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LAYERING AND SCHLIEREN IN GRANITOIDS: A RECORD OF INTERACTIONS BETWEEN MAGMA EMPLACEMENT, CRYSTALLIZATION AND DEFORMATION IN GROWING PLUTONS

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(11 figures)

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ABSTRACT. A review of the literature shows that layering in granitoids is the expression of three processes occurring concurrently during the growth of plutons (injection, hydrodynamic processes coupled with fractional crystallization, and deformation). Layering may result from aggregation (± mingling/hybridization) of magma pulses of contrasting compositions or with variable crystal contents, leading to stratified plutons characterized by macrorhythmic units, or exceptionally to cyclic units in the case of low-viscosity magmas. At smaller scale, layering formation is dependent on the injection dynamics and the rheological state of magmas. Rhythmic layering and depositional features related to gravity- or flow-driven crystal-melt segregation do not necessarily imply pluton-scale convective overturn. They occur preferentially close to rheological boundaries (intramagmatic or country-rock walls), close to eruption vents, in relation with local magma plumes, or in association with mafic injections in mafic-silicic layered intrusions. Rhythmically layered series in the periphery of some plutons may result from sidewall crystallization in relation with pulsed injections, whereas aplite-pegmatite layering results from segregation of undercooled residual melts. However, in situ fractional crystallization of single magma batch is unlikely to produce, in most cases, the large rock units constituting plutons. Ductile deformation and more widely the regional tectonic context appear to exert major controls on the formation of pluton-scale compositional layering related to emplacement of heterogeneous magmas. Deformation-assisted melt segregation also common in syntectonic granites may lead to sheet-like melt segregations or structures analogous to migmatitic layering.

KEYWORDS: Pluton construction; igneous layering; schlieren; magma aggregation; mingling; fractional crystallization; crystal-melt segregation

RESUME. Litage et schlieren dans les granitoïdes: l'enregistrement des interactions entre mise en place du magma, cristallisation et deformation dans les plutons en croissance. Une revue de la littérature dédiée aux granitoïdes montre que le litage est l'expression de trois processus interagissant lors de la croissance des plutons (injection, processus hydrodynamiques couplés à la cristallisation fractionnée et déformation). Le litage peut résulter de l'agrégation de venues magmatiques de composition ou teneurs en cristaux variables, formant des plutons stratiformes constitués d'unités macro-rythmiques, ou exceptionnellement d'unités cycliques dans le cas de magmas à faible viscosité. A plus petite échelle, le litage est contrôlé par la dynamique d'injection et la rhéologie des magmas. Le litage rythmique et les figures de dépôt liés à la ségrégation liquide-cristaux par gravité ou par écoulement n'impliquent pas nécessairement la convection à l'échelle du pluton. Il apparaît préférentiellement à proximité de limites rhéologiques (contacts intra-magmatiques ou avec l'encaissant), à proximité de zones d'alimentation, en relation avec des diapirs locaux, ou en association avec des venues mafiques dans les intrusions litées acides-basiques. Le litage rythmique en périphérie de certains plutons peut résulter de la cristallisation fractionnée aux épontes en relation avec des injections pulsées, tandis que le litage aplo-pegmatitique résulte de la ségrégation des liquides résiduels surfondus. Néanmoins, la cristallisation fractionnée in situ à partir d'un magma parent unique ne semble pas être responsable, dans la majorité des cas, des grandes unités lithologiques constituant les plutons. La mise en place de magmas hétérogènes en régime de déformation ductile, et, plus généralement, le contexte tectonique régional exercent un contrôle majeur sur la formation du litage à grande échelle. La ségrégation des liquides par déformation est commune dans les plutons syntectoniques et peut conduire à des ségrégations stratiformes ou à des structures analogues au litage migmatitique.

MOTS-CLES: Pluton, litage magmatique, schlieren, mélange magmatique, cristallisation fractionnée, ségrégation liquide-cristaux

1. Introduction

« *There is scarcely an igneous mass in which the minerals are not, at least locally, aligned in sub-parallel planes*." By this statement Balk (1937, p.14) points to the widespread nature of fabric in magmatic rocks, which has been expressed in a more direct way by J.L. Bouchez (1997): « *Granites are never isotropic* ». The structural analysis of granites, based on the common view of the high viscosity of granitic magmas and enriched by fluid dynamics (e.g. Balk, 1937; Cloos, 1936, 1946; Pitcher & Berger, 1972; Brun et al., 1990; Brun & Pons, 1981; Fernandez, 1987; Blumenfeld & Bouchez, 1988; Hutton, 1988; Ramsay, 1989; Bouchez et al., 1997; Paterson et al., 1998; Arbaret et al., 2001; among a wealth of references) has led many granitologists to consider viscous flow and aggregation of crystal-laden magmas as the major processes involved in the construction of granitic plutons. Additional geophysical, geochemical, geochronological and numerical approaches emphasized the role of dyking and pulsed injection involving multiple batches, possibly derived independently from the source and emplaced over various time spans (Deniel et al., 1987; Duke et al., 1988; Scaillet et al., 1990; Clemens & Mawer, 1992; Gasquet et al., 1992; Cocherie et al., 1994; Petford, 1996; Wareham et al., 1997; Pressley & Brown, 1999; Vanderhaeghe, 1999; Brown & McClelland, 2000; Petford et al., 2000; Roberts et al., 2000; Vigneresse & Clemens, 2000; Barbey et al., 2001; Coleman et al., 2004; Glazner et al., 2004; Habert & de Saint-Blanquat, 2004; Annen et al., 2006). All these data led to dim the importance of igneous processes at the site of emplacement (i.e. in the growing pluton), and to question the existence of large magma chambers (Glazner et al., 2004) and the likelihood of convection, as well.

Even though most granitologists now agree to consider that the big tank model according to which plutonic bodies were once big magma chambers is unlikely, several studies (e.g. Barrière, 1981, Michael, 1984; Monier et al., 1987; Parsons, 1987; Pons et al., 2006) show that the viscous flow model, alone, cannot account for all the characteristics of granitic plutons. Moreover, experimental investigations have shown that viscosity values of granitic magmas are lower than formerly considered. For instance, Scaillet et al. (1996, 1997, 1998, 2000) show that for H_2O and H_2O-CO_2 bearing silicic magma less than 15% crystallization occurs during the first half of the crystallization temperature interval, and that the viscosity values of magma containing 4.5 to 7 wt.% water remain lower than 10^6 Pa.s over 90% of the crystallization temperature interval (see also Clemens & Petford, 1999). Besides, studies of plutons show numerous structures suggesting that deposition of suspended crystals by density currents or local thermal convection are likely to occur during the formation of plutons (Harry & Emeleus, 1960; Emeleus, 1963; Barrière, 1981; Tobisch et al., 1997; Hodson, 1998; Wiebe and Collins, 1998; Weinberg et al., 2001; Wiebe et al., 2002; Zak & Paterson, 2005; Pons et al., 2006; Solgadi & Sawyer, in press). Therefore, even though magma chamber processes may be, in some cases, of limited importance during pluton growth, they cannot be systematically discarded. On the whole, it appears that construction of granitic plutons is a more complex process than the simple addition of crystal-laden magma batches by viscous flow, or than the sole deposition of crystals within a single convecting magma chamber.

Amongst the various structures recorded in granites, layering is probably one of the most interesting to understand how the various processes involved in the formation of plutons interact. Since the works of Wager & Deer (1939) and Wager & Brown (1968) considering that layering is a "*high-temperature sedimentation features of igneous rocks*" (p.544), numerous studies on ultramafic, mafic and alkaline igneous complexes (e.g. Parsons, 1987; Cawthorn, 1996) have shown the wide variety of layer-forming mechanisms, which were summarized and discussed more particularly by Irvine (1982, 1987b), Naslund & McBirney (1996) and Irvine et al. (1998). These processes may be gathered into four main types:

(i) gravity-driven processes leading to crystal-melt separation, such as crystal settling (floating), or compaction of crystal mush with expelled melt contributing to layering;

(ii) processes of flowage differentiation such as flow segregation of suspended crystals in regions of minimum shear stress in dykes and sills (Bagnold effect), or hydrodynamic sorting and deposition related to density currents (angular unconformities, layer truncation, cross-bedding, slump and scour structures, size-grading), or melt segregation related to non-coaxial deformation of crystal-rich suspensions;

(iii) processes related to variation of intensive parameters such as crystallization in thermal boundary layers, or variation of nucleation and growth rates possibly in association with double diffusive convection, or immiscibility;

(iv) processes related to injection such as magma mixing leading for example to chamber-wide precipitation of oxide minerals, or multiple sill-like injections in nearly solidified rocks, or repeated input of magma into chambers leading to rhythmic units, or foliation parallel emplacement of magmas in the mid-crust.

On the whole, it appears that layered structures record mainly material transfer at various scales, towards or within growing magmatic bodies.

The aim of this review is to show that layering in granitoids is essentially the expression of four processes likely to occur concurrently in growing plutons: (i) injection, flow, mingling and hybridization of magma batches of different compositions or containing various crystal proportions; (ii) hydrodynamic sorting and gravity-driven crystal/melt separation; (iii) fractional crystallization; and (iv) deformation-assisted melt emplacement or segregation. In the next sections the term "layering" is used in a wider sense than the strict definition of Irvine (1982) to designate combinations at any scale of layers differing by composition or texture. The term "schlieren" is used to designate discontinuous thin, dark layers "*that unobtrusively appear and fade out*" (Irvine, 1987a).

2. Aggregation, mingling and hybridization of magma pulses

Numerous examples of stratified magmatic bodies involving gabbroic to granitic rocks are reported in the literature. These bodies may be dominantly mafic layered intrusions disrupted by injection of silicic magma as the remarkable Newark Island Layered Intrusion (Wiebe, 1988), or correspond to granitic plutons episodically replenished by mafic magmas accumulated mainly at the base of the chamber (Gasquet, 1992; Wiebe, 1993, 1996; Wiebe & Collins, 1998; Miller & Miller, 2002; Harper et al., 2004; Kamiyama et al., 2007), or consist simply of the superposition of litho-structural units involving layered granites as the dominant rock type, associated with granitic sills and variable proportions of country-rock xenoliths (e.g. Everitt et al., 1998; Soussi Tanani et al., 2001). Considering the general agreement on the role of recurrent magma recharge in the formation of granitic plutons, and by analogy with ultramafic-mafic layered intrusions consisting of cyclic units, two questions may first be raised: (i) is there any evidence of cyclic units in granitic plutons similar to those encountered in ultramafic-mafic layered complexes; and (ii) what is the role of magma interactions in the formation of layering in granitoids.

2.1. Injection and differentiation: pluton-scale layering and cyclic units in granites

Granitic plutons appear to be commonly formed of nested (e.g. Gasquet, 1992; Johnson et al., 1999) or stratified (e.g. Wiebe & Collins, 1998) lithological units ranging in composition from gabbro to granite. The stratified and recurrent nature of injections is well illustrated by the mafic-silicic layered intrusions characterized by the presence of sheet-like mafic units, which have been considered to be deposited on the floor of an aggrading magma chamber due to density contrast (e.g. Wiebe, 1993; Coleman et al., 1995; Snyder & Tait, 1995; Wiebe, 1996; Wiebe & Collins, 1998; Wiebe et al., 2002; Harper et al., 2004). The upward succession of mafic layers (± cumulative gabbro or diorite), hybrid rocks and evolved granite may form hundreds of meters thick macrorhythmic units showing variations of major and trace element concentrations, which have been interpreted in terms of multiple replenishments that mixed and underwent in situ fractional crystallization (e.g. Fernandez & Gasquet, 1994; Wiebe et al., 1997; 2002).

The existence of cyclic units in granites is suggested by the internal structure of bysmaliths, which show intraplutonic contacts separating sheet-like injections of similar compositions but displaying variable size and proportions of phenocrysts (Habert & de Saint-Blanquat, 2004). The possibility for cyclic units to occur in granite plutons can be shown from two examples: the Variscan Charroux-Civray and Echassières plutonic complexes located in the north-western part of the French Massif Central. An 800 m long borehole drilled in the Charroux-Civray plutonic complex (Soussi Tanani et al., 2001), shows seven magmatic units about 100 m thick. Each unit consists of medium-grained tonalites characterized by regular variations of major and trace element compositions, specific submagmatic fabrics and distribution of mafic enclaves. Variations of the [Fe+Mg+Ti] parameter (Fig. 1a) illustrate the gradual decrease in ferromagnesian minerals from the base to the top suggesting in situ

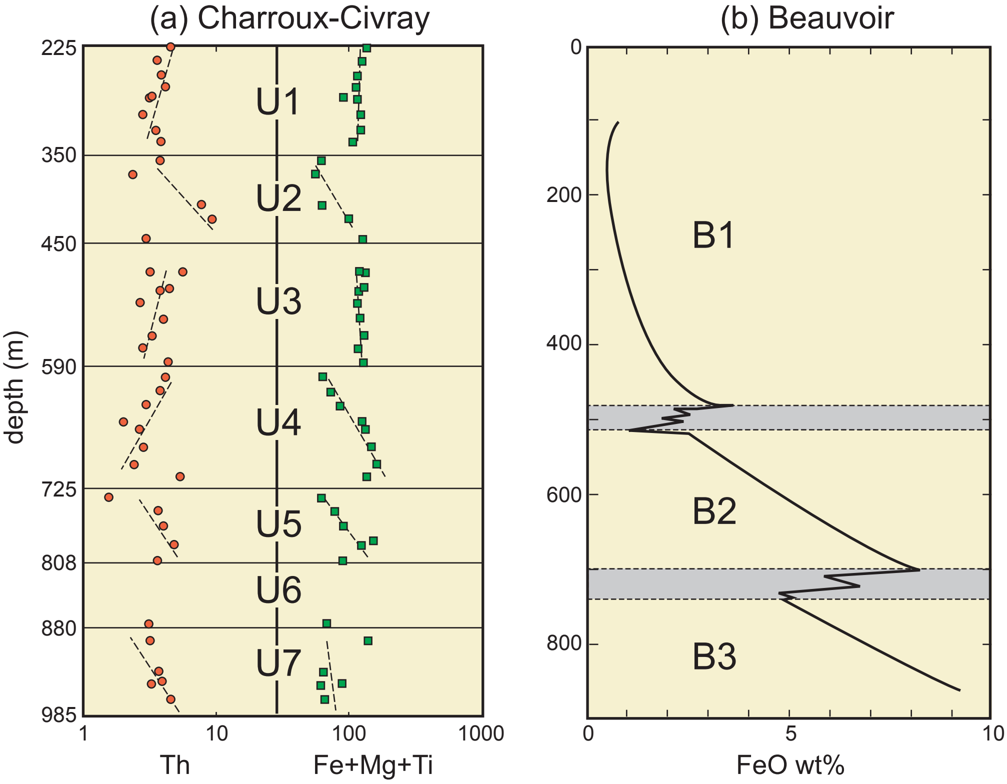

Figure 1. Major and trace element variation diagrams for the Charroux-Civray and Beauvoir plutons showing the possibility for magmatic units to evolve independently from each others. (**a**) Concentrations of Th (ppm) and Fe+Mg+Ti (millications) in the seven megacyclic units of the Charroux-Civray plutonic complex (Vienne, France); simplified from Soussi Tanani et al. (2001). (b) Variation of iron content in lepidolites (atom per formula unit) from the Beauvoir granite intrusion (shaded area: assumed zone of mixing); redrawn from Monier et al. (1987).

differentiation of each unit. The concentrations in Th also show systematic variations (Fig. 1a). The Echassières plutonic complex (Cuney et al., 1986) is even more remarkable. It consists of three main granite bodies (La Bosse, Colettes and Beauvoir). One of them, the Beauvoir granite, is a sheet-like intrusion of evolved topaz-lepidolite granites. A 900 m deep borehole shows the existence of three units (B1 to B3) characterized by distinct whole-rock and mineral compositions. Petrological, geochemical and experimental studies show that the three units represent three distinct batches enriched in F and Li by fractional crystallization (Pichavant et al., 1987). Systematic analysis of the composition of lepidolites (Monier et al., 1987) shows an upward gradual decrease in Fe (Fig. 1b) and correlative increase in Li contents in each unit. The transition zones between B1 and B2 and between B2 and B3 are characterized by more complex variations, with backward and onward evolutions of iron contents in micas (zones of mixing). Overall, the compositional trends of lepidolite show that (i) the Beauvoir granite body was formed from the emplacement of three distinct magma batches, more and more differentiated; (ii) each batches evolved separately by in situ fractional crystallization; and (iii) there was some mingling at the interfaces between units. It should be emphasized that the existence of clear differentiation trends within the three units of the Beauvoir intrusion is probably due to the fact that the magmas were rich in F and Li (e.g. 2.4 and 1.3 wt. % for F and LiO_2, respectively, in the B1 unit) and, therefore, characterized by exceptionally low solidus temperatures (Manning, 1981) and viscosities (Giordano et al., 2004), making easier crystal-melt separation.

In conclusion, the existence of stratified and cyclic units in granitic plutons, involving only granitic magmas or both mafic and silicic magmas, clearly shows the pulsed nature of magma emplacement and the incremental growth of plutons. The discontinuous nature of magma input leading to pluton construction by aggregation of discrete magma pulses, as well as the relationships between successive magma pulses and their ability to mix, are likely to be dominantly source-controlled in relation with the regional strain field, due to the discontinuous nature of melt segregation and depending on magma composition, rate of magma supply, etc. (Hecht & Vigneresse, 1999; Vigneresse & Clemens, 2000; Vigneresse, 2008). However, fractional crystallization (± hybridization) may also exert, in some cases, a significant control (i) during ascent with intermediate stages of differentiation at depth and subsequent emplacement of differentiated batches related by fractional crystallization; and (ii) at the site of emplacement by in situ differentiation as suggested by the characteristics of cyclic units.

2.2. Magma mingling and hybridization: relationships among layering, schlieren and mafic enclaves

Pitcher & Berger (1972) described in the Main Donegal Pluton what they called "*regular banding*", which consists of an alternation of steeply dipping coarser-grained light and finer-grained dark layers. The dark layers fade out along strike as does the whole layered zone, and the light bands are compositionally similar to the host granite. Deformation is considered to have accentuated the layering from compositional heterogeneities. No other sedimentation criteria are observed and material of dark layers may occur as enclaves in the light host granite. Beyond the interpretation of Pitcher & Berger (1972), this example points to the common association of dark layers, schlieren and mafic enclaves in granitic plutons.

Opinions diverge about the genetic relationships between the three above components. Some consider that there may be no filiation between schlieren and mafic enclaves because most enclaves are already formed when disaggregation of mafic injections occurs (e.g. Barbarin, 2005). Others suggest that both mafic layers and enclaves may result from stretching and disaggregation of (monzo)-dioritic to granodioritic pulses (Reid & Hamilton, 1987; Wells & Wooldridge, in Pitcher, 1993; Gasquet et al., 1995; Fernández et al., 1997; Barbey et al., 2008). This is indicated by disaggregating enclaves passing gradually to schlieren, with tip streaming (Fig. 2), or by the complete gradation existing from host-granite to mafic enclaves (e.g. Collins et al., 2000). In fact, these two contrasting opinions are not mutually exclusive, but more likely reflect various enclave/matrix viscosity contrasts and timing of emplacement (Fernandez & Barbarin, 1991; Fernandez & Gasquet, 1994). This may also depend on the site of enclave formation, i.e. in the site of emplacement or during ascent (e.g. Castro et al., 1995; Collins et al., 2000). We illustrate below, from two examples, the role of magma mingling and hybridization in the formation of layering, schlieren and magmatic enclaves within plutons.

In the Brignogan-Plouescat pluton (Brittany), Gasquet et al. (1995) describe gradual stretching and disruption over several tens of metres of a granodioritic pod giving raise to 30cm-thick dark layers alternating with light granitic layers compositionally close to the host granite. Two types of tonalitic enclaves are observed: (i) grey, granodioritic to monzogranitic enclaves showing lobate

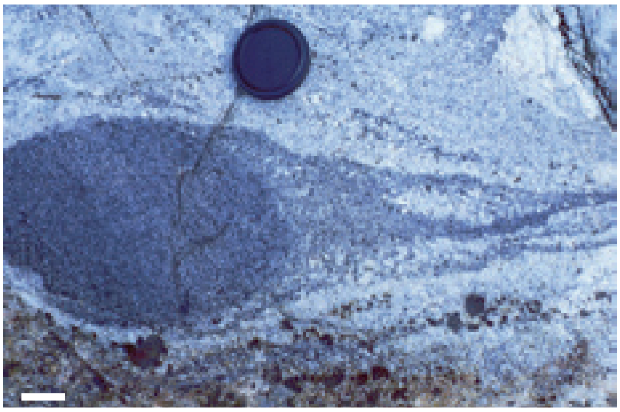

Figure 2. Relationships between enclaves and schlieren layering in granites: dark enclave with tip streaming in Velay leucogranite (Le Peyral, Ardèche, French Massif Central). Scale bar = 2.5 cm.

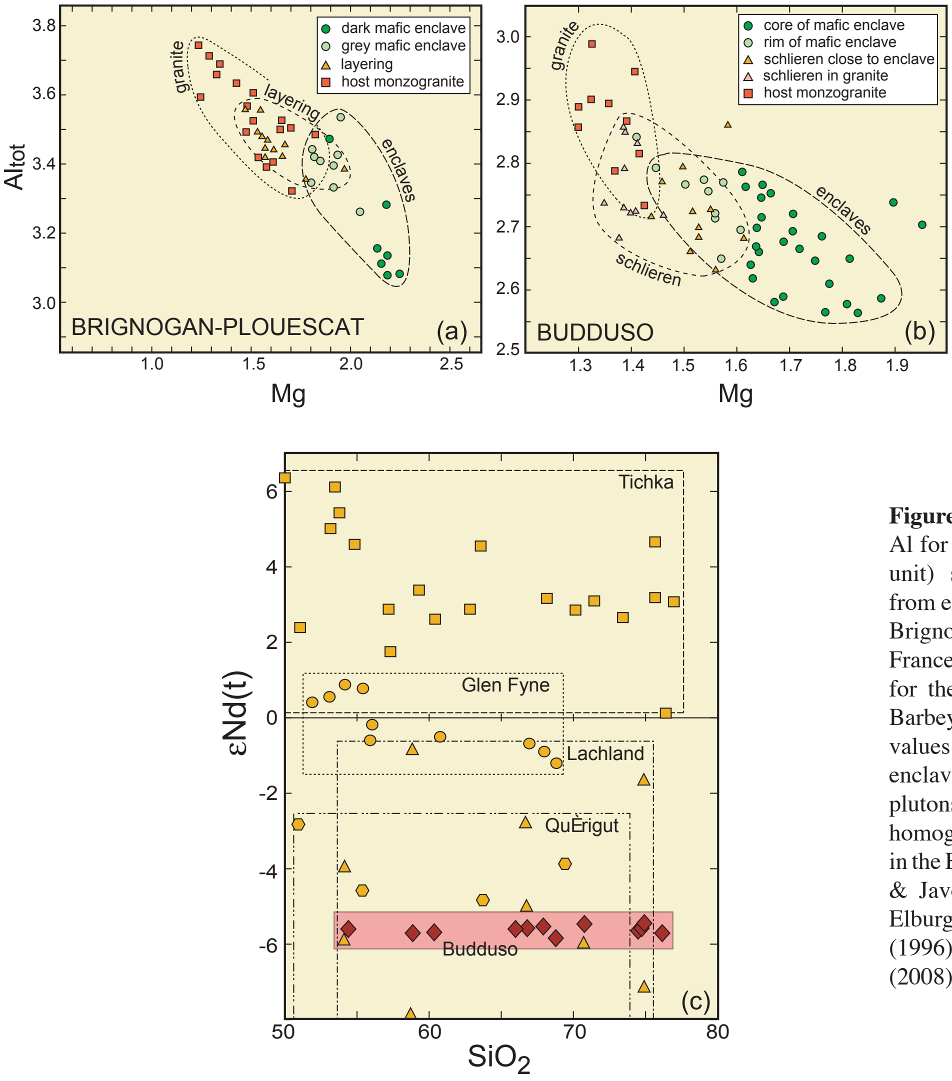

Figure 3. **(a)** and **(b)** Plots of Mg vs. total Al for biotite crystals (atoms per formula unit) showing compositional gradation from enclaves to host granite. Data for the Brignogan-Plouescat pluton (Brittany, France) from Gasquet et al. (1995), data for the Budduso pluton (Sardinia) from Barbey et al. (2008). **(c)** Plot of $\varepsilon_{Nd(t)}$ values vs. SiO_2 content (wt. %) for enclaves and host granite of several plutons, showing the remarkable homogeneity of enclaves and host-granite in the Budduso pluton; data from Fourcade & Javoy (1991), Gasquet et al. (1992), Elburg (1996), Flinders & Clemens (1996), Mass et al. (1997), Barbey et al. (2008).

and diffuse contacts with the host-granite, and containing rounded K-feldspar xenocrysts and ocellar quartz; and (ii) darker, tonalitic to granodioritic enclaves almost xenocryst-free and showing sharp contacts. The composition of biotite shows a progressive shift towards more Fe- and Al-rich compositions from the darker enclaves to the host-granite (Fig. 3a). These relationships are considered as the result of interactions at different rheological states between the host monzogranite and granodioritic pulses: (i) early injection of granodiorite in a weakly crystallized host, leading to the formation of layers by mingling, stretching and hybridization; (ii) injection of granodioritic pulses in a granitic mush with higher crystal fraction, leading to their fragmentation and formation of grey enclaves by moderate interaction (crystal capture) with the host monzogranite; and (iii) injection of the granodioritic magma in a highly crystallized monzogranite with fragmentation, but only limited interaction, leading to less hybridized darker enclaves.

Similar relationships between mafic enclaves, biotite schlieren and host monzogranite occur in the Budduso pluton, Sardinia (Barbey et al., 2008). The pluton consists of three nested units, with the outer and intermediate ones showing common mafic schlieren. The schlieren may correspond to mafic trails affected by shear flow structures, or to centimetre-thick irregular layers joining mafic enclaves, or may result from disaggregation of large mafic enclaves. The large enclaves are locally fringed by a dark biotite-rich rim extending as schlieren into the host granite. The progressive hybridization of the mafic material is clearly supported by the gradual change in the composition of biotite, which shows enrichment in Fe and Al towards the host granite (Fig. 3b).

In both case studies, magma interactions are accompanied by a change in the biotite composition. The similarity of the chemical trends outlines the progressive, though variable, hybridization of the Al-poor mafic (or intermediate) magma by its Al-rich host granitic mush. In some cases these interactions may be accompanied with change in the nature of mineral phases (see for instance Elburg, 1996).

The development of schlieren and layering instead of mafic enclaves are considered to depend on the rheological state of the host granite magma (melt viscosity and crystal proportion) when injection of the mafic magma occurs (Fernandez & Gasquet, 1994). Fractal geometry studies, experimental approaches and numerical simulations

(Brémont d'Ars & Davy, 1991; Grasset & Albarède, 1994; Snyder & Tait, 1995, 1996; Hallot et al., 1996; Perugini et al., 2003, 2005) show that viscous fingering between mafic and silicic magmas may be the main process of interaction. Enclaves would result from rather inefficient mingling dynamics, whereas layering would arise from more efficient dynamics due to stretching of the two components.

Nevertheless, though this seems to be corroborated by the common occurrence of heterogeneous isotopic compositions, enclaves and their host-granites may show, in some cases, homogeneous isotopic compositions (Fig. 3c) coupled with heterogeneous mineral compositions, suggesting several stages of mixing (Barbey et al., 2008). Lastly, modelling of hybridization time-scales (Petrelli et al., 2003) further shows that homogenization is much faster in active than coherent regions of chaotic dynamics, and therefore, that schlieren-like structures may coexist with enclaves at any scale, for time spans consistent with lifetimes of magma chambers.

On the whole, the relationships among mafic enclaves, schlieren and layering reflect variable interactions between mafic and silicic magmas in relation with material transfer towards or within plutonic bodies. Nevertheless, field observations indicate that these interactions are limited to the close proximity of mafic injections in relation with the dynamics of magma emplacement. This shows the fundamental role of mafic pulses to trigger local gravity and flow instabilities. Occurrence of hybrid rocks with evidence of mingling/mixing above mafic replenishments in mafic-silicic layered intrusions emphasizes the role of mafic magmas to delay crystallization and start local convection leading to magma hybridization (e.g. Wiebe & Collins, 1998; Wiebe et al., 2002; Pons et al., 2006). These interactions may occur at any stage during magma emplacement and pluton construction (e.g. Słaby & Martin, 2008).

3. Gravity settling and convection-related phase segregation

This section deals with outcrop-scale rhythmic layering structures, some mimicking sedimentary-type deposits, others showing only modally-graded or isomodal layers. The processes of gravity settling and hydrodynamic sorting will be reviewed, the main issue being here to discuss whether this type of layering implies pluton-scale convection or not, in granitoid plutons. The role of variation of intensive parameters in the formation of these structures will be dealt with in the next section.

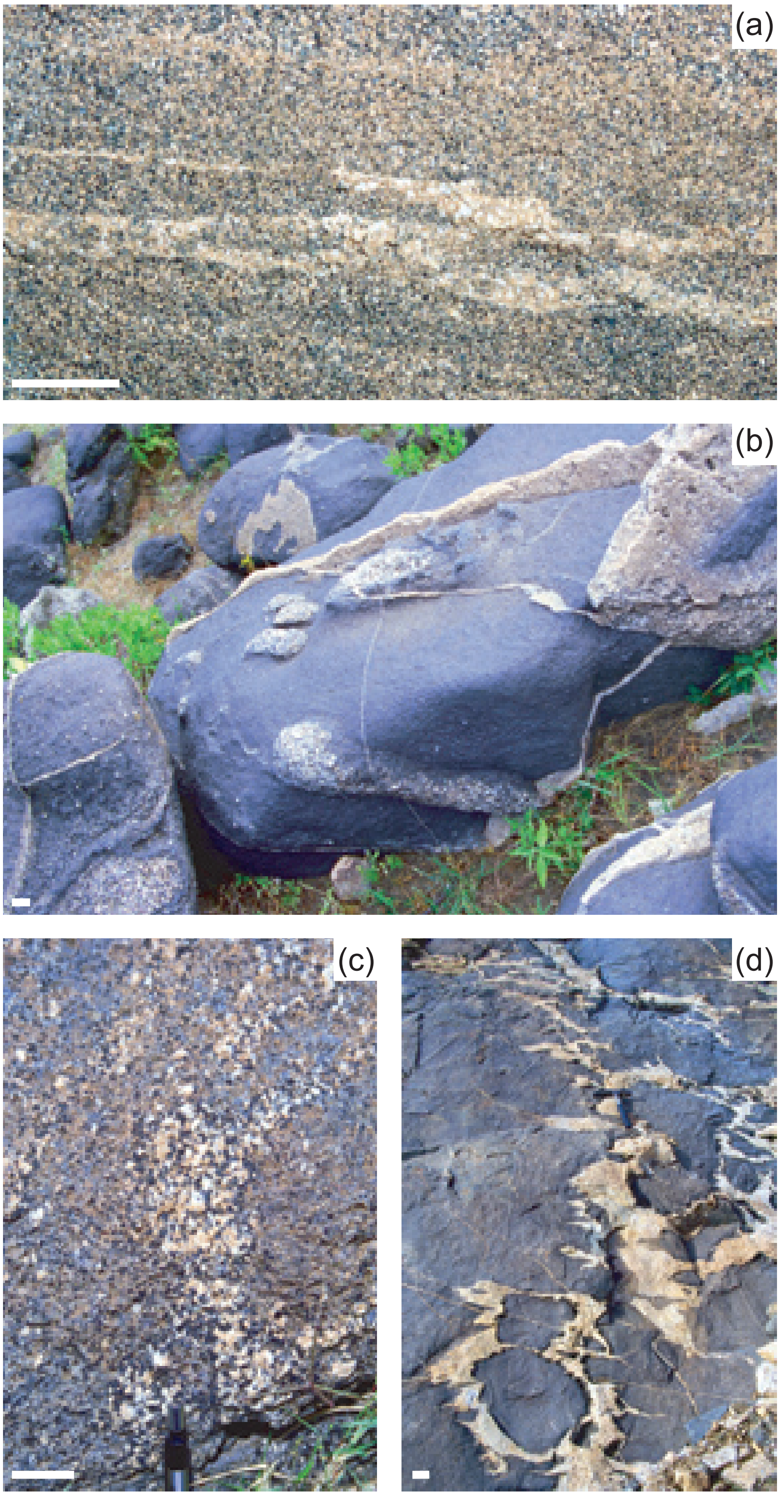

Figure 4. Granitic melt segregations in mafic-silicic layered intrusions. **(a)** Leucogranitic melt segregation layers parallel to igneous layering in granodiorite (Tarçouate pluton, Morocco; vertical cut; scale bar: 2 cm). **(b)** and **(c)** Granitic pipes and veins cutting through mafic layer (Negash pluton, Ethiopia; scale bar: 3 cm). **(d)** Mafic sheets crosscut by net-veining of differentiated granite (Tahala pluton, Morocco; plan view; scale bar: 10 cm).

3.1. Layering and gravity-driven crystal-melt segregation

One of the first processes invoked to account for the presence of size- and modally-graded layers in granites was gravity-driven crystal settling, and it is still advocated as a major layer-forming process in more recent studies (e.g. Clarke & Clarke, 1998). A variant of this process, called "*viscous plates*", was proposed from numerical modelling and field studies (Blanchard et al., 1978; Bébien & Gagny, 1981). Formation of rhythmic layering is attributed to local increase of the bulk viscosity related to local schlieren-like accumulations of crystals by settling, which act as levels of higher viscosity impeding the raise of residual melts formed by crystallization of the subjacent unit. In the case study reported by Bébien & Gagny (1981), the layering consists of 5 to 20 cm thick modally-graded units starting with amphibole- and oxide-rich layers, with sinuous and discontinuous basal contact supposed to result from deformation under gravity forces (ascending bulges of residual melt, sinking ferromagnesian rich parts). This model is in some respect akin to the "*sedimentological barrier*" of Puziewicz & Wojewoda (1984), which corresponds to a rheological boundary between low-viscosity fluid-enriched pegmatitic melt wherein settling of dark minerals is supposed to be easier, and the subjacent more viscous and denser granitic parent magma. Both models invoke changes in densities and viscosities related to local magma differentiation.

Gravity-driven melt segregation can occur by compaction-related melt removal, leading to segregation of differentiated residual melt (Fig. 4a). This process occurs commonly in mafic-silicic layered intrusions, and is expressed by the presence of granitic pipes and net-veining (Figs 4b, c) in the mafic sheets forming the base of macrorhythmic units (e.g. Elwell et al., 1960; Wiebe et al., 2002). The spreading of mafic replenishment over a chamber floor consisting of a granitic mush induces gravitational and viscous flow instabilities, which lead to melt escape structures by viscous digitations (Fig. 4d) or viscoelastic fracturing, depending on the rheological behaviour of mafic and silicic magmas with increasing solidification (e.g. Hallot et al., 1996). The association of melt escape structures in the mafic layers along with load casts at their base, and of cumulate textures and feldspar lamination in the underlying granitic material indicates that compaction and filter pressing trigger migration of interstitial liquids, which contributes to the hybrid rocks above the mafic layer (Wiebe et al., 2002).

On the whole, even though crystal settling is consistent with crystallization time scale and magma viscosities of granite magma (Shaw, 1965; Clarke & Clarke, 1998) and even though it is likely to accompany flow segregation as suggested for long (e.g. Gilbert; 1906; Emeleus, 1960; Wager & Brown, 1968), its exact importance is difficult to assess. Melt segregation by compaction appears as a general process in plutons where mafic injections spread over chamber floor, and may also be significant in processes involving gravity flow (see below).

3.2. Rhythmic layering, material transfer and depositional features in plutons

Field observations, more particularly those made for long in the Sierra Nevada, suggest that rhythmic layering is a rather common feature of orogenic granites. One of the first to mention the existence of layering in granite was probably Gilbert (1906), who reports alternations of dark ferromagnesian and light quartzofeldspathic bands, with thickness ranging from 3 to 30 cm. He noted the presence of several unconformities and observed that the basal contact of the dark layers is sharp, whereas the transition to the quartzofeldspathic layers upwards is more gradual. This led him to consider these structures to be due to deposition from and erosion by "*liquid magma in motion*", each pair of dark and light layers forming a deposition unit.

Numerous descriptions of layering structures related to currents are found in the literature. The most remarkable cases are known in mafic-ultramafic or alkaline layered complexes (e.g. Parsons, 1987; Cawthorn, 1996), but there are also many examples of layering structures in granites (Balk, 1937; Cloos, 1946, 1946; Harry & Emeleus, 1960; Wilshire, 1969; Barrière, 1981; Marre, 1982; Puziewicz & Wojewoda, 1984; Wiebe, 1993; Wiebe, 1996; Tobisch et al., 1997; Clarke & Clarke, 1998; Wiebe & Collins, 1998; Wiebe et al., 2002; Harper et al., 2004; Barbarin, 2005; Zák & Paterson, 2005; Pons et al., 2006). Overall, these structures occur either in the granitic parts of macrorhythmic units in mafic-silicic layered intrusions, or in sheeted intrusions (dykes included), or in the core of plutons, or within pluton along internal contacts between magmatic units, or close to contacts with the country rocks. All these layering structures share common characteristics, which are as follows:

(i) presence of depositional structures similar to sediment gravity flow, with rhythmic succession of modally-graded layers consisting of paired dark ferromagnesian and light quartzofeldspathic layers, low-angle branching, unconformities, cross-stratifications (Fig. 5a), scour and slump structures;

(ii) deposition units with sharp basal contacts and more progressive upper one, but sharp upper contacts are not rare;

(iii) reverse size-grading showing inverse relationship between the proportion of biotite and grain size, with the exception of K-feldspar megacrysts which may be present in the biotite-rich basal layers; layers start commonly by thin seam of accessory minerals overlain by biotite (± hornblende), followed by feldspars and quartz in the upper layer;

(iv) common, if not systematic, association with mafic magmatic enclaves, scattered in the layers or forming sheet-like (locally sorted) deposits concordant with layering (Fig. 5b); layers may be smoothed or interrupted over enclaves suggesting compaction or washing away around the enclaves.

A particular type of schlieren layering has been described under different denominations: ringschlieren, fishingnetschlieren (Cloos, 1936, 1946), curved laminae,

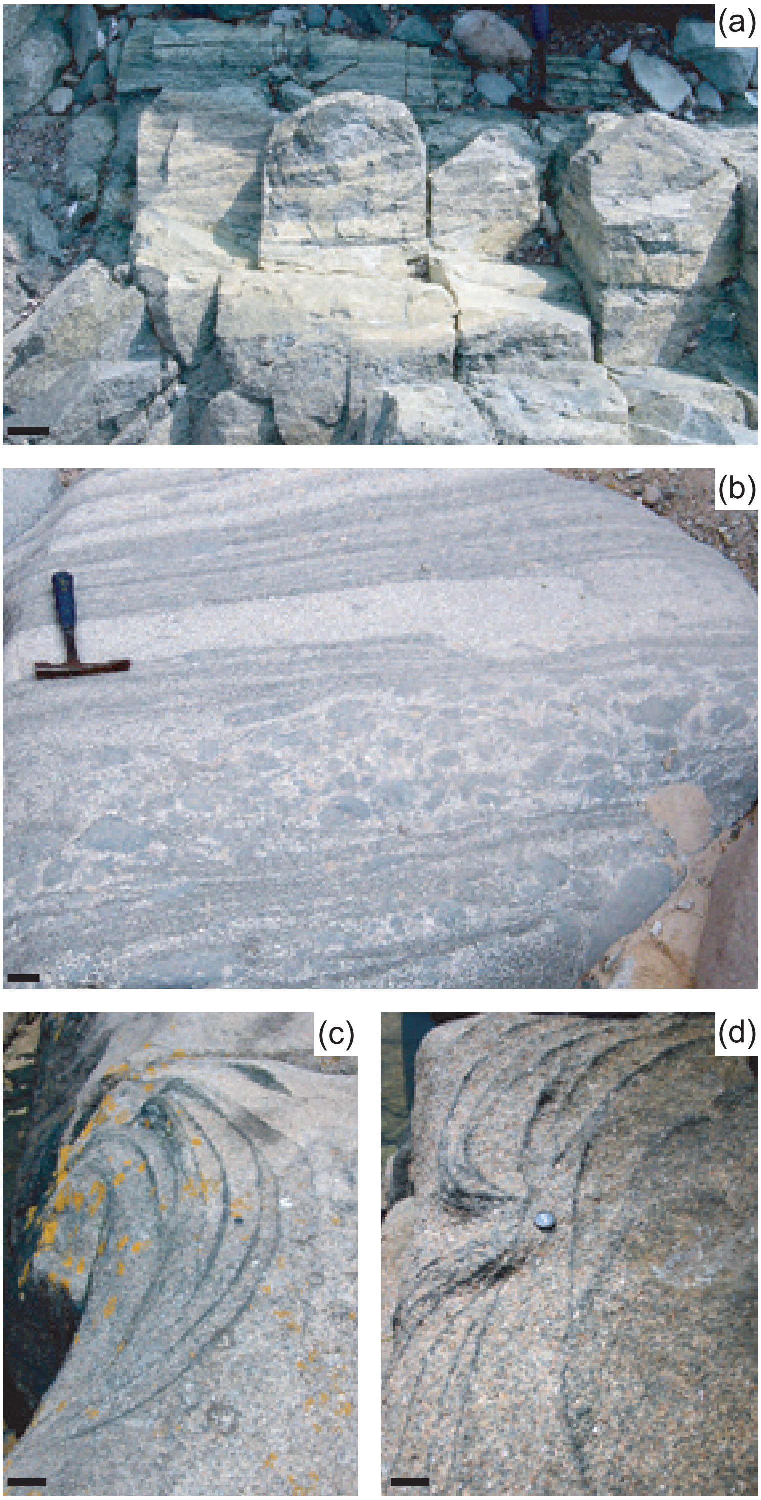

Figure 5. **(a)** Cross-stratifications in diorite (Coastal Batholith, Ilo, southern Peru; photograph T. Sempere). **(b)** Association of mafic enclaves and layering in granodiorite (Coastal Batholith, Huatiapa, southern Peru; photograph T. Sempere). **(c)** and **(d)** Schlieren in the Ploumanac'h massif (photographs F. Bussy). Scale bar: 10 cm.

ladle-shaped layers (Barrière, 1981), ladder dykes (Wilshire, 1969; Reid et al., 1993; Weinberg et al., 2001), layering-dikes (Tobisch et al., 1997), ellipsoids, snail structures and mushroom-shaped blobs (Weinberg et al., 2001), schlieren tubes (Zák & Paterson, 2006). All these structures correspond to stack of crescent-shaped concave-upward cumulate layers showing truncations. They are accompanied with inverse mineral grading, which consists of a basal, fine-grained, dark layer rich in ferromagnesian and accessory minerals, followed by a coarser-grained quartzofeldspathic layer (Fig. 5c). Truncation relationships (Fig. 5d) suggest that the more internal schlieren are younger than the external ones. However, it should be noted that none of these studies on layering in granites gives a detailed account of the compositional and microtextural characteristics of layering.

Various flow instability models have been proposed to account for such sedimentary-type layering in both mafic layered complexes and granitic plutons, for instance: (i) surge-type density currents leading to bimodal normally-graded layers reflecting differences in settling velocities related to differences in grain size and density (Irvine, 1980); (ii) flow sorting related to velocity gradients along the walls of intrusions or in intra-magmatic channels (Barrière, 1976, 1981; Reid et al., 1993; Tobisch et al., 1997); (iii) deposition on the floor of convecting magma chambers of crystal plumes released from the roof (Hess, 1960; Irvine, 1980; Sparks et al., 1992); (iv) gravity-driven settling of mineral grains and enclaves on the floor of the magma chamber in relation with episodic injections (Tobisch et al., 1997; Clarke & Clarke, 1998; Wiebe & Collins, 1998; Collins et al., 2000; Barbarin, 2005). The association of magmatic enclaves with these structures has been considered to result from changes in flow velocity gradients, either parallel (logjam effect) or normal to the flow direction (Tobisch et al., 1997). Weinberg et al. (2001) show that the ellipsoidal structures are related to ladder dykes and are likely to represent heads of local, thermal or compositional plumes, which consist of hot granite magmas from the source or heated from beneath by intrusive dioritic magmas. The curved schlieren are considered to represent walls of magma pipes or bottom of channels, truncations or cross-bedding structures being considered to result from pathway migration.

Recently, i.e. one century after Gilbert mentioned igneous layering in the Sierra Nevada batholith and interpreted it in terms of gravity flow for the first time, Solgadi & Sawyer (in press) have undertaken the first comprehensive study of igneous layering in the Tuolumne Intrusive Suite. It involves measurement of variations in grain-size and orientation of minerals, together with determination of mineral and whole-rock compositional variations, in both layered and non layered rocks. Their main results show that most layers are characterized by normal density and inverse size grading associated with an upward change in the orientation of mineral grains. There is no compositional variation of minerals across layers, and whole-rock compositions suggest that there is no fractionation of rare-earth elements (REE), differences between each layer corresponding to dilution of cumulus phases by a REE-poor phase (i.e. melt ± cumulus crystals). By analogy with sedimentary rocks (Mulder & Alexander, 2001), the authors interpret these structures in terms of gravity flow of hyper-concentrated sediments, eroding the substrate and characterized by grain dispersive pressure insufficient to maintain the dense particles in suspension, leading to deposition of ferromagnesian and oxide phases. Subsequent waning of the flow leads to deposition of the less dense feldspar crystals. The authors further report on the presence of leucocratic segregations interpreted as due to process analogous to dewatering structures in sediments. Initiation of the flows is attributed to slope instability due to crystal piling, or slope steepening related to tectonic movement, or earthquakes.

On the whole, the formation of rhythmic layering and schlieren in granite plutons appears to involve gravity- or flow-driven crystal-melt segregation. The driving force for material transfer within plutons is gravity instability, either related to local density inversion (Weinberg et al., 2001), or due to small convection cells above mafic replenishments (Wiebe & Collins, 1998; Wiebe et al., 2002), or related to the action of sidewall currents (Spera et al., 1982; Bergantz, 2000; Loetterle & Bergantz, 2004), or associated with slope failure (Solgadi & Sawyer, in press). The viscosity properties of granite suggest that crystal deposition related to chamber-wide crystal-bearing plumes is unlikely (Brandeis & Jaupart, 1986). Therefore, formation of layering does not seem to imply large-scale convective overturn, but is more likely to occur close to rheological boundaries (gravity instabilities) or in relation with mafic injections (local convection triggered by heat release).

In conclusion, sedimentary-type rhythmic layering is limited to specific sites within plutons, and its extent is small compared to the size of plutons. It does not imply large-scale convection, but rather suggests material transfer within plutons limited to specific parts, efficient at specific times, and related to local, dynamic and thermal instabilities.

4. Variation of intensive parameters and fractional crystallization

Differentiation by fractional crystallization has been frequently invoked in the literature to account for the association of various rock types in single stratified or nested plutonic bodies. However, there is for long a wide divergence of opinion about the mechanisms and locus of magmatic differentiation (e.g. Daily, 1933). In this section, the possible role of intensive parameters in the development of rhythmic layering and that of fractional crystallization in the development of compositional heterogeneities in plutons will be reviewed successively.

4.1. Rhythmic layering and variation of intensive parameters

Occurrence of isomodal and modally-graded layers without size-grading and erosional structures is not uncommon in granitoid bodies (Fig. 6a). They may be accompanied in some cases with unidirectional growth textures (Fig. 6b). A model of oscillatory nucleation in the vicinity of eutectic points (cotectic lines) from undercooled magma, combined with crystal settling has been proposed to account for the production of rhythmic layering in magmatic systems (e.g. Maaløe, 1978). However, quantitative modelling suggests that this process needs significant undercooling and thick magma bodies to be efficient in the case of granitic magmas owing to their physical properties (Hort et al., 1993). Duchesne & Charlier (2005) propose an alternative model considering variations in nucleation rates in multiple stratified layers formed by double-diffusive process (McBirney & Noyes, 1979), to account for the association of isomodal and modally-graded layers and for the presence of constant two-pole cumulate compositions in the Bjerkreim-Sokndal jotunitic layered intrusion (southwest Norway).

The Bjerkreim-Sokndal intrusion (Michot, 1960; Duchesne, 1972; Jensen et al., 1993; Wilson et al., 1996; Barling et al., 2000) is considered as a compositionally-stratified, periodically replenished magma chamber as

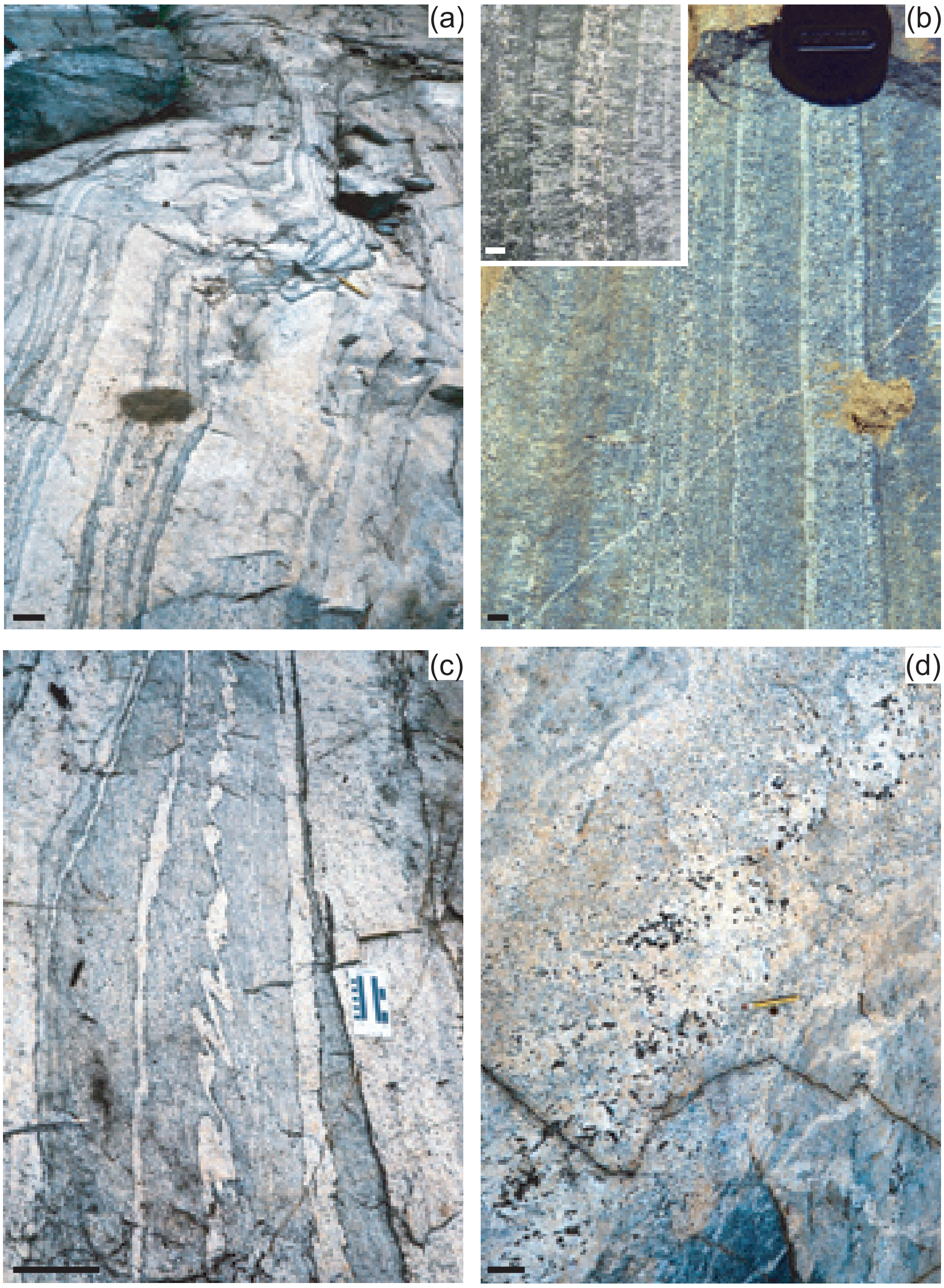

Figure 6. **(a)** Succession of paired isomodal biotite-rich and quartzofeldspathic layers. **(b)** Isomodal layering in a monzodiorite dyke associated with directional growth textures of feldspar (Tarçouate pluton, Morocco; scale bar: 1 cm). **(c)** Pegmatite veins parallel to the rhythmic layering; note the variable thickness of the veins and their distinct states of deformation indicating diachronic emplacement. **(d)**. Diffuse pegmatite patches delineating a loose layering structure. [(a), (c) and (d) Estrela Granite Complex, Carajàs Province, Brazil; scale bar = 10 cm].

suggested by systematic variations of isotopic compositions with height (six megacyclic cumulate units). Two types of layers are observed: (i) modally-graded layers passing from pyroxene + Fe-Ti-oxide at the base to plagioclase-rich top, and locally associated with through and slump structures; (ii) isomodal layers (e.g. leuconorite, gabbronorite), thicker (metre to decametres vs. tens of centimetres for the former) and showing constant grain size. Duchesne & Charlier (2005, 2007) show from major element compositions that the modal layering (whatever the megacyclic unit considered) can be accounted for by two end-members, one corresponding to mafic phases (pyroxenes + Fe-Ti-oxides + apatite in cotectic proportions) and the other to plagioclase. Even though plagioclase has a lower density than the parental magma, gravity-driven crystal sorting and immiscibility of a Fe-Ti rich liquid are considered to be unlikely, mainly because normal size-grading is absent and the minerals remain in constant proportions in the mafic pole despite their contrasted densities. In the model, the mafic phases start to crystallize in cotectic proportions, whereas plagioclase crystallization is delayed due to kinetics needing large degree of supersaturation in both mafic and silicic magmas (Kirkpatrick, 1983; Tsuchiyama, 1983; Couch, 2003). In the modally-graded layers, the increase in plagioclase content is attributed to an increase of nucleation rate due to upwards increase of supersaturation. The constant-mode layers are explained in terms of constant degree of supercooling and nucleation rate. In situ crystallization may locally be combined with depositional and erosional features in region close to the walls where the trapped liquid is exceptionally abundant (Duchesne & Charlier, 2007). Although the role of such a process remains to be clearly indentified in granitoid bodies, it may account for the occurrence of vertical two-poles layering associated with unidirectional growth textures. In such case, layering would result from what may be called “static” instabilities, in contrast with sedimentary-type layering resulting from dynamic instabilities.

4.2. Intrusive suites and fractional crystallization

Trace element analysis and modelling of element partitioning led authors to interpret plutons in terms of crystal/melt segregation leading to vertical or concentric zonations. One such example is the Blue Tier Batholith in Tasmania (McCarthy & Groves, 1979). From major and trace element modelling it was considered that the compositions of the different magmatic units (granodioritic, monzogranitic, and in lesser amount granitic) could be satisfactorily accounted for by in situ fractional crystallization from a single parent magma. A process of inward crystal nucleation and growth (from the roof, floor and walls of the magmatic body), accompanied with expulsion of interstitial melt, was suggested. However, later Sr-Nd and zircon U-Pb isotopic data showed that the Blue Tier Batholith has not a unique source (Mackenzie et al., 1988) and results from a long lasting magmatic activity, with S-type magmas emplaced *ca*. 20 Ma after I-types (Black et al., 2005). These data show that trace element modelling has a limited power of discrimination and that apparent filiations should be carefully examined at the light of others arguments. Even though granitic units in some plutons seem to be related by in situ fractional crystallization of a unique parental magma (e.g. Bachl et al., 2001), their relative proportions preclude in many cases differentiation at the site of emplacement, but rather suggest that these units correspond to pulses differentiated (± mixed) in deep-seated chambers (e.g. Monier et al., 1987; Cocherie et al., 1994; Duchesne et al., 1998; Roberts et al., 2000; Barbey et al., 2001; Vigneresse, 2008; Słaby & Martin, 2008). Lastly, we can be reminded that restite retention has been also advocated as a process of differentiation during magma ascent towards the sites of emplacement (Chappell et al., 1987; see also Montel & Vielzeuf, 1997; Stevens et al., 2007), and that chemical trends linking the main rock types of intrusive suites may be orthogonal to the fractional crystallization trend (Reid et al., 1993). Therefore, should we conclude that fractional crystallization is unlikely to operate in the sites of emplacement of granitic magmas?

Several observations suggest that fractional crystallization in the site of emplacement cannot be discarded. Occurrence of evolved granites, aplites and pegmatites as diffuse patches or submagmatic dikes is indicative of local separation of fractionated, possibly fluid-enriched, liquids from crystal mush (Fig. 6d). Field, geochemical and textural evidence shows that granites from mafic-silicic layered intrusions are cumulates resulting from melt extraction by filter pressing due to the overburden of dense mafic overlying replenishments (Wiebe et al., 1997; Harper et al., 2004). Mineral zoning patterns showing regular decrease in Ba, Sr and Ca in feldspars, as in the Torres del Paine (Michael, 1984) or Dolbel (Pupier et al., 2008) plutons, suggest in situ fractional crystallization from melt batches, which are not renewed but progressively impoverished in compatible elements. Apatite zoning was also shown to record progressive crystallization of granitic magmas within pluton (Dempster et al., 2003). Finally, clear evidence showing the role of fractional crystallization on the compositional evolution of micas has been discussed in the particular case of the Beauvoir intrusion (section 2.1 and Fig. 1b).

4.3. Layering and fractional crystallization in thermal boundary layers

Here, we present an example of igneous layering, which allows the place and role of sidewall crystallization during pluton growth to be assessed. In the case study reported by Pupier et al (2008) the layering occurs close to the periphery of pluton as a sub-vertical layered series. The layering consists of decimetre-thick rhythmic units formed of three layers: (i) the thin basal layer (0.5 cm) consists of amphibole (edenite) and accessory minerals (titanite, apatite, Fe-Ti-oxide) accompanied with plagioclase towards the top of the layer; (ii) the intermediate layer (2-3 cm) consists of amphibole, plagioclase and quartz; and (iii) the upper layer of variable thickness (absent in some cases but reaching one metre in other cases) consists of amphibole, plagioclase, quartz and of K-feldspar phenocrysts. In other words, each layer is characterized by the appearance of a new mineral phase. Accounting for the bulk haplogranitic composition of the granite and excluding the basal amphibole-rich layer, the mineral succession appears to be consistent with an evolution involving liquidus (plagioclase from the basal layer), cotectic (intermediate layer compositionally close to cotectic) and eutectic phase assemblages in the Qz-Ab-Or system. However, the upper layer though characterized by an invariant phase assemblage, is compositionally far from eutectic, and is more likely to represent the composition of the parent magma minus small amounts of liquidus and cotectic phases. The repetition of the same cumulate sequence in each rhythmic unit indicates that the parent melt composition was very similar for every unit (pulsed injection).

Measurement of plagioclase size distribution shows that each rhythmic unit is characterized by the same distribution pattern. Furthermore, the small sized plagioclase grains at the base of each unit probably suggest significant ΔT values between the top and the base of two consecutive units. Overall, the rhythmic units record the same broad thermal history.

All mineral phases are oscillatory zoned and can be gathered in two main groups: (i) amphibole and titanite showing disjointed cores (with evidence of dissolution, regrowth and crystal aggregation), intermediate parts with oscillatory zoning parallel to the growth faces of crystals, and intercumulus overgrowths; and (ii) plagioclase and more particularly K-feldspars consisting of euhedral oscillatory zoned cores and peripheries, surrounded by intercumulus overgrowths. This dual zoning pattern of mineral cores points to distinct conditions of crystallization. Major and trace element zoning of amphibole and titanite

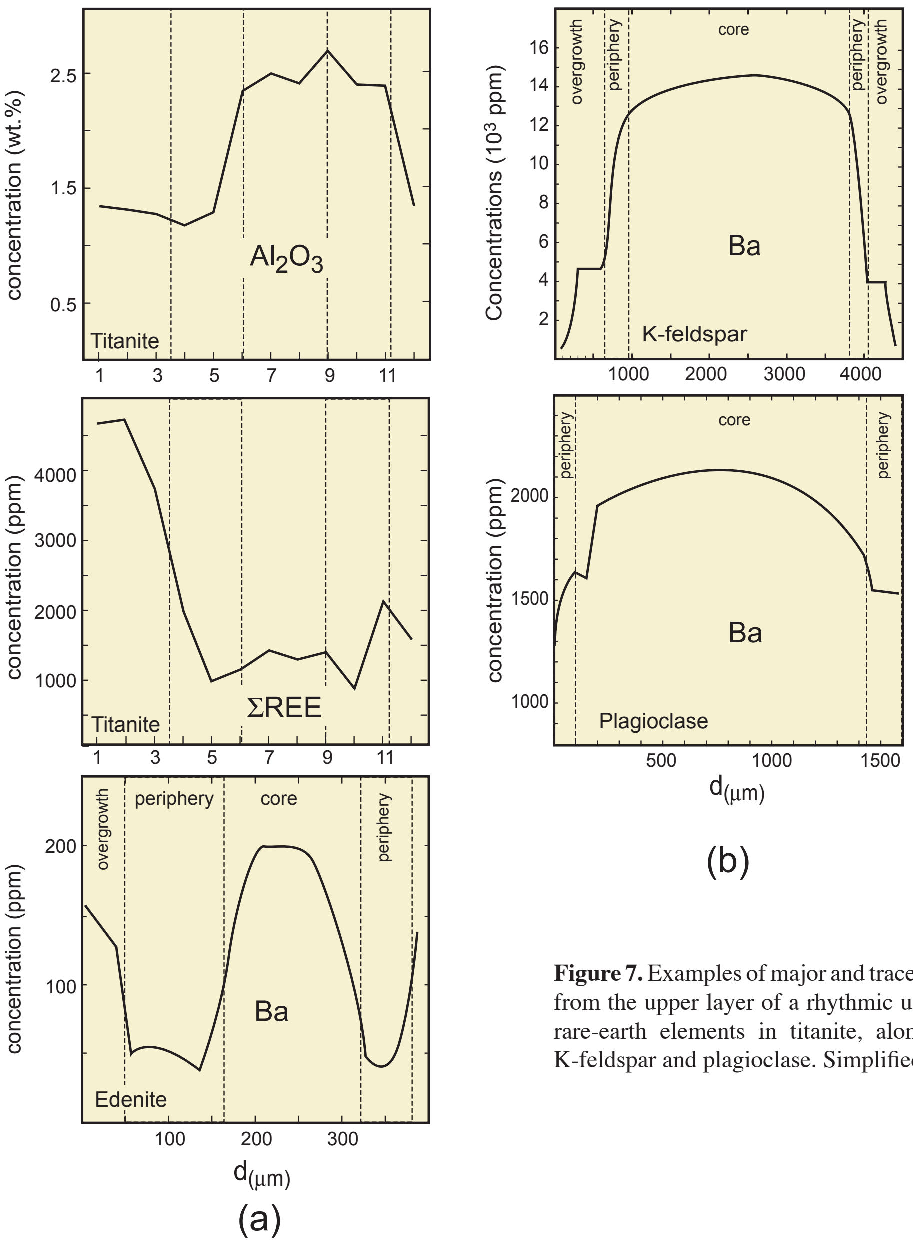

Figure 7. Examples of major and trace element variations in the main minerals from the upper layer of a rhythmic unit of the Dolbel pluton: **(a)** Al_2O_3 and rare-earth elements in titanite, along with Ba in amphibole; (b) Ba in K-feldspar and plagioclase. Simplified from Pupier et al. (2008).

suggests that cores crystallized from hot primitive liquids involving a succession of dissolution/growth episodes (open system conditions), whereas growth of their periphery is concomitant with the onset of feldspar crystallization shown by the decrease in Al_2O_3 and Ba contents (Fig. 7a). By contrast, feldspar core and periphery show a decrease in compatible trace elements, such as Ba (Fig. 7b), indicating crystallization under closed-system conditions.

The succession of layers is considered by Pupier et al. (2008) to result from fractional crystallization in thermal boundary layers (liquidus and cotectic phase assemblages at the base of rhythmic units), followed by en masse crystallization (eutectic phase assemblage at the top of rhythmic units). Each unit represents a new magma pulse. Flow segregation is limited to the early stage of each unit and concerns the cores of amphibole and titanite probably segregated from magma batches containing suspended crystals. Erosion of crystallized units by a new batch is shown by the variable thickness of the upper K-feldspar-bearing layer and by its absence in some units. Textural relationships and especially intercumulus overgrowths show that inflation related compaction and deformation, due to the pulsed magma recharge, occurred before crystallization of the overgrowths but probably after the growth of plagioclase rims.

This example corroborates the model of discontinuous magma input (Clemens & Mawer, 1992). It further shows that fractional crystallization in thermal boundary layer has limited effects on in situ differentiation, the bulk of the melt crystallizing as the upper layer without significant differentiation. These data along with experimental crystallization paths (e.g. Scaillet et al., 1997) indicate that large rocks units in most plutons are unlikely to result from in situ differentiation by fractional crystallization of a unique parent magma. By contrast, the Beauvoir granite (section 2.1) represents probably a very specific example, corresponding to an end-member situation due to the singular F- and Li-enriched composition of the magma.

4.4. Implications on mineral clusters

One striking characteristic in the above example of crystallization in thermal boundary layers is the homogeneous distribution of mineral phases within each layer. This is especially obvious in the case of the eutectic layers in which quartz and plagioclase grains and K-feldspar phenocrysts are evenly distributed (see Figs. 3 and 12 in Pupier et al., 2008). This contrasts with the common occurrence of accumulations of K-feldspar megacrysts, which may in some cases form exceptional occurrences as reported by Abbott (1989). These accumulations occur as layers (Figs 8a, b), or as decimetre to metre-wide bodies (Fig. 8c), and consist of almost matrix-free unbroken K-feldspar crystals. The absence of deformation is considered to imply that sufficient liquid was present during emplacement for the megacrysts to be moved without plastic deformation. The subject has been discussed in a recent review paper by Vernon & Paterson (2008) to which the reader is referred for an extensive literature survey and for a discussion of the magmatic origin of K-feldspar megacrysts.

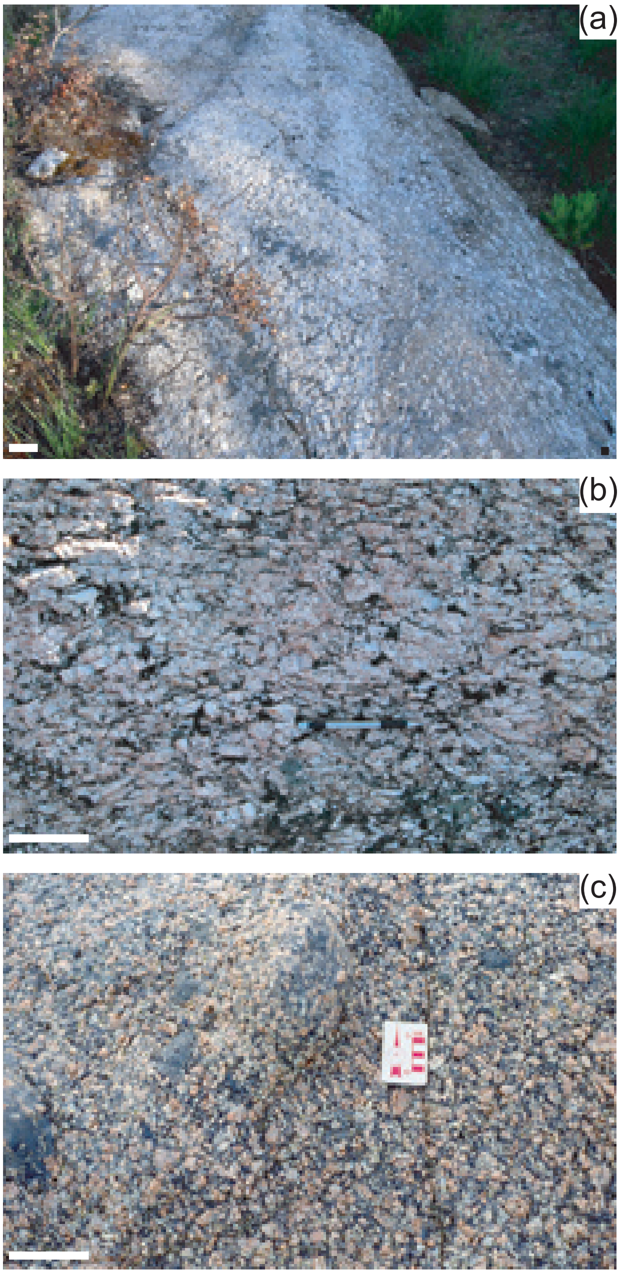

Figure 8. Distribution of K-feldspar megacrysts in granites. **(a)** Layer (dyke?) of K-feldspar megacrysts (Ifanes massif, Aldeia Nova, NE Portugal). **(b)** Enlargement of photograph in (a) showing the quasi-absence of matrix in between K-feldspar megacrysts (photograph D. Gasquet). **(c)** Accumulation of K-feldspar megacrysts in the Ploumanac'h massif (photograph D. Gasquet). Scale bar: 10 cm.

On the whole, with the exception of pegmatite pods, it can be considered that the uneven distribution of K-feldspar megacrysts could be indicative of mechanical segregation process within plutons. It is generally considered that the segregation process may be either differential shear in a visco-plastic material leading to sorting of crystals formed at different times and in different batches (Komar, 1972; Barrière, 1981; Abbott, 1989), or something equivalent to logjam effect with melt loss (Clarke & Clarke, 1998; Tobisch et al., 1997; Vernon & Paterson, 2008).

4.5. Differentiation and segregation of undercooled melts: pegmatite layering

Pegmatites and aplites resulting from solidification of highly differentiated granitic melts show various occurrences, including diffuse bodies, layered units or dyke swarms. The literature flourishes of remarkable examples (e.g. Duke et al., 1986; Frindt & Haapala, 2004). Layering commonly occurring in subhorizontal dykes is defined by either variations in modal composition, grain size and grain shape, or recurrence of veins parallel to former layering (Fig. 6c). These lithologies need careful attention since they must not be mistaken for migmatites showing similar relationships and components (leucosome and mesosome). These layered aplite-pegmatite associations may encompass:

(i) layered aplite with layers consisting of equigranular aplite, alkali-feldspar-quartz intergrowths in aplitic matrix, or alkali-feldspar-quartz pegmatite (Frindt & Haapala, 2004);

(ii) aplo-pegmatite consisting of alternating fined-grained leucocratic granite showing upward directional crystallization from the footwall, and coarse-grained pegmatite showing downward directional growth from the hanging-wall; the repetition of aplite-pegmatite couplets is considered to result from multiple quasi-conformable sheet-like injections (Duke et al., 1988);

(iii) aplite-pegmatite layering consisting of rhythmic units limited at their base and top by millimetre-thick layers of fine-grained albite; each unit is comprised of coarse-grained albite and K-feldspar crystals showing downwards (from the hanging-wall) or upwards (from the footwall) directional growth; quartz occurs in the centre of each unit (Gouanvic & Gagny, 1987);

(iv) aplite-pegmatite dykes with symmetrical arrangement, with alkali-feldspar and quartz crystals grown towards the centre of the dykes (Frindt & Haapala, 2004);

(v) massive pegmatite filling veins parallel to former layering, or following granite jointing, or forming swarms (e.g. Balk, 1937; Marre, 1982; Barros et al., 2001).

Structures and textures of pegmatite and aplite-pegmatite layered complexes have led to various interpretations involving mainly (late)-magmatic processes and deformation-assisted melt segregation. Most studies agree to consider that undercooling has a significant role in the formation of layered aplite-pegmatite complexes, wherein textures result commonly from unidirectional solidification (Lofgren, 1980; Shannon et al., 1982); Fenn, 1986; Baker & Freda, 1999). Several additional processes advocated to account for the characteristics of aplite-pegmatite layering include diffusion-controlled oscillatory crystallization, double-diffusive convection, displacement of phase equilibria related to change in vapour pressure, segregation of a volatile phase (Jahns & Tuttle, 1963; Gouanvic & Gagny, 1987; Rockhold et al., 1987; Stephenson, 1990; Morgan & London, 1999). An up to date review of the origin of pegmatites is given by Simmons & Webber (2008).

5. Deformation-assisted melt emplacement and segregation

Buddington (1959) emphasized the change in the mode of occurrence of intrusions, from discordant in the upper crust, to concordant in the lower crust. On a wider scale, McCarthy & Thompson (1988) suggested that the overall layered nature of the middle and lower crust as imaged by seismic studies probably results from the combination of both ductile strain in thermally weakened crust in response to extension, and magmatic layering resulting from injection of sub-horizontal sheets of magma. More recently, it has been shown that the geometry of plutons depends on the relationships between magma pressure, rheological discontinuities, regional stress field and shear zones (McCaffrey & Petford, 1997; Vauchez et al., 1997; Hogan et al., 1998; Vigneresse et al., 1999; Petford et al., 2000), leading to sheeted or wedge-shaped plutonic bodies. Here are reviewed the main situations likely to result in layered intrusions by deformation-assisted magma emplacement or melt segregation: (i) magma emplacement along pre-existing planar fabrics; (ii) syntectonic magma emplacement; and (iii) melt segregation in solidifying plutonic bodies.

5.1. Foliation-parallel emplacement of magma and "ghost stratigraphy" in plutons

Emplacement of silicate melts along pre-existing foliation (lit-par-lit injection) is well described in migmatites (e.g. Mehnert, 1968), and several examples of granitic melt migration along pre-existing foliation in the middle crust have been reported in the literature (Barbey et al., 1996). In exceptional cases as in the Wuluma granodiorite (Collins et al., 1989), ghost layering has been considered to represent refractory levels forming rafts or schlieren "floating" within a granitic matrix formed by in situ melting of specific lithologies.

As outlined by several authors, the geometry of the granite network, at crustal scale, is controlled by the regional deformation pattern, granite veins being dominantly discordant when the foliation is near-horizontal, but localized within foliation when it is vertical (Brown & Solar, 1998, 1999; Brown et al., 1999;

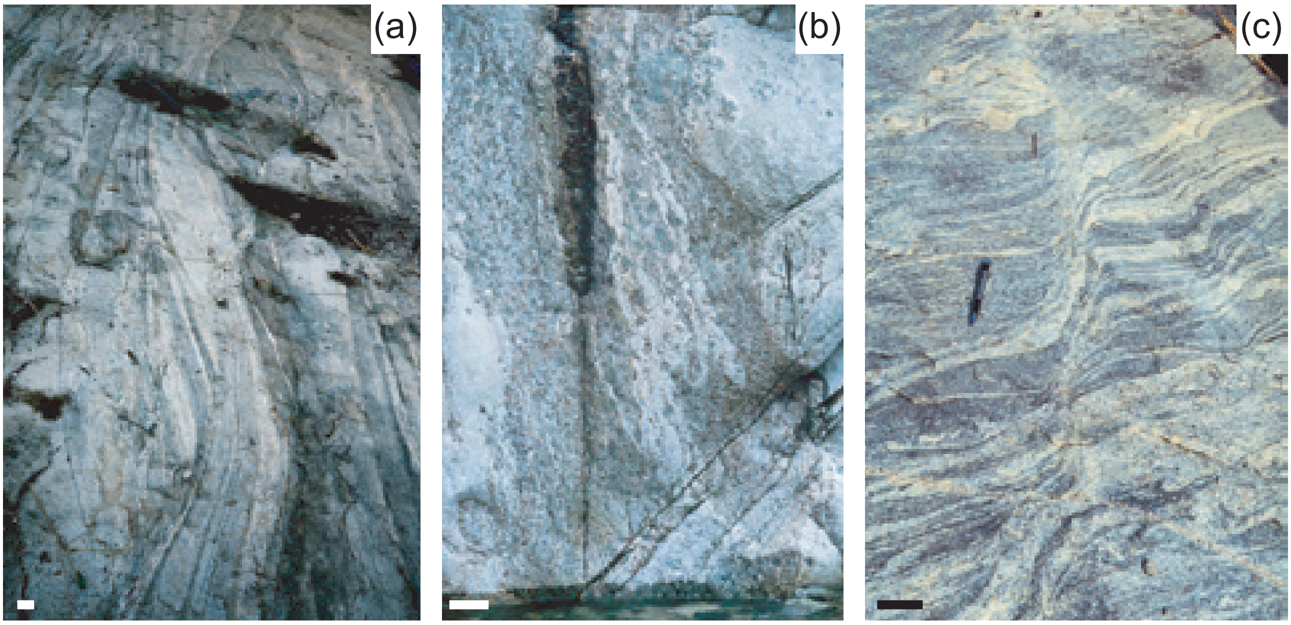

Figure 9. **(a)** Shear zone related transposition of igneous layering shown in figure 6a (Estrela Granite Complex, Carajàs Province, Brazil). **(b)** Layering resulting from viscous flow and mingling of leucocratic granite and dark cordierite-rich monzogranite (Velay massif, French Massif Central). **(c)** Syntectonic layering outlined by residual melts located in segregation veins parallel to the foliation or within shear zone (Dabakala pluton, northern Ivory Coast). Scale bar: 10 cm.

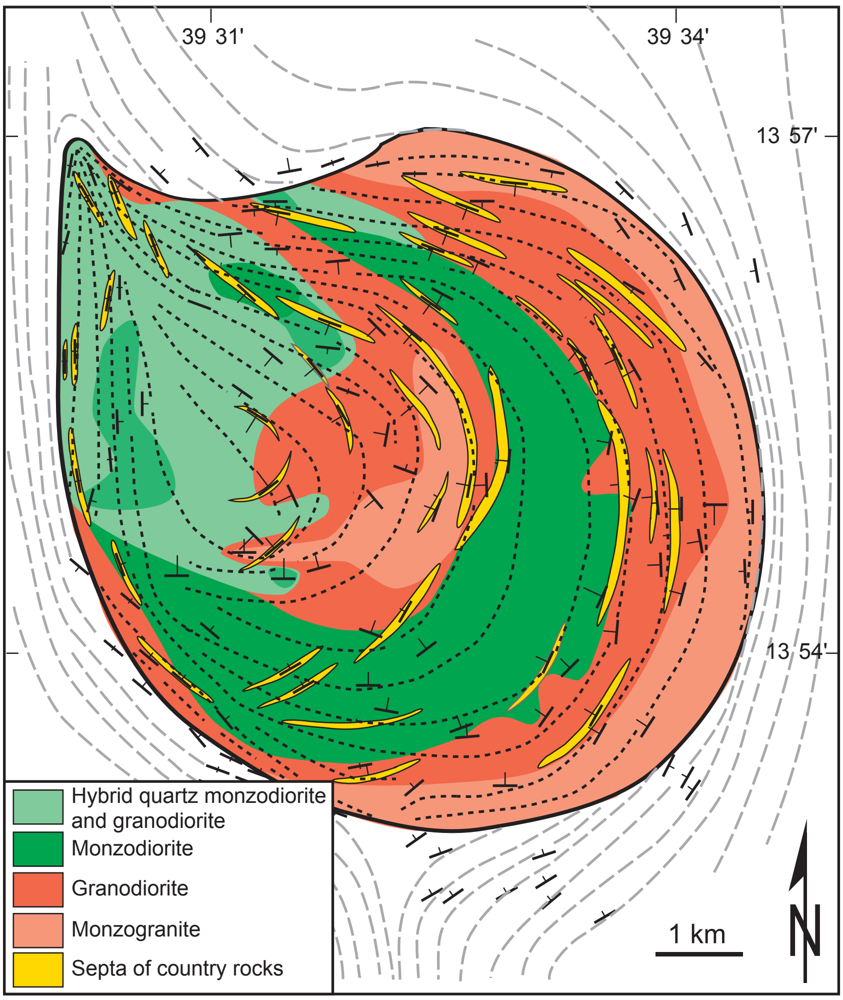

Figure 10. Geological map of the Negash pluton (northern Ethiopia) showing the shape and distribution of the country-rock septa; from Asrat et al. (2004).

Vanderhaeghe, 2001). Lucas & St-Onge (1995) describe large scale compositional layering in mid-crustal Archaean and Palaeoproterozoic terrains resulting from syntectonic emplacement of veins, which parallel pre-existing foliation acting as a mechanical guide, leading to metre- to kilometre-scale alternation of tonalite and quartz-diorite. Even though the regional development of layering by foliation-parallel emplacement of magma appears as a common process in the middle crust, the conformable nature of granite sheets may also result from tectonic attenuation or transposition of a former magmatic layering (Fig. 9a) or of dykes, depending on the regional tectonic context (e.g. Myers, 1978; Barros et al., 2001; Vanderhaeghe, 1999, 2004).

Foliation-parallel injection of granitic magmas may occur close to contact zones of plutons and result in sheeted intrusions. This is for instance the case of the Main Donegal Pluton (Pitcher and Berger, 1972) showing an 800m thick marginal zone, consisting of numerous concordant sheets of granites, which coalesce to form the main body of the pluton. The granitic sheets are separated by abundant xenoliths, which still reflect the stratigraphy of the country series ("ghost stratigraphy"). Brown & McClelland (2000) describe plutons with remarkable sheeted margins, 3km thick, with sills ranging in thickness from centimetres to hundred of metres. These structures are considered to result from the forcible emplacement of magma pulses fed with dikes, which leads to sill formation followed by variable inflation to accommodate magma volumes, resulting in tabular granites (e.g. McCaffrey & Petford, 1997; Duke et al., 1988; Blenkinsop and Treloar, 2001; Saint-Blanquat et al., 2001). Foliation-parallel emplacement of magma corresponds in some cases to the first stage of pluton growth, such as the Negash pluton (Asrat et al., 2004), which shows tens to hundreds of metres long concentric septa of country-rocks representing probably remnants of an initial stage of sheeted injection (Fig. 10). The duality in pluton shape, i.e. tabular *vs.* wedge shaped, is considered to depend on the relationships between internal magma pressure and regional stress field (Vigneresse, 2008).

5.2. Syntectonic magma emplacement and sheeted intrusions

Sheeted granite bodies related to shear zones may be compositionally monotonous and consist of cm to m scale, leucogranite sheets emplaced in shear zones cutting through crystallizing granitic bodies (Pawley et al., 2002), or may involve various rock types ranging from gabbros to porphyritic granites showing layered structures from the pluton scale as in the McDoogle pluton in California (Mahan et al., 2003) or the apophysis of the Bjerkreim–Sokndal intrusion (Bolle & Duchesne, 2007), to the outcrop scale as in the Sanabria plutons in Spain (Vegas et al., 2001). These granites are made up of numerous sheets, commonly steeply dipping, with thickness ranging from centimetres to hundred of metres. In the McDoogle pluton, intrusive contacts are broadly concordant with the fabric, and sheets are outlined by abundant concordant wall-rock enclaves and screens, with the preservation of a ghost stratigraphy in the distribution of enclaves. Moreover, there is a general concordance between the tectonic fabric in the wall-rocks and the magmatic, submagmatic and solid-state fabrics in the pluton. At a wider scale, Vauchez et al. (1997) describe examples of magma emplacement controlled by shear zones in the Borborema Province (Brazil), leading to emplacement of swarms of undeformed or variably mylonitized dykes (sub)-parallel to the high-temperature foliation of mylonites. These magmatic bodies, comprised of different rock types ranging from diorite to leucogranite, encompass decimetre to several hundred metres thick dykes to dyke-like plutons, such as the Teresinha (1 km wide, 10 km long) or the Pedra Lisa plutons (~1 km wide, 50 km long). This type of sheeted granites is interpreted in terms of incremental flow in active shear zones, leading to aggregation of multiple parallel or coalescing intrusive sheets, each one representing a pulse stretched by laminar flow. Melt pressure and effective stress is influenced by deformation-induced dilatancy, with feed-back relation between increase in melt fraction, non-coaxial strain localization and melt migration. Built up of melt pressure will cause embrittlement, tensile or dilatant shear fracturing and channelized flow, leading to complex relationships between deformation-assisted magma emplacement and magma-assisted nucleation of shear zones (Neves et al., 1996; Vauchez et al., 1997; Brown & Solar, 1998).

Magma emplacement in extensional tectonic context may lead not only to lenses such as the Gangotri granites (Scaillet et al., 1990), but also to sheeted and layered plutonic bodies such as the stratoid granites of Madagascar (Nédélec et al., 1994), or the Velay massif in the French Massif Central (Ledru et al., 2001), or the late Carboniferous granitoids of Calabria forming sheet-like intrusions at the scale of the middle crust (Caggianelli et al., 2000). Layering, which extends over large distances, corresponds to the association of magmas with compositions covering a wide compositional range (Fig. 9b). This large scale layering of granite plutons involving heterogeneous magmas may be considered as a compositional layering reflecting magma intrusion associated to ductile flow at the scale of the middle crust (Vanderhaeghe & Teyssier, 2001; Teyssier et al., 2005).

5.3. Layering and deformation-assisted mineral/melt segregation during pluton growth

As outlined by Weinberg (2006) segregation structures are much rarer in granites than in migmatites. This is interpreted as due to the relatively short duration of mush solidification, and to melt extraction through the pores of the solid framework. However, segregation structures in syntectonic granites are not so uncommon and closely resemble those observed in migmatites wherein melt segregation is mainly controlled by deformation and anisotropy (Sawyer, 2000). Melt segregation may affect the whole granite mass, or be localized to discrete zones related to either pre-existing anisotropy or fracture.

Melt segregation veins are common in syntectonic granites, leading to alternation of dark ferromagnesian and light granitic layers (Fig. 9c). This is to some extent analogous to the development of synmigmatitic layering characterized by regularly alternating cm to m thick granitic veins and mesosome layers, interpreted as the result of deformation-assisted melt segregation in partially molten material (e.g. Sawyer, 2000; Vanderhaeghe, 2001).

Formation of sheet-like structures by melt segregation within plutons has been reported from the Adamello massif (John & Stünitz, 1997). The segregations form anastomozing zones showing almost the same mineralogical and whole rock composition as the host quartz diorites and granodiorites, with the exception of a smaller grain size. Although the segregations are foliated, they do not show evidence of intracrystalline deformation. In the wider segregation veins, mafic enclaves may be common, with orientation parallel to the segregation. These structures are considered to result from emplacement of melt along intergranular extension fractures following the pre-existing foliation, under magma pressure exceeding the cohesion of the foliation.

On the whole, the regional tectonic context may play a major role in the development of layering at various scales, due to interactions between magma intrusion and ductile flow in the middle crust, or to magma emplacement controlled by pre-existing anisotropies, or to melt segregation under non-coaxial strain regime.

6. Discussion and conclusion

This review shows that layering structures in granitoid plutons occur at different scales and depend on the interplay between injection, magma chamber processes (hydrodynamic processes and fractional crystallization) and the regional tectonic context (Fig. 11).

(1) Injection process controls the large-scale layering (macro-rhythmic units) resulting from the aggregation of magma batches of various composition and crystal charge, and is responsible for the incremental growth of plutons. The pulsed nature of magma input is dominantly controlled by the source in relation with the regional strain field (nature of the source, rates of melting, discontinuous melt extraction, etc.). However, the large-scale organization of plutons may also depend on the existence of fractional crystallization and hybridization in deep-seated intermediate chambers or during magma ascent towards their site of emplacement, a process implicit in the restite unmixing model (Chappell et al., 1987). This raises the question of the change in the characteristics of plutons as a function of their emplacement level. Pluton-scale layering may also depend, in rather exceptional situations, on composition and thus viscosity of magmas, which may

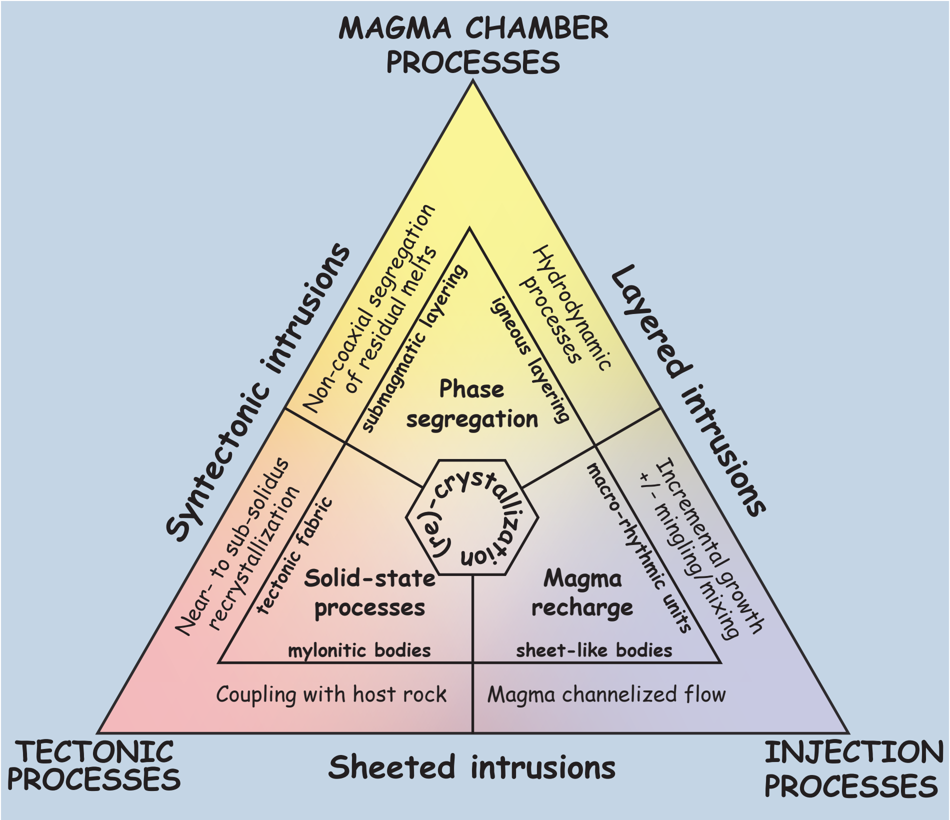

Figure 11. Synthetic representation showing the main processes involved in the construction of plutons.

facilitate crystal-melt separation and in situ differentiation (cyclic units). At outcrop scale, the development of layering and schlieren is mainly controlled by mingling (± hybridization) dynamics, which depends more particularly on the rheological state of magmas.

(2) Magma chamber processes may be efficient in the site of emplacement under specific conditions. They first depend on the frequency and volume of injections, and are therefore to some extent source-controlled, sporadic low volume pulses being less favourable to the development of hydrodynamic processes. They also depend on the thermal regime and, therefore, on the level of emplacement, very shallow-level intrusions (e.g. bysmalith) generally lacking evidence of convection, gravity flow, fractional crystallization and phase segregation. Occurrence of rhythmic layering and depositional features related to gravity- or flow-driven crystal-melt segregation does not imply large-scale convective overturn, but appears more likely as local characteristics related to density inversions, sidewall currents, eruption vents, slope failure, or small-scale convection above mafic replenishments. It is worth of note that this type of layering occurs frequently in high-K calc-alkaline granitoids, characterized by the close association of mafic and silicic magmas. The role of intensive parameters (nucleation rate, double-diffusive process), invoked in more mafic magmas, could account for the occurrence of isomodal vertical layering structures in granites, but remains to be clearly demonstrated. Fractional crystallization is probably a common process during pluton growth as shown by chemical zoning of crystals and occurrence of aplite-pegmatite segregations, though its effects are limited. In specific cases it may lead to layered series, but does not appear to be responsible for in situ differentiation of the large rock units constituting most plutons. Mineral clusters (especially K-feldspar megacrysts) can be considered to be indicative of mechanical segregation process within plutons (differential shear, logjam effect, etc.).

(3) The regional strain field may have a significant role at different stages of pluton construction, involving complex interplay between injection, deformation and crystallization. Coupled with injection, the regional strain field may control the shape of plutonic bodies leading to sheet-like intrusions, and have a major role in the development of some large-scale layering, leading to outcrop- or pluton-scale compositional layering, by foliation-parallel injection of magmas. However, it should be kept in mind that the conformable nature of granite sheets may result from tectonic attenuation. Emplacement of heterogeneous magmas may also lead to strain localization as they correspond, at the time of emplacement, to weak layers. Magma emplacement thus contributes to layering at the crust scale. Lastly, deformation has a significant role in the segregation of residual melts from the deforming crystalline matrix in syntectonic granites, leading to composite layering analogous to that observed in migmatites (deformation at the solid-liquid transition in both cases).

On the whole, layering appears as a record of the physical and chemical processes involved in the growth of granitoid plutons. The different types of layering structures, and their absence as well, may therefore bring us with useful information to decipher the processes involved in the construction of any plutonic body. Although pluton growth appears to result mainly from magma accumulation and is probably dominantly source-controlled, the relative importance of the three processes involved in the formation of plutons and layering (injection, magmatic differentiation and regional strain field) may be variable, each one being susceptible to prevail in specific plutons or in specific parts of plutons, and at specific periods of pluton growth.

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