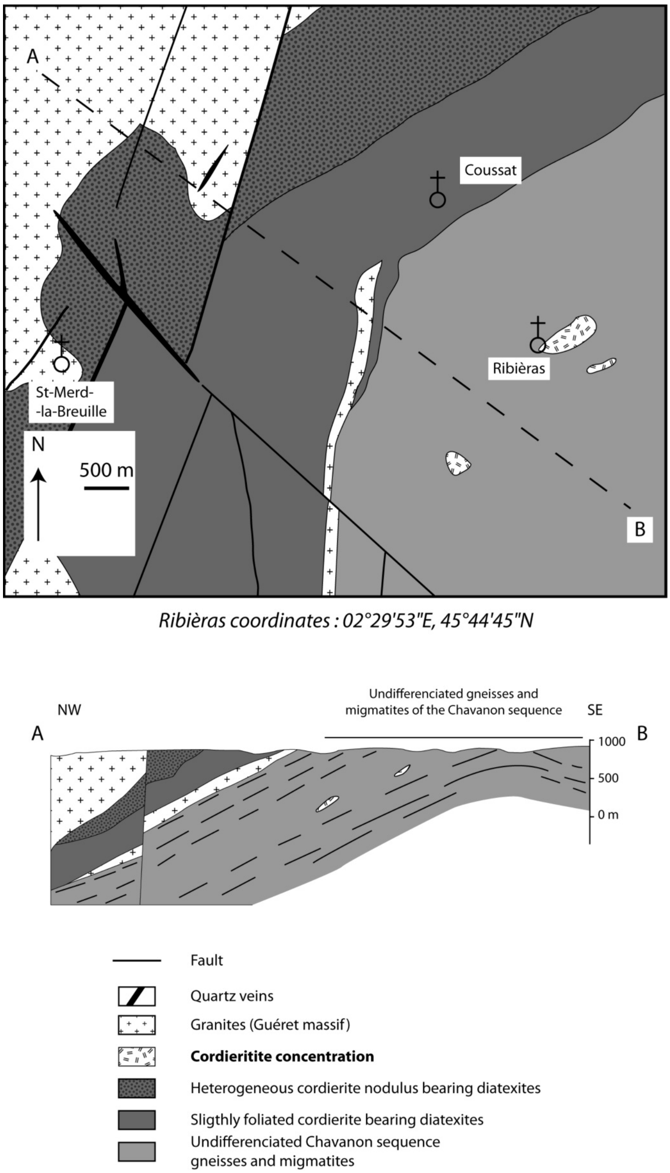

Figure 2. Simplified geological map and cross section of the upper part of the Chavanon sequence (Rolin et al., 2008; Thiéry, 2010).

grained granite; the abundance of cordierite nodules gives the rock a “leopard skin” aspect. Finally, those diatexites coexist with metatexites and often contain biotitic schlieren. The conditions of anatexis that led to their formation have been estimated to 5 kbar for 680 °C thanks to the presence of relictual garnet (Chenevoy and Ravier, 1989). The anatexis have been dated between 377 and 373 Ma on several regional samples (U-Th-Pb on monazite, Rolin et al., 2006). In this area, the migmatization events are older than for example the cordierite migmatites of the wide granite-migmatite Velay area (Ledru et al., 2001), in the eastern part of the French Massif Central, where melting events took place from 340 to 300 Ma. Nevertheless, in the Limousin area (western part of the French Massif Central), the Devonian anatexis is well documented (Be Mézème, 2005; Faure et al., 2008).

The lowermost migmatites from the Chavanon sequence ranges from metatexites to diatexites. The main part of the migmatitic domain of the sequence consists on garnet-biotite-sillimanite rich metatexite.

Analytical procedure

Microprobe analyses were carried out at the BRGM (French Geological Survey) in Orléans on a Cameca SX 50 operating at 15 kV and 12 nA with a beam size of 2 mm. The following standards have been used for calibration: K on orthose, Ca on andradite, Cr on Cr_2O_3, Si and Na on albite, Mn and Ti on $MnTiO_3$, Mg on olivine, Fe on Fe_2O_3 and Al on Al_2O_3. Cathodoluminescence (CL) imaging was carried out at the Besançon University using a cold CL system coupled to an optical microscope and operating at 20.0 ± 0.5 kV and 300 ± 30 mA. CL is used here only as an imaging tool to underline textural relationships. For further information, see Ramseyer and Mullis (2000). SEM was performed at the Besançon University.

Sample description

Petrographic features on sample and microscope scales

On the outcrop scale, the cordieritite forms dark (Figure 3a) metric rounded boulders. These rocks produce a high pitched tone under the hammer and are very hard to break. Mineralogically, they

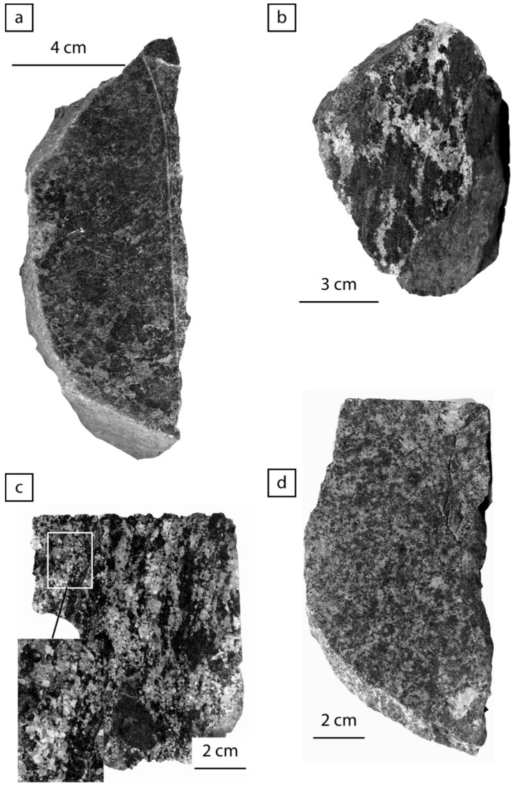

Figure 3. Cordieritite and related migmatites from the upper part of the Chavanon sequence; a) the so-called cordieritite is a dark, fine grained rock, which contains scattered patches of leucosomes within a cordierite-rich matrix. The white line is due to a defect of the saw; b) the leucosome proportion may become more important and dismember the cordierite-rich matrix; c) slightly foliated cordierite migmatite (note the euhedral shape of the plagioclase); d) equant cordierite-bearing diatexite.

are very monotonous but the texture can change dramatically from one sample to another since the amount of crystallised melt (i.e. the leucosomes) is quite variable. Indeed, the cordieritite are found vamong other cordierite-rich migmatites. Cordierite-bearing diatexites are widespread and are characterised by euhedral plagioclase (Figure 3b) in the leucosomes and cordierite nodules with an irregular shape, they lack a clearly defined foliation. However, the cordierite nodules tend sometimes to flatten in a poorly defined foliation plane (Figure 3c). The diatexites have locally a granitic habit (Figure 3d); all of these rocks types are intimately associated in a kind of complex "frozen mush".

Due to the relatively large size of the cordierite crystals, it appeared necessary to scan a whole thin section using a document scanner. Indeed, this technique offers the possibility to study far more crystals than under a standard microscope, even under the lowest magnifications. Moreover, the thin section have been put between two crossed polarizing films so as to mimic the observation conditions of the petrographic microscope. The resulting scan (Figure 4) reveals clearly the cumulative texture of the rock. It is characterised by a high amount of euhedral cordierite. The transverse sections are rectangular while the basal section are more or less rounded. The rock shows no clear foliation and is not transected by any leucosome.

The cordierite crystals are characterised by their subeuhedral shape and their abundant inclusions. They consist of rounded quartz, biotites and abundant sillimanite (Figure 5, Figure 6a, b and c). This mineral outlines the successive stages of cordierite growth (Figure 5a, c and e). This is particularly clear when using

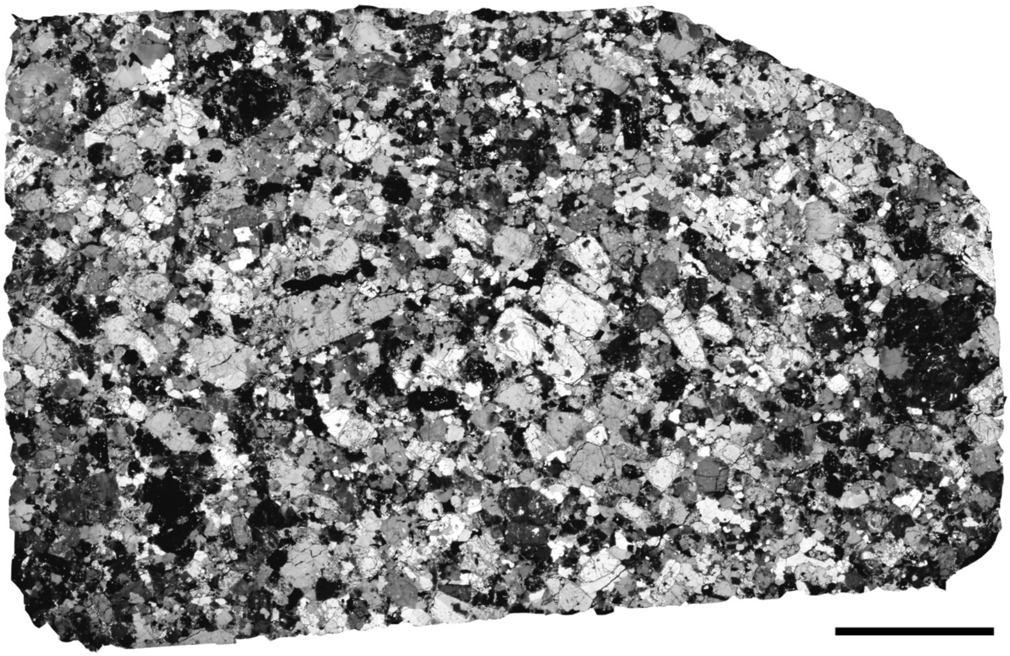

Figure 4. Whole thin section, scanned with a standard document scanner under crossed polarizing films, of a characteristic sample of cordierite cumulate, the so-called cordieritite. Note the large euhedral cordierite crystals that display both basal and transverse sections. Scale bar is 0.5 cm.

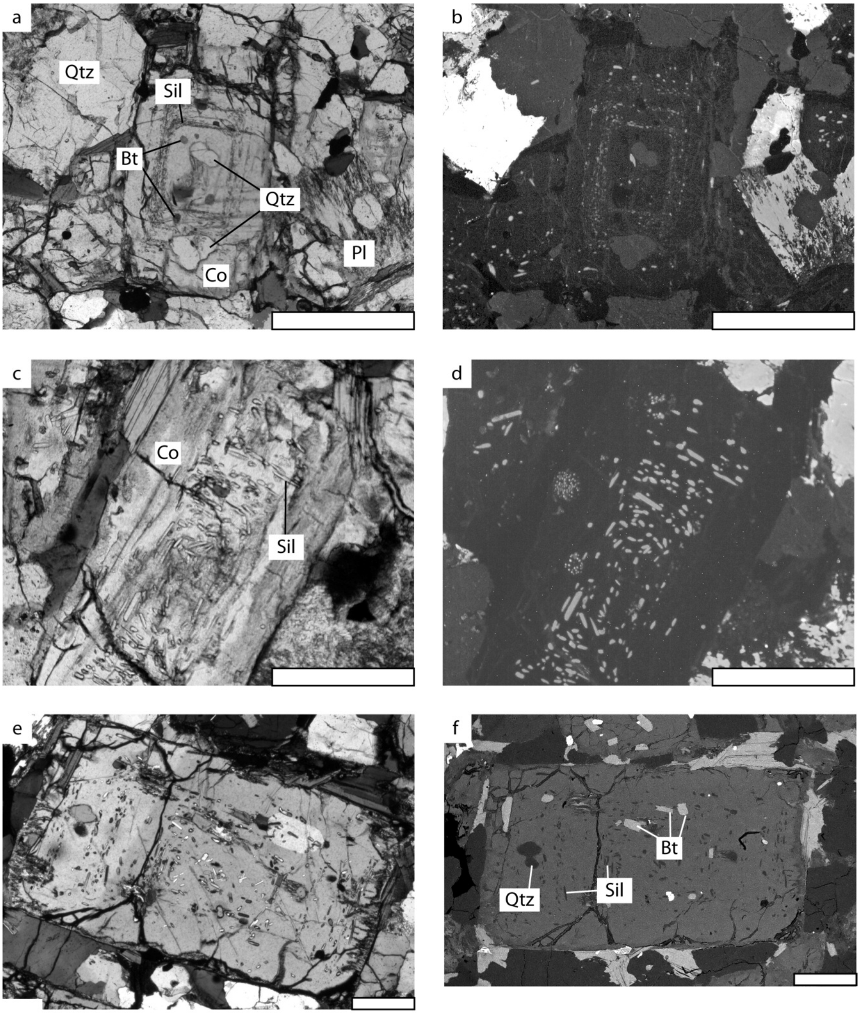

Figure 5. Photomicrographs of sillimanite-inclusion-rich cordierite crystals under an optical microscope in plane polarised light (a and c) and using cathodoluminescence (b and d). The cathodoluminescence pictures levels have been changed to enhance the colour contrasts. Scale bars are 500 μm; e) photomicrograph of a large cordierite crystal under crossed polars. Scale bar is 500 μm; f) view of the same crystal using BSE imaging (the black dot on the right of the cordierite is a dust particle) to outline the different types of inclusions. The quartz is dark grey, the biotite is clearer than the cordierite. Scale bar is 500 μm.

cathodoluminescence imaging (Figure 5b and d), since the red luminescence of sillimanite significantly contrasts with the deep blue tones of quartz and cordierite. The BSE imaging enhances the compositional contrast (Figure 5f).

The biotites of the quartzo-feldspathic matrix are characterised by highly lobate shapes (Figure 6d). It also forms numerous inclusions in cordierite (Figure 6e) where it is characterised by a rounded shape. Plagioclase is anhedral

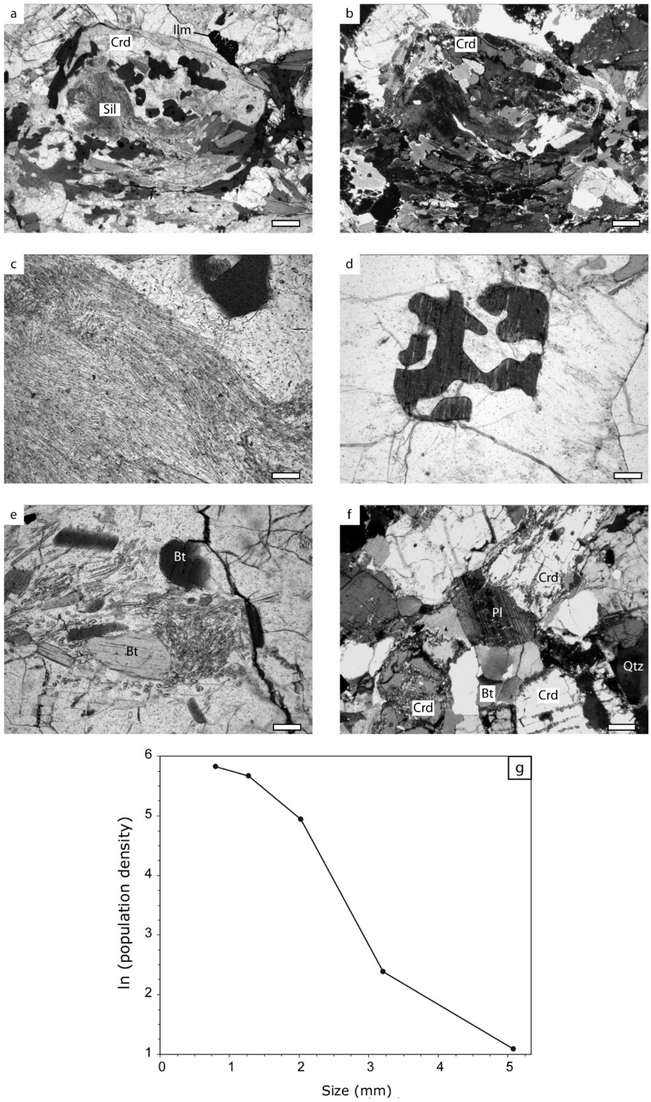

Figure 6. Photomicrographs of textures related to the cordieritites. Scale bars are 200 μm, except when precised. Abbreviations after Kretz (1983). Bt: biotite. Crd: cordierite. Pl: plagioclase. Qtz: quartz. Sil: sillimanite. a) euhedral crystal of cordierite growing at the expense of rounded biotite crystals and sillimanite (fibrolite) needles. Plane polarised light; b) same view under crossed polars; c) detailed view of the core of the cordierite crystal to show the density of fibrolite. Scale bar is 50 μm. Plane polarised light; d) highly lobate biotite of the cordieritite matrix. Plane polarised light; e) rounded flakes of biotites in a cordierite crystal, associated with sillimanite needles. Scale bar is 100 μm. Plane polarised light; f) plagioclase in contact with biotite and cordierite. Crossed polars; g) crystal size distribution (CSD) pattern of the measured cordierites. The CSD have been calculated using “CSD Corrections” (Higgins, 2000). The cordierite crystals have been parametred as rectangular prisms with a 1 : 1 : 4 ratio and no foliation.

(Figure 6f), quite scarce and is in contact with quartz, biotite and cordierite. Scattered ilmenite is present and is sometimes abundant.

The paragenesis suggests the following incongruent melting reaction for the growth of cordierite : Biotite + Sillimanite + Quartz + Plagioclase ↔ Cordierite + Melt. The high amount of fibrolitic sillimanite as inclusions in the core of cordierite crystals suggests a sillimanite-rich protolith (i.e. metamorphic protolith prior to anatexis).

Microprobe analyses

Cordierite group minerals have the general formula $(Mg,Fe)_2[Si_5Al_4O_{18}].nH_2O$ (Deer et al., 1992). It is a continuous solid solution between two end members, cordierite s.s. (Mg) and sekaninaite (Fe). In the present study, the analysed crystals are characterised by an intermediate composition between the two end members with a XMg ranging from 0.47 to 0.57 (Table 1). They are unzoned from core to rim.

Biotites are characterised by a relatively high Ti content (Table 2). A distinction can be made between biotites that are present in the rock matrix, which have a relatively constant Ti content (ca. 0.19 a.p.f.u.), and biotites that are present as inclusions in the cordierite crystals, which have a slightly higher Ti content, with a variation range from 0.22 to 0.24 a.p.f.u.

Geothermometry and geobarometry

Due to the monotony of the mineralogy of the cordieritites (garnet have never been observed), and also due to their anatectic nature, it is difficult to use conventional thermobarometry based on cation exchanges between mineral species. We have thus used the Na-in-cordierite calibration (Mirwald, 1986) and also its new developments (Wyhlidal et al., 2007; Wyhlidal et al., 2009). This geothermometer is pressure independent and can be used if Na is available. This is the case in metapelites, which mainly form the Chavanon sequence. It must be noted that the artificial calibration of this thermometer with NaOH may lead to an overestimation of temperature (Kalt et al., 1998).

The use of the abacus of Mirwald (1986) allows an estimation of a temperature range from 750° to 850°. It can be precised by the use of the low-Na thermometer (Wyhlidal et al., 2007; Wyhlidal et al., 2009) since there is only a few amount of plagioclase in the rock. The results are in good agreement with Mirwald's abacus since the variation range is 725-781° (Table 3). The

Table 1. Representative analyses of cordierite crystals.

Pt	core	core	rim	rim
SiO_2	48.46	48.22	47.38	47.99
TiO_2	0.00	0.04	0.03	0.03
Al_2O_3	32.73	32.41	32.12	32.78
FeO	11.00	11.23	12.36	10.17
MnO	0.26	0.25	0.34	0.24
MgO	6.86	6.81	6.25	7.48
CaO	0.05	0.01	0.00	0.00
Na_2O	0.25	0.18	0.17	0.19
K_2O	0.04	0.01	0.00	0.02
Cr_2O_3	0.00	0.00	0.05	0.00
LOI	n.d.	n.d.	n.d.	n.d.
Total	99.65	99.14	98.70	98.89
Cations based on 18 oxygens				
Si	4.991	4.996	4.966	4.963
Ti	0.000	0.003	0.002	0.002
Al	3.974	3.958	3.967	3.996
Fe^{2+}	0.947	0.973	1.083	0.879
Mn	0.022	0.022	0.03	0.021
Mg	1.054	1.052	0.976	1.154
Ca	0.006	0.001	0.000	0.000
Na	0.050	0.036	0.035	0.038
K	0.006	0.001	0.000	0.003
Cr	0.000	0.000	0.004	0.000
XFe	0.468	0.475	0.518	0.428
XMg	0.521	0.514	0.467	0.562

XFe = Fe/(Mg+Fe+Mn) and XMg = Mg/(Mg+Fe+Mn).

Table 2. Representative analyses of biotite crystals, from the matrix and as inclusions in cordierite crystals.

Location	matrix	matrix	matrix	matrix	inclusion	inclusion	inclusion
SiO_2	33.39	34.27	33.91	34.65	34.72	35.07	35.38
TiO_2	3.16	3.19	3.33	2.51	4.11	4.11	3.86
Al_2O_3	19.38	19.55	19.61	19.92	19.81	19.55	19.37
FeO	23.80	22.80	22.70	22.60	19.30	20.00	19.83
MnO	0.05	0.04	0.00	0.06	0.10	0.10	0.13
MgO	5.82	5.94	5.94	6.63	7.66	8.02	8.22
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na_2O	0.18	0.21	0.15	0.18	0.24	0.22	0.21
K_2O	9.42	9.30	9.32	9.26	9.59	9.43	9.28
Cr_2O_3	0.09	0.12	0.16	0.09	0.05	0.00	0.00
LOI	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total	95.30	95.41	95.13	95.90	95.57	96.50	96.26
Cations based on 11 oxygens.							
Si	2.61	2.65	2.63	2.66	2.64	2.65	2.67
Ti	0.19	0.19	0.19	0.15	0.24	0.23	0.22
Al	1.79	1.78	1.80	1.80	1.78	1.74	1.72
Fe^{2+}	1.56	1.48	1.47	1.45	1.23	1.26	1.25
Mn	0.00	0.00	0.00	0.00	0.01	0.01	0.01
Mg	0.68	0.69	0.69	0.76	0.87	0.90	0.92
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.03	0.03	0.02	0.03	0.04	0.03	0.03
K	0.94	0.92	0.92	0.91	0.93	0.91	0.89
Cr	0.01	0.01	0.01	0.01	0.00	0.00	0.00

widespread occurrence of sillimanite in those rocks is also in agreeement with the temperature range ; the relatively high amount of Ti in biotite is also coherent with a high temperature metamorphism (Henry and Guidotti, 2002; Henry et al., 2005).

As stated above, one possible reaction for the formation of those rocks is Biotite + Sillimanite + Quartz + Plagioclase ↔ Cordierite + Melt. It is important to note that this reaction does not involve any K-feldspar. There may be an influence from an initial K-poor composition but metamorphic reactions can also account for this. Indeed, White (2008) proposed a petrogenetic grid based on White et al. (2001; 2007) in which there is the reaction Sillimanite + K-felspar + Biotite + H_2O ↔ Cordierite + Melt. This reaction in the KFMASH (+q) system accounts for the complete consumption of K-feldspar and the production of peritectic cordierite in the 3-5 kbar range for temperatures around 725 °C. The prograde consumption of K-feldspar depends on the H_2O/K_2O ratios between melt and biotite (Carrington and Watt, 1995). Spear et al. (1999) calibrated a petrogenetic grid for the partial melting of metapelites in which the isobaric heating at 5 kbar leaves very little K-feldspar in the final assemblage; this one is expected to be restricted to the leucosomes.

Table 3. Results of the calculations of the low-Na thermometer (Wyhlidal et al., 2007; Wyhlidal et al., 2009).

Location	Na p.f.u.	Low Na
Rim	0.038	749
Rim	0.035	755
Rim	0.033	759
Rim	0,022	781
Rim	0.020	785
Rim	0.036	753
Rim	0.024	777
Rim	0.041	743
Rim	0.036	753
Rim	0.035	755
Rim	0.035	755
Rim	0.040	745
Core	0.041	743
Core	0.050	725
Core	0.030	765
Core	0.050	725
Core	0.036	753
Core	0.032	761

Crystal size distribution (CSD)

Theory

CSD is a useful tool in textural studies, mainly used in igneous petrology. It corresponds to the 3-D distribution of crystals sizes. Developped since the 1960's (Higgins, 2000, and references therein), it became of interest since the works of Marsh (1988). Cashman and Marsh (1988) studied lava crystallisation with this method while Cashman and Ferry (1988) developed its application on metamorphic rocks. Later on, Higgins (1994; 2000; 2006) developed this method.

From simple 2D measurements (such as length or area of crystals), it gives quantitative data on the 3D growth of a mineral (Higgins, 1994; Jerram and Higgins, 2007; Morgan and Jerram, 2006). CSD diagrams shape depends on the rock type and can be associated with several theories of crystal growth (Berger and Roselle, 2001). As an example, the nucleation and the constant crystal growth that occur along crystal faces give linear CSD curves that are well known in volcanic rocks (Cashman and Marsh, 1988). A CSD diagram is drawn from histograms (Higgins, 2000) but is generally represented as a curve. Several parameters are also taken into account, such as the rock texture (massive or foliated), the minerals shape (ellipsoids or rectangular prisms) and the overall proportions of the crystals (length/width/depth ratio).

Application and results

The CSD diagram has been computed using the "CSD corrections" software (Higgins, 2000), which is available for download at the following address: http://wwwdsa.uqac.ca/~mhiggins/csdcorrections.html (accessed on 2011/05/31). The measurement of the cordierite crystals have been performed randomly on a scanned thin section (Figure 4).

The cordierite crystals have been parametred as rectangular prisms with a length/width/depth ratio of 1 : 1 : 4 and the rock as massive since no clear foliation is defined. The obtained diagram (Figure 6g) allows a dualistic interpretation. For the small grain size (< 2mm), the curve is similar to what Higgins (1998) describes in an anorthosite which texture fits with the "communicating neighbour theory" (Dehoff, 1991). Nevertheless, the following part of the curve (i.e. for the 2-5 mm range grainsizes) shows similarities with Denison et al. (1997) results for interface controlled crystal growth.

Those results are quite similar to Berger and Roselle's (2001) ones on cordierite-bearing migmatites from the Bayerische Wald (Variscan Orogeny, Germany). Quantitative CSD measurements on those rocks allowed them to demonstrate that crystal growth in migmatites is similar to crystal growth in magmatic rocks. In the present case, cordierite grew as a peritectic phase during partial melting, as precised above. The high amount of cordierite in the rock, which is inferred as being restitic, may indicate a high amount of melt during one of the steps of the formation of the rock. During this step, the melted matrix was weak enough to allow cordierite to grow while developing its faces, giving the rock a magmatic texture, which is an important point for considering this rock as a migmatite (Vernon and Collins, 1988).

Discussion

Are cordierite-rich rocks restitic or due to local compositional variations?

Dealing with rocks that are enriched in a single mineral type often leads to several interpretations. In metasedimentary rocks, one can think about an extreme compositional chemical variation within the original sediments such as clay-rich horizons (Ugidos et al., 2008). As the upper part of the Chavanon sequence is mainly migmatitic (Faure et al., 1993; Martin, 1980; Thiéry, 2010), it is reasonable to think that such compositional variations have been removed by intense melt production, segregation and accumulation, for there are locally kilometre-scale secondary diatexite massifs in this sequence (Thiéry et al., in press).

The link between cordierite-rich rocks and cordierite-bearing granites have been extensively studied (see for example Diaz-Alvarado et al., 2011; Ugidos and Recio, 1993; Ugidos et al., 2008 and references therein). As presented in Figure 2, the migmatites from the upper part of the Chavanon sequence are intruded by the Guéret massif granites. Those are mainly peraluminous granitoids (see Cartannaz, 2006, for a review). Peraluminous granites are generally interpreted as the result of melting of metasedimentary protoliths (Miller, 1985). Ugidos et al. (2008) describe cordieritite (more than 60 % cordierite) as enclaves (several square meters) in such granites and demonstrate geochemically that they cannot be restitic. On the other hand, Rapela et al. (2002) argue for a strong convection in the magma chamber, leading to segregation between cumulate cordierite and leucogranites. This idea implies movement of a segregated melt fraction and will be discussed below.

Melt segregation in the Chavanon sequence

As presented in the introduction, in migmatitic terranes, there is a need to distinguish between what has melted, what has not melted, what have been formed during incongruent melting (e.g. cordierite) and what has been left by the anatexis. It is now admitted that the melt generated during anatexis will segregate as soon as a melt volume threshold is reached (Vigneresse et al., 1996). The system melt + restite loses its cohesion and becomes permeable, which implies that melt is expected to move. Although the scale of melt displacement is still discussed, one can expect more than a simple outcrop scale melt movement: melt is collected on a metric scale and can migrate towards the upper levels of the crust (Brown, 2004; 2007; Brown, 2008; Brown et al., 1999; Kisters et al., 2009; Sawyer, 1994; 2001).

It must be noted that on the field, the present extension of the inferred melt-bearing structures is not necessarily the maximal extension that has been reached by the system since leucosomes may have been "closed" after the passage of a certain quantity of melt (Berger and Kalt, 1999; Brown et al., 1999; Sawyer, 2001). Thus, it is possible that on a regional scale, all the intermediate stages can coexist.

The described rocks are characterized by a cumulate-like texture dominated by abundant euhedral cordierite crystals. These cumulate-like rocks lack well defined leucosomes, which is subordinated to interstitial melt pools in a cordierite dominated crystal framework. As cordierite is a peritectic phase, which is formed together with melt, the cumulate-like texture can be interpreted as resulting from melt extraction, leaving a cordierite rich residue with minor melt trapped as a leucosome. The K-feldspar, inferred to occur as small amounts limited to the leucosomes (Spear et al., 1999), can thus be absent of the cumulative cordieritite as we infer that the main part of the melt migrate from its source. Spear et al. (1999) also account for the presence of resorbed garnets in such melted metapelites. We did not observe them in the cordieritites s.s. but they have been described in the surrounding migmatites (Chenevoy and Ravier, 1989). Moreover, H_2O is expected to leave the system with the melt so there is no late muscovite in the cordiéritites.

Another proof of anatexis lies on the presence of lobate biotites (Figure 6d and e), either as inclusions in cordierite as in the matrix. Indeed, Sawyer proposes to rely on this criteria to argue for partial melting. Biotite breakdown leads to the release of Fe and Mg, which will diffuse in the melt and lead to the growth of cordierite (Barbey, 2007). Moreover, the Ti content of biotite is quite high (0.22-0.24 a.p.f.u.) and their colour is reddish brown, which implies a high temperature metamorphism and also a biotite dehydration melting process (Faye, 1968; Guidotti, 1984; Henry and Guidotti, 2002; Henry et al., 2005; Sawyer, 2008). Another evidence of high temperature metamorphism lies on the systematic presence of fibrolite, the fibrous variety of sillimanite, in the gneisses of the studied area. It forms systematically before the prismatic sillimanite (Sassi et al., 2004) and is probably stabilised at higher temperatures (Kerrick, 1990; Pattison, 1992). The geothermometric calibration underline here temperatures in the 750-850 °C range ; moreover, this calibration and the field relationships of the cordieritite resembles grealty the cordierite-bearing migmatites from the Bayerische Wald (Berger and Kalt, 1999; Kalt et al., 1999) despite a poorer mineralogy. The fibrolitic sillimanite is found as inclusions in cordierite crystals, revealing a high temperature metamorphism prior to anatexis.

In the cordieritite of the present study, several stages of evolution are frozen. For example, in Figure 6a and b, an "unfinished" cordierite crystal show the early stages of its formation. Subsequent stages of cordierite growth are outlined by sillimanite, which mimics the previous crystal faces and are probably in epitaxial relationship with the cordierite host : this phenomenon have been described as "Frasl inclusions" (Bard, 1986).

The cordierite-bearing migmatites are widespread in the French Massif Central but are poorly characterized in terms of geothermo-barometry. A regional study have been carried out by Chenevoy and Ravier (1989). On the basis of the presence of scarce relictual garnet, they argued for a temperature range of 650-700 °C for 5 kbar for the conditions of anatexis leading to the formation of those migmatites. In the Velay area, which is the largest granite-migmatite massif of the French Massif Central, the P-T conditions of the melting stage in the cordierite stability field have been estimated at 760-850° for 4.4-6 kbar (Dallain et al., 1999; Ledru et al., 2001; Montel et al., 1992).

Conclusion: proposition of a sequence of formation for the cordieritites

Cordierite cumulates or "cordieritites" of the uppermost part of the Chavanon sequence are characterized by their high modal amount (~ 60-70 %) of cordierite crystals. Those ones are euhedral and their CSD distribution argues for their growth in the presence of melt. They contain abundant sillimanite crystals that outline their growth.

The cordieritites formed during an anatexis event and several evolutions stages are recorded, particularly concerning melt movement. The initial lithology was fertile for anatexis and its paragenesis was a sillimanite (fibrolite) rich +

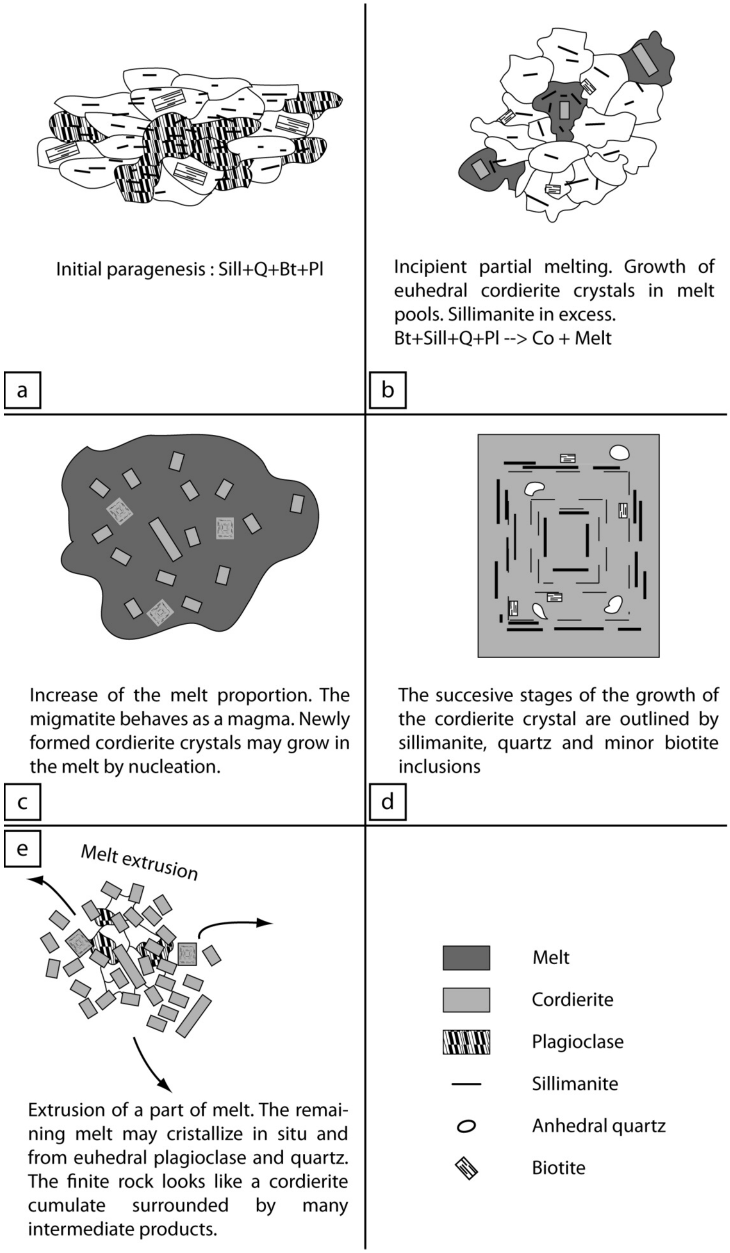

Figure 7. Conceptual sketch of the successive stages of the cordieritite evolution.

quartz + biotite + plagioclase gneiss (Figure 7a). The melting reaction is biotite + sillimanite + quartz + plagioclase ↔ cordierite + melt (Figure 7b). As the melt proportion increased, the migmatite began to behave like a magma (Figure 7c) since the numerous rock types reveal complex melt movement (Figure 3). The cordierite crystals were then free to grow in a melt-rich environment that allowed them to develop their euhedral shape (Figure 7d), coeval with the inclusion of sillimanite needles along the cordierite crystal faces. Locally, newly formed cordierite crystals formed when the melt crystallised. Finally, the cordieritite gained its cumulative texture when a part of melt was expulsed (Figure 7e).

Acknowledgements

The author wishes to thank P. Rolin for constructives comments, N. Rouge for the MEB imaging, J. Richard for the use of the CL and C. Gilles and G. Wille for the microprobe. Discussions with C. Cartannaz were greatly appreciated. Thanks to A. Castro Dorado and H.J. Massonne whose constructive reviews significantly enhanced the manuscript. This paper is a part of the author's thesis which benefited of a grant from the BRGM (French Geological Survey) under the direction of P. Rossi.

References

Barbey P. (2007) - Diffusion-controlled biotite breakdown reaction textures at the solid/liquid transition in the continental crust. *Contributions to Mineralogy and Petrology*, 154, 707-716.

Bard J.P. (1986) - Microtextures of igneous and metamorphic rocks. Springer, 280 p.

Be Mézème E. (2005) - Contribution de la géochronologie U-Th-Pb sur monazite à la compréhension de la fusion crustale dans la chaîne hercynienne française et implication géodynamique. 249 p., Orléans.

Berger A. and Kalt A. (1999) - Structures and Melt Fractions as Indicators of Rheology in Cordierite-Bearing Migmatites of the Bayerische Wald (Variscan Belt, Germany). *Journal of Petrology*, 40 (11), 1699-1719.

Berger A. and Roselle G. (2001) - Crystallization processes in migmatites. *American mineralogist*, 86, 215-224.

Brown M. (2002) - Retrograde processes in migmatites and granulites revisited. *Journal of Metamorphic Geology*, 20, 25-40.

Brown M. (2004) - The mechanism of melt extraction from lower continental crust of orogens. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, 95 (1-2), 35-48.

Brown M. (2007) - Crustal melting and melt extraction, ascent and emplacement in orogens: mechanisms and consequences. *Journal of the Geological Society*, 164 (4), 709-730.

Brown M. (2008) - Granites, Migmatites and residual granulites: relationships and processes. Working with migmatites - Mineralogical Association of Canada Short Course Series 38, 97-144.

Brown M.A., Brown M., Carlson W.D. and Denison C. (1999) - Topology of syntectonic melt-flow networks in the deep crust: inferences from three-dimensional images of leucosome geometry in migmatites. *American mineralogist*, 84, 1793-1818.

Burg J.P. and Matte P. (1978) - A cross section through the French Massif central and the scope of its Variscan geodynamic evolution. *Zeitschrift der Deutschen Geologischen Gesellschaft*, 129, 429-460.

Burg J.P., Matte P., Leyreloup A. and Marchand J. (1984) - Inverted metamorphic zonation and large-scale thrusting in the Variscan Belt: an example in the French Massif Central. *Geological society, London, Special Publications*, 14, 47-61.

Burg J.P., Van Den Driessche J. and Brun J.P. (1994) - Syn- to post-thickening extension in the Variscan Belt of Western Europe: Modes and structural consequences. *Géologie de la France*, 3, 33-51.

Carrington D.P. and Watt G.R. (1995) - A geochemical and experimental study of the role of K-feldspar during water-undersaturated melting of metapelites. *Chemical Geology*, 122, 59-76.

Cartannaz C. (2006) - Magmatismes et déformations polyphasés: exemples des massifs de Guéret et de Millevaches (Massif Central Français). Origine des magmas et contexte de mise en place. Thèse, Université de Franche-Comté, Besançon. 317 p.

Cashman K.V. and Ferry J. (1988) - Crystal size distribution (CSD) in rocks ans the kinetics and dynamics of crystallization. III. Metamorphic crystallization. *Contributions to Mineralogy and Petrology*, 99, 401-405.

Cashman K.V. and Marsh B.D. (1988) - Crystal Size Distribution (CSD) in rocks ans kinetics and dynamics of crystallization. II. Makaopuhi lava lake. *Contributions to Mineralogy and Petrology*, 99, 292-305.

Chenevoy M. and Ravier J. (1989) - L'histoire des "gneiss d'Aubusson", migmatites à cordiérite du Massif central français, d'après le chimisme de leurs grenats. *Bulletin de la société géologique de France*, 8 (V, n°2), 295-307.

Clarke D.B. (1995) - Cordierite in felsic igneous rocks: a synthesis. *Mineralogical Magazine*, 59, 311-325.

Dallain C. and Schulmann K.P.L. (1999) - Textural evolution in the transition from subsolidus annealing to melting process, Velay Dome, French Massif Central. *Journal of Metamorphic Geology*, 17 (1), 61-74.

Deer W.A., Howie R.A. and Zussman J. (1992) - An introduction to the rock-forming minerals, 2nd edition. Pearson, 696 p.

Dehoff R.T. (1991) - A geometrically general theory of diffusion controlled coarsening. *Acta Metallurgica et Materialia*, 39 (10), 2349-2360.

Denison C., Carlson D. and Ketcham R.A. (1997) - Three dimensional quantitative textural analysis of metamorphic rocks using high resolution computed X-ray tomography: Part II. Application to natural samples. *Journal of Metamorphic Geology*, 15, 45-57.

Diaz-Alvarado J., Castro A., Fernandez A. and Moreno-Ventas I. (2011) - Assessing Bulk Assimilation in Cordierite-bearing Granitoids from the Central System Batholith, Spain; Experimental, Geochemical and Geochronological Constraints. *Journal of Petrology*, 52 (2), 223-256.

Droop G.T.R., Clemens J.D. and Dalrymple D.J. (2003) - Processes and coditions during contact anatexis, melt escape and restite formation: the Huntly gabbro complex, NE Scotland. *Journal of Petrology*, 44 (6), 995-1029.

Echtler H. and Malavieille J. (1990) - Extensional tectonics, basement uplift and Stephano-Permian collapse basin in a Late Variscan metamorphic core complex (Montagne Noire, Southern Massif Central). *Tectonophysics*, 177, 125-138.

Faure M. (1995) - Late orogenic carboniferous extensions in the Variscan French Massif central. *Tectonics*, 14, 132-153.

Faure M., Be Mézème E., Cocherie A., Rossi P., Chemenda A. and Boutelier D. (2008) - Devonian geodynamic evolution of the Variscan Belt, insights from the French Massif Central and Massif Armoricain. *Tectonics*, 27 (2), 1-19.

Faure M., Be Mézème E., Duguet M., Cartier C. and Talbot J.-Y. (2005) - Paleozoic tectonic evolution of medio-europa from the example of the french massif central and massif armoricain. *Journal of the Virtual Explorer*, 19 (5), 1-25.

Faure M. and Becq-Giraudon J.F. (1993) - Sur la succession des épisodes extensifs au cours du désépaississent carbonifère du Massif Central français. *Comptes rendus de l'Académie des Sciences*, II (315), 967-973.

Faure M., Grolier J. and Pons J. (1993) - Extensional ductile tectonics of the Sioule metamorphic series (Variscan French Massif Central). *Geologische Rundschau*, 82, 461-474.

Faure M., Lardeaux J.-M. and Ledru P. (2009) - A review of the pre-Permian geology of the Variscan French Massif Central. *Comptes Rendus Geosciences*, 341 (2-3), 202-213.

Faure M., Leloix C. and Roig J.-Y. (1997) - L'évolution polycyclique de la chaine hercynienne. *Bulletin de la Sociéte Géologique de France*, 168 (6), 695-705.

Faye G.H. (1968) - The optical absorption spectra of certain transition metal ions in muscovite, lepidolite and fuchsite. *Canadian Journal of Earth Sciences*, 5, 31-38.

Gébelin A. (2004) - Déformation et mise en place des granitoïdes (360-300 Ma) dans un segment de la chaîne varisque (Plateau de Millevaches, Massif Central). 324 p., Montpellier.

Giuliani G., Fallick A., Rakotondrazafy M., Ohnenstetter D., Andriamamonjy A., Ralantoarison T., Rakotosamizanany S., Razanatseheno M., Offant Y., Garnier V., Dunaigre C., Schwarz D., Mercier A., Ratrimo V. and Ralison B. (2007) - Oxygen isotope systematics of gem corundum deposits in Madagascar: relevance for their geological origin. *Mineralium Deposita*, 42 (3), 251-270.

Godin L., Grujic D., Law R.D. and Searle M.P. (2006) - Channel flow, ductile extrusion and exhumation in continental collision zones: an introduction. *Geological Society, London, Special Publications*, 268 (1), 1-23.

Grolier J. and Lacour A. (1982) - La naissance du concept de "Gneiss d'Aubusson". *Revue des Sciences Naturelles d'Auvergne*, 48, 31-38.

Grolier J. and Letourneur J. (1968) - Evolution tectonique du grand Sillon Houiller du Massif Central Français. XXIII International Geological

Congress, 1, 107-116.

Guernina S. and Sawyer E.W. (2003) - Large-scale melt-depletion in granulite terranes: an example from the Archean Ashuanipi Subprovince of Quebec. *Journal of Metamorphic Geology*, 21 (2), 181-201.

Guidotti C.V. (1984) - Micas in metamorphic rocks. In S.W. Bailey Ed. Micas. Reviews in mineralogy, Mineralogical society of America 13, 357-467.

Henry D.J. and Guidotti C.V. (2002) - Titanium in biotite from metapelitic rocks: Temperature effects, crystal-chemical controls, and petrologic applications. *American Mineralogist*, 87 (4), 375-382.

Henry D.J., Guidotti C.V. and Thomson J.A. (2005) - The Ti-saturation surface for low-to-medium pressure metapelitic biotites: implications for geothermometry and Ti-substitution mechanisms. *American mineralogist*, 90, 316-328.

Higgins M.D. (1994) - Numerical modeling of crystal shapes in thin sections; estimation of crystal habit and true size. *American Mineralogist*, 79 (1-2), 113-119.

Higgins M.D. (1998) - Origin of anorthosite by textural coarsening: quantitative measurements of a natural sequence of textural development. *Journal of Petrology*, 39, 1307-1323.

Higgins M.D. (2000) - Measurement of crystal size distributions. *American Mineralogist*, 85 (9), 1105-1116.

Higgins M.D. (2006) - Quantitative Textural Measurements in Igneous and Metamorphic Petrology. Cambridge University Press, 276 p.

Holness M.B. (2008) - Decoding migmatite microstructures. Workin with migmatites - Mineralogical Association of Canada Short Course Series 38, p. 57-76.

Holness M.B. and Sawyer E.W. (2008) - On the Pseudomorphing of Melt-filled Pores During the Crystallization of Migmatites. *Journal of Petrology*, 49 (7), 1343-1363.

Jerram D.A. and Higgins M.D. (2007) - 3D Analysis of Rock Textures: Quantifying Igneous Microstructures. *Elements*, 3 (4), 239-245.

Joly A. (2007) - Relations plutons et discontinuités lithosphériques. Approche pluridisciplinaire de la mise en place de plutons granitiques le long du Sillon Houiller (Massif Central Français). Apports des études de terrain et des données gravimétriques, magnétiques et ASM pour des modélisations 3D. 307 p., Orléans.

Kalt A., Altherr R. and Ludwig T. (1998) - Contact Metamorphism in Pelitic Rocks on the Island of Kos (Greece, Eastern Aegean Sea): a Test for the Na-in-Cordierite Thermometer. *Journal of Petrology*, 39 (4), 663-688.

Kalt A., Berger A. and Blümel P. (1999) - Metamorphic evolution of cordierite-bearing migmatites from the Bayerische Wald (Variscan belt, Germany). *Journal of Petrology*, 40 (4), 601-627.

Kerrick D.M.E. (1990) - The Al_2SiO_5 polymorphs. Mineralogical society of America. Reviews in mineralogy n°22. 406 p.

Kisters A.F.M., Ward R.A., Anthonissen C.J. and Vietze M.E. (2009) - Melt segregation and far-field melt transfer in the mid-crust. *Journal of the Geological Society*, 166 (5), 905-918.

Kretz R. (1983) - Symbols for rock-forming minerals. *American mineralogist*, 68, 277-279.

Lardeaux J.M., Ledru P., Daniel I. and Duchene S. (2001) - The Variscan French Massif Central-a new addition to the ultra-high pressure metamorphic ‘club’: exhumation processes and geodynamic consequences. *Tectonophysics*, 332 (1-2), 143-155.

Le Breton N., Duthou J.L., Grolier J., Lacour A., Meyer G. and Treuil M. (1986) - Les diatexites à cordiérite d’Aubusson (Creuse): pétrographie, composition, âge. *Comptes rendus de l’académie des sciences*, 303 (II), 1557-1562.

Ledru P., Courrioux G., Dallain C., Lardeaux J.M., Montel J.M., Vanderhaeghe O. and Vitel G. (2001) - The Velay dome (French Massif Central): melt generation and granite emplacement during orogenic evolution. *Tectonophysics*, 342, 207-237.

Ledru P., Lardeaux J.M., Santallier D., Autran A., Quenardel J.M., Floc’h J.P., Lerouge G., Maillet N., Marchand J. and Ploquin A. (1989) - Où sont les nappes dans le Massif central français? *Bulletin de la société géologique de France*, 3, 605-618.

Malavieille J., Guihot P., Costa S., Lardeaux J.M. and Gardien V. (1990) - Collapse of the thickened Variscan crust in the French Massif Central: Mont Pilat extensional shear zone and St. Etienne Late Carboniferous basin. *Tectonophysics*, 177 (1-3), 139-149.

Marsh B.D. (1988) - Crystal size distribution (CSD) in rocks and the kinetics and dynamics of crystallization. I. Theory. *Contributions to*

Mineralogy and Petrology, 99, 277-291.

Martin D. (1980) - Etude structurale, pétrologique et gîtologique de la série du Chavanon (Massif Central Français). Ph.D. Dissertation. 140 p., Clermont-Ferrand, France.

Matte P. (1986) - Tectonics and plate tectonics model for the variscan belt of europe. *Tectonophysics*, 126, 329-374.

Matte P. (1991) - Accretionary history and crustal evolution of the Variscan Belt in western Europe. *Tectonophysics*, 196, 309-339.

Matte P. and Burg J.P. (1981) - Sutures, thrusts and nappes in the Variscan arc of the western Europe. Plate tectonics interpretation. *Geological society, London, Special Publications*, 8, 353-358.

Mercier L., Johan V., Lardeaux J.-M., and Ledru P. (1989) - Découverte d'éclogites dans l'Artense (Massif Central Français). Implications pour la définition des nappes à l'est du Sillon Houiller. *Comptes rendus de l'académie des sciences*, 308, 315-320.

Miller C.F. (1985) - Are strongly perlauminous magmas derived from pelitic sedimentary sources? *Journal of geology*, 93, 673-689.

Mirwald P. (1986) - Ist cordierit ein geothermometer? *Fortschritte der Mineralogie*, 64, 119.

Montel J.M., Marignac C., Barbey P. and Pichavant M. (1992) - Thermobarometry and granite genesis: the Hercynian low-P, high-T Velay anatectic dome (French Massif Central). *Journal of Metamorphic Geology*, 10 (1), 1-15.

Morgan D.J. and Jerram D.A. (2006) - On estimating crystal shape for crystal size distribution analysis. *Journal of Volcanology and Geothermal Research*, 154 (1-2), 1-7.

Pattison D.R.M. (1992) - Stability of Andalusite and Sillimanite and the Al2SiO5 Triple Point: Constraints from the Ballachulish Aureole, Scotland. *The Journal of Geology*, 100 (4), 423-446.

Rakotondrazafy A.F.M., Giuliani G., Ohnenstetter D., Fallick A.E., Rakotosamizanany S., Andriamamonjy A., Ralantoarison T., Razanatseheno M., Offant Y., Garnier V., Maluski H., Dunaigre C., Schwarz D. and Ratrimo V. (2008) - Gem corundum deposits of Madagascar: A review. *Ore Geology Reviews*, 34 (1-2), 134.

Ramseyer K. and Mullis J. (2000) - Geological application of cathodoluminescence of silicates. In M. Pagel, V. Barbin, P. Blanc, and D. Ohnenstetter Eds. Cathodoluminescence in Geosciences, p. 177-192. Springer Verlag.

Rapela C.W., Baldo E.G., Pankhurst R.J. and Saavedra J. (2002) - Cordieritite and leucogranite formation during emplacement of highly peraluminous magma: The El Pilon granite complex (Sierras Pampeanas, Argentina). *Journal Of Petrology*, 43 (6), 1003-1028.

Rolin P. (1987) - Tectonogenèse comparée de deux segments de la chaîne hercynienne: le Massif Central français septentrional et la Meseta marocaine septentrionale. Thèse, Université de Paris-Sud. 470 p.

Rolin P., Cartannaz C., Salen F., Delwaulle B. and Thalouarn N. (2006) - Carte géol. France (1/50 000), feuille Saint-Sulpice-les-Champs (666). Orléans: BRGM. Notice explicative par P. Rolin C. Cartannaz, P. Henry, M. Rossy, A. Cocherie, F. Salen, B. Delwaulle, B. Mauroux. (2006). 178 p.

Rolin P., Thiéry V., Dumont N., Choulet F. and Mavel J. (2008) - Carte géol. France (1/50.000), feuille de Felletin (n°691). Orléans: BRGM 157 p. Notice explicative par Rolin P., Thiéry V., Cartannaz C., Cocherie A., Rossy M., Henry P., Constant J.

Sassi R., Mazzoli C., Spiess R. and Cester T. (2004) - Towards a Better Understanding of the Fibrolite Problem: the Effect of Reaction Overstepping and Surface Energy Anisotropy. *J. Petrology*, 45 (7), 1467-1479.

Sawyer E.W. (1994) - Melt segregation in the continental crust. *Geology*, 22, 1019-1022.

Sawyer E.W. (1999) - Criteria for the Recognition of Partial Melting. *Physics and Chemistry of the Earth*, 24 (3), 269-279.

Sawyer E.W. (2001) - Melt segregation in the continental crust: distribution and movement of melt in anatectic rocks. *Journal of Metamorphic Geology*, 19 (3), 291-309.

Sawyer E.W. (2008) - Atlas of migmatites. The Canadian Mineralogist special publication n°9. 371 p.

Solar G.S. (2008) - The interplay between tectonics/structure and migmatite morphology in the field. Working with migmatites - Mineralogical Association of Canada Short Course Series 38, p. 145-158.

Spear F.S., Kohn M.J. and Cheney J.T. (1999) - P-T paths from anatectic pelites. *Contributions to*

Mineralogy and Petrology, 134, 17-32.

Thiéry V. (2010) - Métamorphismes et déformations des séries cristallophylliennes du Chavanon, de la Sioule et d'Ussel (Massif Central français). Discussion du modèle de nappes du Massif Central. Ph.D. Dissertation, Université de Franche-Comté. 273 p., Besançon, France.

Thiéry V., Rolin P., Barrau F., Belle P., Boucly J., Catimel F., Choulet F., Eglinger A., Juppé E., Lafay R., Moreau E., Ravier M. and Reilé M. (in press) - Carte géologique de la France, feuille Ussel. Notice explicative par Thiéry V. et Rolin P.

Thiéry V., Rolin P., Marquer D.A., C., Fanning C.M. and Rossi P. (2009) - Visean sinistral wrench faulting along the Sillon Houiller in the French Massif Central: Late Variscan tectonic implications. *Bulletin de la Société Géologique de France*, 180 (6), 513-528.

Ugidos J.M. and Recio C. (1993) - Origin of cordierite-bearing granites by assimilation in the Central Iberian Massif (CIM), Spain. *Chemical Geology*, 103, 27-43.

Ugidos J.M., Stephens W.E., Carnicero A. and Ellam R.M. (2008) - A reactive assimilation model for regional-scale cordierite-bearing granitoids: geochemical evidence from the Late Variscan granites of the Central Iberian Zone, Spain. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, 99 (3-4), 225-250.

Vanderhaeghe O. (2009) - Migmatites, granites and orogeny: flow modes of partially-molten rocks and magmas associated with melt/solid segregation in orogenic belts. *Tectonophysics*, 447 (3-4), 119-134.

Vanderhaeghe O. and Teyssier C. (2001) - Partial melting and flow of orogens. *Tectonophysics*, 342 (3-4), 451-472.

Vernon R.H. and Collins W.J. (1988) - Igneous microstructures in migmatites. *Geology* (16), 1126-1129.

Vigneresse J.L., Barbey P. and Cuney M. (1996) - Rheological transitions during partial melting and crystallization with application to felsic magma segregation and transfer. *Journal of Petrology*, 37 (6), 1579-1600.

White R.W. (2008) - Insights gained from the petrological modeling of migmatites: particular reference to mineral assemblages and common replacement textures. Working with migmatites - Mineralogical Association of Canada Short Course Series 38, 77-96.

White R.W., Powell R. and Holland T. (2001) - Calculation of partial melting equilibria in the system Na_2O-CaO-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O (NCKFMASH). *Journal of Metamorphic Geology*, 19 (2), 139-153.

White R.W., Powell R. and Holland T. (2007) - Progress relating to calculation of partial melting equilibria for metapelites. *Journal of Metamorphic Geology*, 25, 511-527.

Wyhlidal S., Thöny W.F. and Tropper P. (2007) - New experimental constraints on the Na-in-cordierite thermometer and its application to high-grade rocks. Goldsmith conference abstract.

Wyhlidal S., Tropper P., Thöny W.F. and Kaindl R. (2009) - Minor element- and carbonaceous material thermometry of high-grade metapelites from the Sauwald Zone, Southern Bohemian Massif (Upper Austria). *Mineralogy and Petrology*, 97, 61-74.

Submitted, December 2010 - Accepted, June 2011