Magma differentiation and contamination: Constraints from 2 experimental and field evidences

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Abstract

Differentiation and contamination of silicic magmas are common phenomena characterizing the granite batholiths and large igneous provinces that build up most of the continental crust. Although they can be identified by means of geochemical relations of igneous rocks exposed in the continents, the mechanisms allowing magmas to undergo the necessary crystal–liquid separation and digestion of country rocks for differentiation and contamination are poorly constrained. In this paper we show two independent approaches that are essential to understand fractionation and contamination of magmas. These are (1) the study and interpretation of field relations in exposed deep sections of batholiths, and (2) the results of laboratory experiments carried out at middle–upper crust pressure. Experiments support that fractionation is intrinsic to crystallization of water-bearing magmas in thermal boundary layers created at the sidewalls of ascent conduits and walls of magma chambers. Gravitational collapse and fluid migration are processes identified in experimental capsules. Similarly, reaction experiments in mixed capsules support reactive bulk assimilation as a plausible mechanism that is compatible with field and petrographic observations in contaminated granitic rocks.

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Abstract

Differentiation and contamination of silicic magmas are common phenomena characterizing the granite batholiths and large igneous provinces that build up most of the continental crust. Although they can be identified by means of geochemical relations of igneous rocks exposed in the continents, the mechanisms allowing magmas to undergo the necessary crystal–liquid separation and digestion of country rocks for differentiation and contamination are poorly constrained. In this paper we show two independent approaches that are essential to understand fractionation and contamination of magmas. These are (1) the study and interpretation of field relations in exposed deep sections of batholiths, and (2) the results of laboratory experiments carried out at middle–upper crust pressure. Experiments support that fractionation is intrinsic to crystallization of water-bearing magmas in thermal boundary layers created at the sidewalls of ascent conduits and walls of magma chambers. Gravitational collapse and fluid migration are processes identified in experimental capsules. Similarly, reaction experiments in mixed capsules support reactive bulk assimilation as a plausible mechanism that is compatible with field and petrographic observations in contaminated granitic rocks.

1 Introduction

Magmatic fractionation (closed system) and contamination (open system) are common processes involved in the overall differentiation of igneous rocks in the continental crust [*Bowen*, 1928]. The two processes can act jointly in magma chambers and conduits. Many silicic (SiO_2 > 53 wt%) igneous rocks, in particular those formed in active continental margins, can be modeled geochemically as resulting from a combination of assimilation and fractional crystallization (AFC) [*Bohrson and Spera*, 2001; *DePaolo*, 1981]. However, the relative contribution of each process and the mechanisms of operation in magmas remain unconstrained.
Many igneous rocks appearing in the continental crust, and particularly those richer in SiO_2, contain isotopic signatures indicating contamination with older crustal rocks [*Allègre and Ben Othman*, 1980; *Hawkesworth and Kemp*, 2006; *Kemp et al.*, 2007; *McCulloch and Wasserburg*, 1978]. Contamination may be acquired either during

ascent and emplacement in the crust, or may be inherited from an already crustal-contaminated source. Trace elements and isotopic ratios, which are regularly used to make AFC modeling, are unable to discern between the two processes. Fortunately, the major element compositions of melts are dependent on the composition of the solid saturation assemblage, which is in turn imposed by intensive variables in a given system, in such a way that the composition of melts in closed systems will follow cotectic lines that can be determined by means of phase equilibrium experiments and thermodynamic modeling. Comparisons between rocks and experimental liquids may help to distinguish open from closed magmatic systems. It is expected that open system processes may introduce characteristic departures in the composition of rocks from that of cotectic liquids. In a theoretical case, rocks belonging to a magma fractionation series will represent liquids extracted at any time in the course of crystallization. These are the so-called *liquid lines of descent* (LLD) [*Bowen*, 1928]. However, in practice, rock series may depart from the ideal composition of LLDs, even in case that the system is closed. The reason is that the extracted liquid fraction may carry magmatic crystals in suspension from a magma chamber or may drag crystals from the consolidated parts of the chamber or conduits in the way upward. These are self-contaminated liquids (Fig. 1). Similarly, the crystal rich residue left after a partial extraction of melt becomes a new magma system that neatly departs form the cotectic. This is a very common case in granitic rocks, in which a residual liquid escaped in the course of crystallization. These are called *disguised cumulates [Lee and Morton, 2015]*, as a cumulate texture is not recognized while an off-cotectic composition is identified. Magmatic differentiation by crystal fractionation is possible if either a liquid fraction is removed from the crystallizing magma or a fraction of crystals is separated away from the magma. Both process differ significantly each other and can operate under different circumstances. The virtual absence of monomineralic layering in silica-rich calc-alkaline systems, indicate that crystal settling is not a dominant mechanism.

Understanding how crystals and liquids are separated in crustal magmas requires special attention to physical and chemical features of crystallizing magmas. Most crustal magmas are characterized by high silica contents. The implication is that viscosity is much higher than that of basaltic magmas, making crystal–liquid separation difficult to achieve [*Glazner*, 2014]. However, many lines of evidence, mostly supplied by geological and geochemical relations, point to an effective fractionation in nearly closed magma systems. Solution to this paradox has been addressed by several approaches, including numerical modeling [*Bachmann and Bergantz*, 2004; *Bachmann and Huber*, 2016; *Burgisser and Bergantz*, 2011; *Gelman et al.*, 2014], analog experiments [*Michioka and Sumita,* 2005; *Shibano et al.,* 2012; 2013] and experiments with silicate melts at high pressure and high temperature (*Masotta et al.* [2012]; *Huang et al.* [2009]; *Rodríguez and Castro* [2017]). Magma crystallization in a thermal boundary layer (TBL), created for instance at the walls of magma chambers and conduits [*Rodríguez and Castro*, 2017], is the most plausible mechanisms that contributes to separation of liquids from crystals within a solidification front [*Marsh*, 2002].

Because assimilation is usually considered an energy-consuming process, its role in accounting for significant differentiation of igneous rocks has been questioned [*Bowen*, 1922; *Glazner*, 2007; *Thompson et al.*, 2002]. Energy balance is applied in terms of xenolith melting and, thus, assimilation is considered as a particular case of magma mixing [*Thompson et al.*, 2002] between melts from the xenoliths and the intruding magma. Also limiting is the assumed low temperature for the country rocks to be assimilated [*Glazner*, 2007]. However, the reach of assimilation, far from being a self-limiting process, can be enlarged in cases of hot country rocks and repeated intrusions of magma [*Glazner*, 2007]. In addition, country rock xenoliths can be disaggregated mechanically by inducing melting at low melt fractions, contributing to the so-called *reactive bulk assimilation* [*Beard et al.*, 2005] in which energy consume is minimized. The observation of contaminated rocks over kilometric extensions of plutonic intrusions from the Variscan Gredos batholith in Central Spain, which were emplaced in repeated layers into migmatitic metasediments [*Díaz–Alvarado et al.*, 2011], points to country rock assimilation as an efficient mechanism that contributes to differentiation of magmas in the continental crust. These areas provide relevant field relations that may help to understand the intricacies of assimilation. A summary of these relations is shown in this paper.

In regard of the mechanisms of assimilation, essential questions are: How is in detail the process of assimilation? How do exotic elements incorporate to the magmas? What is the scope of assimilation in nature? Answering these questions require a knowledge of the process. Although some geochemical features may be indicative of magmatic assimilation, the study of field relations between igneous intrusions and country rocks in deep-seated plutons is essential to reveal the mechanisms of magma–host interactions. Even in field-based examples, the intricacies of the processes of magma–host interaction leading to contamination are poorly constrained. Experiments are useful to set limits to possible processes involving chemical equilibrium and disequilibrium. Integration of petrological phase equilibrium relations and field-based studies are essential to discern between competing processes. Furthermore, the identification of paleotectonic environments through the geochemistry of magmas requires a wholly understanding of petrogenetic processes, contamination being a very common one and, at the same time, the most difficult to reveal. At this purpose, we present new field description from the Gredos batholith (Central Spain) that are interpreted in the light of evidences from relevant laboratory experiments on magma differentiation and crustal contamination

2 Geological and Geochemical Inferences on Fractionation

On the basis of geochemical studies, granites of the Cordilleran batholiths are linked to fractionation from an intermediate magma precursor of andesitic to basaltic andesitic composition (e.g., Sierra Nevada batholith [*Lee et al.*, 2006]; Patagonian batholith [*Castro et al.*, 2019; *Castro et al.*, 2011; *Pankhurst et al.*, 1999]). Experimental phase equilibria [*Castro*, 2019 and refs herein] also point to a similar way, adopting an intermediate precursor as the parental magma to batholiths. Even in intracontinental calc-alkaline batholiths (e.g., Caledonian Newer granites and Variscan batholiths of Iberia), whose origin points to fluid-assisted melting of the lower crust (secondary I-type granites) [*Castro*, 2019], a fractionation trend from tonalites and quartz-diorites to granodiorites and granites is observed. Curved patterns in Harker diagrams are characteristic of cotectic variations and, hence, of liquid fractionation from one or various parental magmas. By contrast, rectilinear patterns are considered as indicative of magma mixing or contamination, as they result from a mechanical mixing between two systems, namely magma–host or magma–magma. However, mixing of fractionated liquids with their cognate crystals may also produce rectilinear patterns while the system is closed to external contaminants [*Bea et al.*, 2005]. Figure 1a shows internal mixing relations between liquid and crystals in the MgO–CaO diagram, which can be taken as a proxy of cotectic variations in an ample variety of mafic and intermediate systems, including the calc-alkaline series. The two components, MgO and CaO, are preferentially partitioned into the solid saturating assemblage, which is dominated by Pl+Cpx or Pl–Amp (mineral abbreviations after *Whitney and Evans* [2010]) along a wide temperature interval from near-liquidus to near-solidus conditions. Commonly, rocks fractionated in closed systems within the continental crust evolve following the curved patterns dictated by the thermodynamic cotectic. However, rock series evolving in a closed system may plot outside the cotectic, as internal mixing between fractionated liquid and crystals from the cumulate is also possible (Fig. 1a). In sum, the geochemical inferences on fractionation must be taken with care. Only curved patterns are indicative of fractionation, as they are governed by thermodynamic cotectic variations. A better way to delimitate patterns of fractionation from those of assimilation is by plotting rocks on triangular diagrams using a multicomponent space projected onto the plane Orthopyroxene–Orthoclase–Anorthite (Fig. 1b).

In calc-alkaline plutonic systems, layered monomineralic cumulates are rare. Paradoxically, plutons are formed by rocks that display nearly-cotectic variations. Thus, where are the cumulates from which fractionated liquids were extracted? The explanation is that fractionation proceeds by expulsion of liquid from a crystallizing magma, and not by separation of crystals from the magma. The resulting cumulates are hardly identified by textures or compositions. Many diorites and gabbros of the calc-alkaline plutonic associations are “disguished” cumulates [*Lee and Morton*, 2015]. That is, they represent crystals aggregates, or mushes, that lost a residual liquid in the course of crystallization. For this reason, rocks of intermediate composition (diorites and quartz-diorites) from batholithic associations are scattered in MgO–silica and MgO–CaO diagrams. These cumulate-like diorites share the same scattered region of lower crust granulites, pointing to fractionation as an overall process responsible for the differentiation of the lower and upper continental crust [*Castro et al., 2013*].

3 Mechanisms of Liquid–Crystal Separation

Although fractionation by liquid–crystal separation is a necessary process to account for geochemical (e.g., cotectic variations in closed systems) and geological (e.g., zoned plutons) observations, the mechanisms of such a physical separation remain debated. Liquid expulsion from a crystallizing aggregate is a preferred mechanism in silicic magmas in which, individual crystal separation by gravity settling is impeded by the high viscosity of melts and the low density contrast between melt and crystals [*Brandeis and Jaupart*, 1986]. However, gravity compaction and expulsion of liquid may be encountered in the crystal-rich mush formed atop of solidification fronts. Also, the interstitial melt trapped in the mush may undergo water saturation leading to boiling and vesiculation that may force deformation and expulsion of the liquid from a crystalline aggregate. The two processes, gravitational collapse and fluid-assisted filter pressing are analyzed here.

3.1 Gravitational Collapse and Compaction

In spite of the scarce theoretical support to an efficient process of crystal–liquid separation that allows large volumes of silicic magmas to be available in the continental crust in short periods of time [*Bachmann and Huber*, 2018], it is a fact that fractionation is identified on the basis of geochemical nearly-cotectic trends [*Castro*, 2013; *Castro*, 2019], continuous variations in zoned intrusions and large volcanic eruptions of silicic (rhyolitic) magmas [*Lipman*, 1988]. The two main approaches to understand the mechanisms of silicic magma fractionation, namely analog modeling and experimental, have failed to account for the generation of fractionated liquids in the required volumes and at the necessary rate, in a time span shorter than the cooling time in the upper crust. Mechanical interaction of falling particles (crystals) in silicic magmas can occur even at low crystal fractions, leading to a “hindered” settling processes with the implication of slow rates of melt extraction [*Bachmann and Bergantz*, 2004; *Bachmann and Huber*, 2018]. An alternative mechanism is compaction of a crystal-rich matrix, which is considered as effective in increasing the rate of melt extraction [*McKenzie*, 1984]. Compaction is a common phenomenon in long-duration (> 10 days) experimental runs. We discuss below evidences from analog materials and high pressure-high temperature experiments carried out in presence of temperature gradients. These may shed light on the relative importance of gravity settling and compaction in magma chambers.

3.1.1 Analog Experiments and Modeling

Separation of liquid and crystals in the magma chambers was explained in the conceptual and analytical model of *Marsh* [1988] as due to convection beneath the *capture front*, defined as the surface separating the rigid crust and crystal mush layers (crystallinity larger than 25%) from a crystal suspension zone. According to that model, the resulting convection pattern includes crystal-laden plumes falling from the suspension zone to the deeper parts of the chamber. The analog experiments of *Michioka and Sumita* [2005] simulated a solidifying magma chamber by means of an experimental cell consisting of a thin particle layer (glass beads) at the top, overlying a thick liquid layer (glycerine solution or silicone oil). A limited zone, located at the interface between the particle-rich and the liquid-rich layers, became unstable, forming descending plumes, thereby presenting an experimental confirmation of the convection model of *Marsh* [1988]. The similar analog experiments of *Shibano et al.* [2012] extended those results to the case of a thick particle-rich layer and found that the downwelling crystal-laden plumes actually come from a dilated boundary layer located beneath a granular layer whose particles are in a jammed state. Descent of the plumes caused a cellular convection pattern within the liquid layer, which eroded the dilated boundary layer. This mechanism differs from those of compaction, Stokes settling, hindered settling, and Rayleigh–Taylor instabilities, and permits the upward migration of the liquid layer, becoming a potentially efficient process of melt transport within magma chambers. Interestingly, some of the experiments performed by *Shibano et al.* [2012] do not rule out the activity of permeable flow (compaction and hindered settling) as a secondary mechanism for liquid transport, particularly when the granular layer slides downwards as a whole, allowing the generation of a liquid-rich layer at its top. This mechanism is akin to that described by *Marsh* [2002] to explain the presence of large silicic lenses in the upper part of mafic intrusions. Finally, *Shibano et al.* [2013] advanced in the analysis of magma chamber processes simulating roof melting by means of experimental cells filled with wax and glass beads. Those experiments, which do not preclude the effects of crystallization within the magma chamber, are able to explain the generation of rhythmic layering at the bottom of the chamber, and showed that magma ascent can be a cyclical and intermittent process.

3.1.2 Compaction Experiments at High Pressure–High Temperature

Crystal accumulation is commonly observed in experimental capsules in long-duration runs of several days, overcoming the limitations imposed by the small size of crystals and the expected high viscosity of silica-rich liquids. This phenomenon allows us to simulate experimentally the role of gravity compaction and expulsion of an interstitial liquid from a crystal-rich mush and to compare the results with magmatic differentiation series. In this way, geological inferences and mechanical analysis on a possible collapse of the partially crystallized solidification front atop of magma chambers [*Marsh,* 2002], were confirmed experimentally by *Masotta et al.,* [2012] and contrasted with petrological relations of mush fragments (crystal-rich enclaves) in volcanic rocks

[*Masotta et al.,* 2016]. Another interesting experiment of crystallization, possibly accompanied by compaction, was carried out by *Huang et al*. [2009] using a natural andesite (the AGV USGS standard [*Flanagan*, 1967]) as starting material with added water, crystallizing within a thermal gradient of 600 °C. The favored interpretation was differentiation by ion migration in response to the thermal gradient [*Huang et al*., 2009]. However, the presence of monomineralic crystal layers at the bottom of the capsule indicates that compaction was an effective mechanism of differentiation by crystal–liquid separation in that experiment. It is interesting to mention that experiments with a dry andesite in a thermal gradient (ca. 300 °C) produced no significant differences in composition along the capsule, while marked differences were found in capsules with the same starting material with added water [*Rodríguez and Castro*, 2017]. Thus, the cause of element fractionation must be found in the presence of water and not in the thermal gradient. One of the experiemnts reported by *Rodríguez and Castro* [2017] was carried out with the above mentioned AGV andesite within a 30°C/mm gradient at 5 kbar in the classical vertical position of the piston–cylinder. In this arrangement, identical to the experiment by *Huang et al*. [2009], the thermal gradient within the capsule acts in the same direction than gravity. This vertical experiment was carried out as a benchmark run (Run CRV2; *Rodríguez and Castro* [2017]) to compare with horizontally arranged runs of the same study in which, thermal gradient and gravity are orthogonal (see next section). After comparison, fractionation was less effective compared with horizontal runs as crystal–liquid separation is controlled by gravity compaction and not by exsolution of a strongly fractionated (rich in silica and alkalis) fluid phase within the solidification front (see below). Nevertheless, we found interesting relations in that vertical run that merit the attention here. By contrast with the other thermal gradient experiments, in which temperature remains constant at the hot spot, in the run CRV2 [*Rodríguez and Castro*, 2017] a dynamic thermal gradient is imposed following a programmed cooling ramp of 0.6 °C/hour, representing a more realistic scenario of a cooling magma chamber or dike. A half polished section of the vertical run CRV2 is compared with a horizontal run crystallized under identical conditions but with the gravity vector arranged orthogonal to the gradient temperature vector (Fig. 2). It can be observed that crystals are mostly concentrated at the bottom of the capsule (Fig. 2b) compared with the horizontal run (Fig. 2a). Because both experiments were set at the same initial conditions and both were slowly cooled at the rate 0.6 °C/hour during 309 hours, the only explanation for the observed differences is compaction and liquid expulsion from the cumulate in the vertical run. Moreover, a thin monomineralic carapace of Amp, the *liquidus* phase of this water-rich system, is broken and collapses down leaving free space near the walls allowing interstitial liquid to scape upwards (Fig. 2e). The upper layer, containing tiny magnetite crystals, is possibly formed during intrusion of upwards moving liquid plumes. The composition of glass (quenched melt) along the capsule is fractionated. In the crystal-free zone, glasses are richer in SiO_2 and K_2O, and poorer in CaO (Fig. 2d) compared with the original composition of the AGV andesite [*Rodríguez and Castro*, 2017]. The constant composition of glasses in the crystal-free zone, within a strong thermal gradient of ~30 °C/mm (see green curve in Fig. 2b) precludes a Soret effect [*Huang et al.*, 2009] as the cause of liquid fractionation. By contrast, these results reinforce the role of gravitational instability as an efficient mechanism to produce liquid–crystal separation. In summary, application of a dynamic thermal gradient enhances fractionation of the bulk magma system accompanied by compaction of the crystal-rich mush formed at the solidification front. Moreover, the results of other compaction experiments [*Huang et al.*, 2009; *Masotta et al.,* 2016] are totally comparable as they are characterized by expulsion from the mush zone (i.e., the side walls of conduits and/or magma chambers) of a fractionated liquid that mixed with the pristine liquid ahead of the front leading to fractionation of the whole system.

3.2 Crystallization in a Vertical (Non-Gravitational) Thermal Boundary Layer (TBL)

The mechanism of compaction and gravitational collapse of a crystal-rich mush requires that the thermal gradient that creates the solidification front is closely parallel to the gravity vector. This condition is satisfied in both the roof and bottom of magma chambers for which, most mechanical models have been developed [*Bachmann and Bergantz*, 2004; *Lake*, 2013; *Marsh*, 2002]. However, the processes of magma crystallization at the vertical walls of magma chambers and the sidewalls of ascent conduits have received less attention [*Humphreys and Holness*, 2010; *Namur et al.,* 2013]. The case of vertical conduits are relevant as most intermediate magmas (e.g., calc-alkaline batholiths) that feed plutons at the upper crust have traveled tens of km from the source region of melt segregation at the lower crust or the upper mantle. In case of horizontal thermal gradients, as the sidewalls of conduits, the alternative to hindered settling and gravitational collapse is liquid expulsion by *gas-driven filter pressing* [*Pistone et al.*, 2015].

3.2.1 Effects of Volatile Exsolution

Rodríguez and Castro [2017] demonstrated experimentally that *gas-driven filter pressing is a* mechanism able to operate in a water-bearing magma crystallizing in a thermal boundary layer (TBL) in which, a continuous variation in the crystal fraction or crystallinity (X_c=crystals/crystals+liquid) from all-solid ($X_c = 1$) to all-liquid ($X_c = 0$) is established. Other properties, as magma viscosity and strength, also changes across the TBL, making the walls of magma conduits and chambers places of special relevance in the generation of textural heterogeneities in magmas [*Fernández and Castro*, 2018]. In this section, only the petrological consequences of gas expulsion and vesiculation by second boiling are explored on the basis of laboratory experiments [*Rodríguez and Castro*, 2017].

The principle is that any water-bearing liquid, the general case of calc-alkaline magma systems, will reach saturation by second boiling in the course of crystallization, in the way as water is partitioned into the remaining liquid, reaching saturation at a given state of crystallinity. The value of X_c for boiling depends on the initial water content (in wt% H_2O) of the magma (W_0) and the water solubility at the pressure of crystallization $[W_s]_{(P)}$. The fraction of water-saturated liquid (X_{sl}) is given by the expression:

$$X_{sl} = W_0 / [W_s]_{(P)} \qquad (1)$$

Water solubility is strongly dependent on pressure and weakly on temperature [*Burnham*, 1979]. A relation between pressure and solubility is obtained by second order polynomial regression of the Burnham´s solubility curve for granite liquids [*Castro*, 2013]:

$$W_s = -0.27\,P^2 + 3.54P + 0.42; \text{ (for } P < 6 \text{ kbar)} \qquad (2)$$

By substitution in Eq. (1) we get the empirical relation:

$$X_{sl} = W_0 / -0.27\,P^2 + 3.54P + 0.42; \text{ (for } P < 6 \text{ kbar)} \qquad (3)$$

From this relation it is possible to know the critical crystallinity ($X_{cc} = 1 - X_{sl}$); That is, the crystal fraction at which the remaining liquid reaches saturation. The value of X_{cc}

depends on the pressure of crystallization and the initial water content of magmas (Fig. 3). The effectiveness of boiling and vesiculation in promoting liquid expulsion and fractionation depends on the rheological state of the partially crystallized magma at the time of water saturation. At relatively high crystallinity (X_{cc} > 0.7), deformation of the rigid crust is impeded by the crystal interlocking structure of the magma. Formation of tension gashes can be formed at this state [*Fernández and Castro*, 2018]. Many aplites and pegmatites in granite plutons are true *degassing* structures. These form dikes and irregular pods in which the contacts with the host granite are at the scale of crystals, denoting that the host was a crystal-rich magma, and not a solid rock, at the time of fracturing and fluid segregation. It can be expected that fluids expelled out via fractures (dikes) from the rigid crust of a solidification front, will carry strongly fractionated components that may mix and/or dissolve into the liquid-rich area ahead of the saturation front. Such a mechanism of "fluid migration" is very efficient in granitic magmas giving rise to zoned intrusions and fractionated cupolas atop of plutons. This principle is the basis for crystallization experiments of a water-bearing magma in a thermal gradient (see below).

Depending on the initial water content and the pressure of crystallization, the magma can reach water saturation at varied crystal contents and, thus, varied rheological states within the saturation front can be found [*Rodríguez and Castro*, 2017; *Fernández and Castro*, 2018]. The most favorable state is that of a deformable mush in which the formation of bubbles can push liquid away of the crystal framework by promoting compaction of the crystal aggregate [cf. *Bachmann and Huber*, 2018]. In the case of the sidewalls of conduits, shear deformation of the solidification front may favor liquid expulsion by compaction of the mush. Many flow structures with high concentration of K-feldspar crystals can be explained by this mechanism. Outside the mush zone, in the suspension zone (X_c < 0.25), flow is controlled by the liquid phase as crystals are "floating" in the liquid with scarce mechanical interactions. Moreover, water saturation can only be reached in the suspension zone in anomalous cases of high initial water contents and very low pressure (Fig. 3). For a magma to reach saturation at X_c < 0.5 at the pressure of 3 kbar, the initial water content must be higher than 6 wt% H_2O.

The most favorable mechanical conditions for water saturation and vesiculation to effectively promote the expulsion of liquid from the crystalline framework, are found within the rigid crust (X_{cc} > 0.55), within a critical zone of X_{cc} from 0.6 to 0.7, for magmas with initial water content W_0 > 3 wt% [*Pistone et al.*, 2015]. These critical conditions can be encountered within a wide range of pressure from 3 to 6 kbar (Fig. 3). For shallower conditions (P < 2 kbar), low initial water contents (W_0 < 3 wt%) are required to get X_{cc} within the critical zone of rigid crust of a solidification front. In sum, the rheological state of the magma must be deformable at the time of melt water saturation to promote liquid expulsion. At values of X_{cc} > 0.7 the rigid crust can experience hydraulic fracturing and segregation of a water-saturated melt.

3.2.2 Magma Splitting in a TBL: An Experimental Finding with Implications

The sidewalls of magma ascent conduits represent large transient interfaces along which magma looses heat to the surrounding host with the consequent generation of thermal boundary layers (TBL) along several tens km from the region of magma segregation to the final level of emplacement. It is inferred that these large TBL structures play an important role in magma differentiation during ascent; particularly in the case of water-bearing magmas as water saturation will be encountered within the TBL. All phenomena referred to above in the previous section can operate along the conduits. The main inference for differentiation in TBL at the conduits comes from the presence of autoliths in granite (sensu lato) plutons. It has been demonstrated that most mafic microgranular enclaves characterizing calc-alkaline batholiths are true autoliths and not fragments from synplutonic dikes [*Paterson et al.*, 2016; *Žák and Paterson*, 2010]. Autoliths represent eroded fragments from different parts of the TBL (chilled margins) of conduits. All textural observations in autoliths, as the fine-grain size, the presence of resorbed crystals of plagioclase, the presence of double enclaves, together with the observed geochemical and isotopic features [*Rodríguez and Castro*, 2019], are supporting such an interpretation. A mechanical analysis of the rheology of conduits at the TBL accounts satisfactorily for the observed field relations, shape and size of autoliths [*Fernández and Castro*, 2018].

Rodríguez and Castro [2017] carried out experiments to simulate the crystallization of a water-bearing magma in a vertical TBL representing the sidewalls of conduits. The results constituted a significant finding: The liquid ahead of the solidification front is fractionated only if water is present as an initially dissolved phase in the magma [*Rodríguez and Castro*, 2017]. Under identical conditions, runs with dry compositions produced no differentiation effect on the liquid phase. Other interesting result is the sharp boundary between the crystalline zone (the solidification front) and the liquid. The consequence is that a water-bearing magma splits into two systems with a compositional jump. One system is a differentiated liquid and the other is a crystal-rich mush (Fig. 4). The latter is comparable to natural autoliths [*Rodríguez and Castro*, 2019].

In sum, differentiation in a TBL is interpreted as the result of liquid expulsion from the solidification front in the course of crystallization and water saturation. The liquid ahead of the solidification front is modified by two combined phenomena, namely the expulsion of a water-saturated liquid and the arrival of fluids released by boiling and vesiculation. Because the system under study is a high-silica andesite (the AGV standard), the residual water-saturated liquid has the minimum composition of the granite system. This residual melt will be mixed with the pristine liquid ahead of the TBL leading to its fractionation. The change in the composition of the system has been modeled by using the general equation for *in-situ crystallization* [*Langmuir*, 1989]:

$$C_M = C_0\, F^{(f_A(E-1)/(f_A-1)} \qquad (4)$$

Where C_0 is the initial magma composition (in this case the standard AGV andesite), F is the fraction of melt (liquid / liquid + crystals), f_A is the fraction of liquid returned to the magma from the solidification front, and E is the partitioning coefficient, in this case taken as the ratio of the composition of the saturated liquid in the element of reference (C_{SL}) to the composition of magma in the same element of reference (C_M). The composition at any distance from the wall, after separation of the cumulate, requires integration over discrete increments of magma crystallization in which, F, E and f_A must be recalculated for every increment (Δ) of magma crystallization. We have introduced a restriction in the equation to calculate the amount of solid fraction at which the intercumulus liquid is expulsed from the crystal-rich mush. That solid fraction (1-F), or cumulate, at every discrete increment (Δ) is determined by the fraction of saturated liquid (X_{sl}), which is dictated by the ratio of the water content of magma (W_0) to the water content at saturation (Eq. 1). An iterative calculation at fixed increments of a unit volume of magma allows us to know the composition of the modified liquid ahead of the solidification front and, by simple mass balance, the composition of the solid residue. A plot of silica content of the modified liquid versus the fraction of remaining magma is shown in Fig. 5 for three values of initial water content (W_0) of 2, 3 and 5 wt% H_2O and at pressure of 5 kbar. Because water saturation is key in determining the fraction of saturated liquid that is available to modified the pristine liquid, it is clear that the effect of fractionation is higher for systems containing the higher initial content of water (W_0). For values of $W_0 = 5$ the modified liquid reaches minimum silica values ($SiO_2 > 63$ wt%) of granitic rocks when only 20% of the whole magma is crystalized. However, magma with initial water content $W_0 = 3$ must crystalize about 50% of its initial volume to produce a fractionated liquid with $SiO_2 > 63$ wt%. Interestingly, the composition of cumulates remains almost constant compared with the continuous changing compositions of liquids. In nature, cumulates are represented by the fine-grained microgranular enclaves interpreted as autoliths, whose composition is very uniform within a particular pluton. Also notice that the most fractionated magma ($W_0 = 5$) yields the most mafic (less silicic) cumulates.

4 Magma Contamination by Country-Rock Assimilation

Contamination can be seen as an open-system mechanism of magma differentiation in the crust; as in the most general case contaminants are richer in evolved components, as alkali elements and silica, than the pristine magmas. Contamination may proceed in two ways that are not exclusive each other: (1) Assimilation of country rocks and (2) contamination by fluids derived from the host. Although contamination can be traced by means of isotopic ratios, source contamination can be difficult to distinguish from crustal-related processes. Fluids released by prograde metamorphic reactions in the thermal aureoles of plutons may expectedly contaminate the intruding magmas. However, this process is rarely identified in plutonic intrusions. Assimilation is the most documented process in crustal intrusions. Partial or total digestion of country rocks by the intruding magma is intrinsic to assimilation as an efficient mechanism that contributes to the contamination of magmas in the continental crust.

Although contamination by country-rock assimilation can be identified in geochemical diagrams, the intricacies of the process can be varied. The study of field relations in plutons is essential to constrain possible mechanisms. Experimental studies on magma–rock interactions are also relevant to test reactions and mineralogical implications and to assess the feasibility of assimilation on a regional scale. The two ways, field relations and experiments, are explored here on the basis of recently developed studies.

4.1 Field Relations Supporting Assimilation and Magma Contamination

Contamination of magmas with their host rocks can be identified easily by means of geochemical and isotopic relations. Paradoxically, although intermediate and silicic magmas have travelled long distances through the crust until their final storage in magma chambers or plutons and volcanic eruptions, not all silicic rocks are contaminated in the same extend and many of them maintain their pristine composition. There will be scenarios in which magma-host interactions are favored. Assimilation not only depends on the reactiveness between magma and country rocks but on the dynamics of ascent and emplacement and the rheological behavior of the two systems. An approach to the mechanical processes leading to assimilation of country rocks, and the consequent contamination of intruding magmas, can be made on the basis of field relations in areas on intense assimilation. A summary of these relations, based on relevant exposures of hybrid granites from the Gredos batholith (Central Spain), is shown in this section.

The Gredos batholith has been revealed during the last decade as one of the most outstanding and voluminous granitic exposures (more than 300 km in length and 60 km in width) to explore the interactions between intrusive magmas and a medium- to high-grade crustal sections. The batholith is mainly composed of Bt ±Crd granodiorites and monzogranites and minor amounts of basic rocks [*Scarrow et al.*, 2009] that depict a K-rich calc-alkaline suite characteristic of I-type post-collisional batholiths [*Castro*, 2019], emplaced during late D2 and D3 Variscan phases (320-290 Ma) [*Díaz Alvarado et al.*, 2013; *Díaz–Alvarado et al.*, 2011]. Detailed studies of the central area of the batholith have evidenced a laminar structure formed by mostly migmatitic host-rocks and intrusive layers. The conspicuous magmatic fabrics (foliations, lineations, folds and shear zones) are continued through the migmatitic structure of the host-rocks, which involve the synkinematic and sequential emplacement of intrusive magmas assisted by crustal-scale extensional shear zones, as have been revealed by structural and U–Pb geochronological studies [*Díaz Alvarado et al.*, 2013; *Díaz–Alvarado et al.*, 2012]. These characteristics of the emplacement process reinforced the long-lasting and close interaction between magmas and partially melted host-rocks that promoted the intense mingling and, finally, the chemical hybridization between both systems.

Geochemical, field and experimental evidences have shown that the hybridization between an intrusive magma and its host rock is an effective mechanism of magma diversification during its ascent and emplacement [*Beard et al.*, 2005; *Díaz–Alvarado et al.*, 2011; *Erdmann et al.*, 2007]. The high diffusivity of some elements (e.g., the alkali elements) may favor the crystallization in the magma of particular phases, like Kfs, in areas far from the external contacts of the pluton with the host rocks [*Díaz–Alvarado*, 2017; *London et al.*, 2012]. However, Al-rich phases present in calc-alkaline granodiorites, like Crd and Grt, are diagnostic of assimilation processes and only appear in reactive domains where metasedimentary xenoliths were consumed or at least they lost their integrity (Fig. 6). In those cases, the original mineralogy of the xenoliths has been in part consumed by peritectic melting reactions to yield residual and peritectic minerals plus a granite melt, and in part is dispersed and camouflaged within the host magma. The only mineral species that can be considered exotic, in the sense that they are not present in the pristine magma, are the peritectic phases, cordierite or garnet. The amount of assimilated material in hybrid granites can be estimated by mass balance using the fraction of Crd [*Díaz–Alvarado et al.*, 2011; *Erdmann et al.*, 2007].

The main conditioning factor for this process is the effectiveness of the heterogeneous interaction process between the partially crystallized magma and the partially molten metasedimentary host rocks. The rheological characteristics of both systems tend to approach during the emplacement process, that is, while the migmatitic system increases its melt percentage and the magma continues its crystallization process (e.g. [*Vigneresse et al.*, 1996]. The driving forces of the emplacement process, including the stress state and the tectonic evolution of the crust, trigger the joint flow and deformation of the two systems, which yields a number of heterogeneous structures at all the scales [e.g. *Paterson et al.*, 2018; *Paterson et al.*, 1998], that are evidenced by the observed field relations (Fig. 7). Those structures can be ascribed to the following mechanisms of mechanical interaction between intruding magma and host rock: (1) Viscous folding; (2) Host-rock dragging; and (3) Migmatitic tearing apart. These structures can be ascribed to the following mechanisms of mechanical interaction between intruding magma and host rock: (1) Viscous folding (Fig. 7a–d); (2) Host-rock dragging (Fig. 7e); and (3) Migmatitic tearing apart (Fig. 7f).

4.1.1 Viscous Folding and Shearing

Complex fold geometries and distinct types of brittle and ductile shear zones are the most common structural features in migmatitic terrains [e.g. *Hopgood*, 1999]. In the case of a migmatitic crust intruded by a partially crystallized magma whose viscosities approach during the evolution of both systems, the development of ductile deformation structures such as folds and shears considerably increases the contact surface between both systems and the isolation of host rock fragments within the intrusive magma (Fig. 7a, b). This process has been shown as a necessary condition for the complete hybridization that results in contaminated magma [*Gogoi and Saikia*, 2018]. Assimilation through reaction of host-rock fragments implies the successive injection of low crystal fraction magma batches, simultaneous development of assorted structures under a viscous but evolutionary regime, melting reactions and chemical diffusion. Therefore, deformation of the complex, composite system may be achieved through a mechanism of viscous folding, which implies a viscosity contrast between magma and host rock bodies (Fig. 7c, d) [e.g., *Biot*, 1961; *Chapple*, 1968; *Johnson and Fletcher*, 1994; *Ramberg*, 1961]. It is expected a viscosity switch along the interaction process, such that the less viscous unit at the very beginning of the interaction process (i.e., the intruding magma) becomes the more viscous one as it crystallizes, generating a very complex and heterogeneous set of folding structures. This is evidenced by the complex arrangement of Kfs megacryst fabrics that results firstly from the flow and interaction of crystals in a fluid flow and the subsequent orientation of the same rigid particles according to the contacts and the stress regime in a highly crystallized magma (Fig. 7a, b).

4.2 Experiments on Contamination

One of the most outstanding criteria to identify a process of assimilation is the presence of the peritectic phase Crd and/or Grt, which formed by fluid-absent (dehydration) partial melting of pelitic metasediments, in a non-anatectic granodiorite or monzogranite. A proof that Crd is not in equilibrium is such Ca-rich granite magma composition is supplied by experiments with a Crd-bearing monzogranites, as these failed to reproduce the Crd-bearing assemblage observed in nature [*García–Moreno et al.*, 2017]. These experiments were performed using a synthetic glass with the composition of a Crd-bearing peraluminous monzogranite of the Iberian Massif. This is the Cabeza de Araya granite, whose composition is taken as representative of the so-called “mixed granites” [*Capdevila et al.*, 1973], characterized by sharing features of typical anatectic granites (S-type) and Bt-granodiorites (I-type). Crd-bearing monzogranites appear in the Variscan belt of Iberia as isolated intrusions or as large irregular domains inside calc-alkaline granodiorite batholiths. The origin of these "atypical" granitic series has attracted much attention from petrologists over decades. We contend on the basis of geochemical, geological and experimental grounds that they are the products of crustal contamination by pelitic and semipelitic host rocks. In the case of Cabeza de Araya intrusion [*Corretgé*, 1971], the Crd-bearing monzogranites are located at the margins of the pluton. These represent the less evolved rocks that gradually transition into the central parts composed of two-mica granites and aplitic leucogranites. Emplacement age of the Cabeza de Araya granites obtained by SHRIMP lies between 308±1.5 Ma and 305±2 Ma for the different facies that compose the batholith [*Rubio–Ordóñez et al.*, 2016].

Large prismatic crystals (1 to 4 cm) of cordierite (Crd) are the most distinguishing feature of these "mixed" granites. The presence of Crd in this kind of granites has been interpreted as result of a peritectic reaction in the local domain of the xenoliths after wall-rock assimilation [*García–Moreno et al.*, 2017]. Interestingly, the outer zone of the pluton, in contact with the pelitic metasedimentary host, is the richer in Crd. The abundance of mafic microgranular enclaves (autoliths) and xenoliths is also greater in the margin zones compared to the inner parts. The inferences from field relations were tested with varied experimental designs using that and similar compositions.

Experimental approaches to test contamination processes are rooted in field and geochemical relationships in large composite batholiths, which point to physical and chemical interactions between the intruding magmas and its host rocks during ascent and emplacement [e.g. *Beard et al.*, 2005; *Díaz–Alvarado et al.*, 2011; *Erdmann et al.*, 2007; *London et al.*, 2012]. Different experimental procedures and strategies have led to relevant conclusions about diffusion and reactions between both subsystems.

4.2.1 Selective Assimilation Experiments

Experimental simulations in granodioritic and monzogranitic systems have shown that Crd or Grt do not precipitate during crystallization sequences, even when synthetic starting materials representing the whole composition of Crd- or Grt-bearing granitic rocks are used [*Díaz–Alvarado*, 2017; *García–Moreno et al.*, 2017]. The addition of aluminous phases to experimental capsules simulates the usual presence of And-, Sill- or/and Crd-rich restites in the migmatitic contact zones of intrusive bodies [*Acosta–Vigil et al.,* 2002*; Díaz–Alvarado et al.*, 2011]. Local domains are observed around xenocrysts in doped experiments, resembling reactive zones of high Al activity in melts around crystals or along layered contacts [*Acosta–Vigil et al.,* 2002*; Díaz–Alvarado et* *al.*, 2011; *García–Moreno et al.*, 2017], but far from the conditions expected for the massive crystallization of large euhedral diagnostic phases as Kfs and Grt or Crd. The dissolution of exotic phases is goberned by the mineral reaction rates and diffusion through the melt, besides other conditions as H_2O content and convection [*Acosta–Vigil et al.*, 2002, 2006]. Nonetheless, the above mentioned experiments show the resilience of exotic xenocrysts in the intrusive magmas and the presence of local reactive domains.

4.2.2 Layered Experiments

Reaction at the interface between metasedimentary rocks and granitic melt (granodioritic or haplogranitic depending on the experimental study) indicate that homogenization took place for particular components as K, Na and H_2O between partial melts at both sides of the interface [*Díaz–Alvarado*, 2017; *Erdmann et al.*, 2007; *London et al.*, 2012]. The melt percentage increases in the pelitic system as it shifts to a more haplogranitic composition (Erdmann, London op cit.). Two-layer experiments represent static situations, being the crystallization of diagnostic phases restricted to a narrow zone close to contact [*Erdmann et al.*, 2007; *London et al.*, 2012]. However, the application of these results to the dynamic scenario of an ascent conduit, in which the narrow zone of contaminated magma is continuously removed by flow, contamination can be effective for large volumes of magma feeding an upper reservoir or pluton. Contaminated granites can occupy large areas of zoned plutons. The process can demise with time as the later magma pulses use the core of conduits and are prevented of contamination. This, combined with increasing fractionation in conduits by crystallization in a TBL (see above), can be a plausible explanation to many zoned plutons in which the most contaminated and most mafic granites are disposed at the outer rims, and the less contaminated and more felsic types are at the core.

4.2.3 Bulk-Assimilation Experiments

Bulk assimilation [*Beard et al.*, 2005] has been reproduced experimentally by introduction of pelitic fragments into a granodiorite powder (Fig. 8) [*Díaz–Alvarado et al.*, 2011], with significant implications for the linkage of this assimilation mechanism with geochemical and mineralogical changes observed in large batholiths [*Díaz–Alvarado et al.*, 2011; *Saito et al.*, 2007]. Partially disintegrated xenoliths are still recognizable in the experimental runs (Fig. 8). Partial melts inside and far from the xenolith domain still have important compositional differences (Al, Mg#) except for the alkalis, expelled from the xenoliths towards the granodioritic host, with the consequent enrichment in K and the early crystallization of Kfs, denoting a sort of mixing between the granodioritic and the xenolith-derived melts [*e.g. Díaz–Alvarado*, 2017; *Massota et al.,* 2018]. As in the layered experiments, euhedral Crd and Kfs are crystallized along the reactive xenolith area [*Díaz–Alvarado et al.*, 2011]. A dynamic scenario, as it was mentioned above, may contribute to disaggregation of xenoliths, leading to total digestion and dissemination of minerals within the intruding granite. Xenocrystic Pl, Bt or Qz are camouflaged in the contaminated magma, the euhedral Crd (Fig. 8) remaining as the only diagnostic mineral of the bulk assimilation, as described in natural examples (Fig. 6). However, a rapid segregation of interstitial melts in the crustal xenoliths may inhibit mineral–melt equilibrium and prompt the zonation of residual minerals [*Massota et al.,* 2018].

Although a significant percentage of the assimilated material gained by the contaminated magma is unrecognizable, it is possible to assess the extend of assimilation by measuring the abundance of Crd in the contaminated granites [*Díaz–Alvarado et al.*, 2011]. The results show that the assimilated material is approximately five times the proportion of Crd. This figure depends on the amount of pelitic components (Al, Fe, Mg) of the contaminant; the more pelitic the less fraction of contaminant in the final hybrid rock. Mass balance calculations and other approximations through Sr–Nd isotopic ratios are in agreement with these results [*Clarke et al.*, 2004; *Díaz–Alvarado et al.*, 2011; *Erdmann et al.*, 2007; *Fowler et al.*, 2001; *Ugidos and Recio*, 1993].

Batholithic examples, as the Gredos batholith (Iberian Massif), show that hybrid magmas may contain between 50% and 10% of assimilated material, depending on the proximity to the metasedimentary host, which fits well with the volume of Crd and Kfs estimated in the contaminated rocks [*Díaz–Alvarado et al.*, 2011]. The layered structure of the batholith and the coherent and tectonically induced viscous deformation of intrusive magmas and migmatitic host-rocks favored the increase of the contact surfaces between both subsystems, which has been proven essential for the efficacy of bulk assimilation. Besides, the sequential character of the emplacement process involves a long-lasting high-grade area in the host crust. The similar crystallization ages obtained from intrusive magmas and anatectic leucogranites [*Díaz Alvarado et al.*, 2013] formed and locally segregated in the migmatitic host-rocks, imply that both the intrusive magmas and partially melted metasediments sustain a similar, albeit changing, rheologic state during their heterogeneous and intense interaction, triggering the geochemical and mineralogical changes that are characteristic of the assimilation process and similar to the experimentally proved conditions that favor magma mixing [*Laumonier et al.*, 2014a, b].

5 Concluding remarks

Differentiation and contamination are common processes in continental environments. On a large extent the fractionated character of the continental crust with respect to the underlying mantle is in sum the result of a protracted process of combined differentiation and contamination. The latter is particularly relevant if available contaminants are terrigenous metasediments, as these represent substantial geochemical fractionation imposed by surface weathering. In most cases isotopic relations are good indicators to distinguish between fractionation (closed systems) and contamination (open systems). However, understanding the mechanisms that lead to magmas to fractionate and/or to assimilate portions of country rocks, requires a deep knowledge of complex magma systems. Two approaches, experimental and geological, have been used in this paper to address the problem.

Field evidences from the Gredos batholith (Central Spain) support that assimilation of pelitic metasediments caused the formation of Crd in local domains of the intrusive granodiorite (calc-alkaline) magmas. Partial digestion of pelitic migmatites is common at the contacts, where Crd formed by peritectic melting reactions in the pelites in the course of xenolith disaggregation. These reactions are confirmed by means of laboratory experiments using magma–pelite heterogeneous systems at conditions of granodiorite emplacement of 850 °C and 4 kbar. Experiments reported that Crd is not reproduced otherwise by crystallization of a glass with composition of a Crd-bearing monzogranite. These results reinforce the idea that Crd in non-anatectic monzogranites and granodiorites is in equilibrium within local subsystem created by assimilation of country rock xenoliths. The existence of a thick (>5 km) sequence of Neoproterozoic pelites and greywackes, as the regional host of Variscan batholiths, is the reason for the conspicuous presence of Crd in varied types of granites from tonalites to monzogranites. For the same reason, anatectic leucogranites with primordial (peritectic) Crd are so abundant in Iberia. Granites emplaced into older igneous, either volcanic or plutonic, host rocks are less prone to undergo contamination. This is the general case of the Cordilleran granite batholiths. In sum, the reactiveness of the host is a fundamental factor determining the feasibility of assimilation and contamination. Pelites are the most reactive systems and the formation of Crd in non-anatectic granites is diagnostic in such cases.

In regard of differentiation, our experiments in a thermal gradient or thermal boundary layer (TBL) are conclusive about the role of dissolved water in the magma in the separation of crystal and liquid, a necessary process to account for the origin of rock series that are linked to a parental magma by fractionation. Experiments with a natural andesite in horizontal capsules, not affected by gravitational processes, produce an interesting phenomenon that may help to understand geological and geochemical observations. This is we call *splitting*. Basically, a water-bearing magma crystallizing in a TBL is broken in two subsystems with a sharp boundary between them. One subsystem is formed by a crystal-rich aggregate, whose composition resembles the fine-grained microgranular enclaves that commonly appear in calc-alkaline batholiths, and the other subsystem is a fractionated liquid. The latter showing a composition that resembles that of the calc-alkaline granodiorites and granites. As enclaves are mostly autoliths, they represent magmas fragments with high crystal contents that are dragged from walls of ascent conduits. In this sense, we contend that conduits may have a primordial role to produce magmatic differentiation in the crust. We found that a plausible cause for liquid expulsion form the partially crystallized mush at the TBL is boiling and vesiculation, as water saturation is necessarily encountered at any point of the solidification front generated in a TBL. Vertical experiments, in which the thermal gradient and gravity acceleration vector are parallel, yield that crystal settling can be impeded by solid particle interactions, but that gravitational collapse of magma mushes from the top of the solidification front is possible.

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Captions to figures

Figure 1. Geochemical variation plots, taken as proxies of phase diagrams, depicting possible arrays of fractionation and contamination in calc-alkaline magma systems. (**a**) The CaO–MgO diagram showing the curved array of experimental cotectic liquids (orange dots) and their corresponding solid assemblages (blue hexagons) formed in equilibrium at 3 kbar from an andesitic parental magma [*Castro 2013*]. The orange field below the cotectic line represents the area of magmas that carry crystals from the cumulate. The blue area represents the field crystal mushes that retain a liquid fraction after extraction. Many rocks in batholiths plot in the two areas indicating that fractionation is not perfect. Also shown as the lines of contamination with metasedimentary rocks in case of open systems. (**b**) Projected space in the diagram Opx–An–Or showing cotectic lines from experimental liquids at varied conditions of pressure and water contents Rocks of the Gredos batholith in Central Spain are shown as an example. These plot in part in the array of fractionation and in part in that of assimilation (Modified from *Castro,* 2013]).

Figure 2. Electronic compositional images (backscattered electrons) and compositional relations of a vertically arranged experimental run simulating magma crystallization in a thermal gradient at 5 kbar. (**a**) Capsule section from a horizontally arranged run at the same conditions of the vertical run (**b**). The thermal gradient of the assembly is shown in (**b**) with a green curve and green diamonds from double thermocouple measurements. The dashed curves L_0 in (**b**) represent the liquidus temperature taken from run CRH5 (See Fig. 4a). (**c**) Phase map of the bottom part of the vertical capsule (**b**). (**d**) Compositional profiles of glasses (quenched liquid) along the vertical capsule. (**e**) Interpretation of gravitational collapse of the upper carapace and liquid expulsion at the bottom of the vertical capsule. The dashed curve represent the theoretical position of the liquidus in the absence of gravity collapse (**a**).

Figure 3. Plot of critical crystallinity (X_{cc}=1–X_{sl}) versus initial water content (W_0) of a granitic liquid using Eq. (3) at variable pressures from 3 to 6 kbar. The critical crystallinity represents the crystal fraction at which the remaining liquid reaches water saturation and boiling. The three zones of the solidification front (suspension, mush and rigid crust) are marked using the boundaries given by [*Marsh*, 2002]. The most

favorable conditions to promote crystal–liquid separation by fluid-assisted filter pressing according to experiments [*Pistone et al.*, 2015] are also depicted.

Figure 4. (**a**) Mosaics of backscattered electron images from two polished sections of runs CRH5 and CRH4 with the AGV andesite (Rodríguez and Castro, 2018) using the thermal gradient imposed by the experimental assemblage. Initial conditions are P=5 kbar and T=1200 °C at the distance 0–3 mm from the thermocouple. CRH5 was quenched after 315 hours at the initial conditions. The liquidus (Cpx) is set approximately at 980 °C. In CRH4 T was dropped at the rate of 0.6 °C/hour during 308 hours (until 1016 °C at the thermocouple). The composition of glass (quenched liquid) at 2 mm of the thermocouple is more fractionated (richer in K_2O and SiO_2 and poorer in CaO and MgO) in CRH4 compared with CRH5, in which no gradient was applied. (**b**) Field photographs of partially dismembered autoliths from the Gredos batholith in Puente del Congosto (Central Spain).

Figure 5. Variation in the silica content of liquids (in a unit magma chamber) that are modified by influx of residual water-saturated liquid coming from the solidification front (thermal boundary layer) at the sidewalls. Liquid curves are calculated with Langmuir's equation [*Langmuir, 1989*] for in-situ crystallization (See text for further explanations).

Figure 6. Field relations of partially digested pelitic xenoliths enclosed in calc-alkaline monzogranites and granodiorites of the Gredos batholith (Central Spain). (**a**) Large xenolith of partially molten (migmatite) metasediments showing irregular contacts. (**b**) Detail of another xenolith showing the concentration of large Crd crystals (dark dots) around the contacts. (**c**) Sketch in two stages showing the possible digestion of xenoliths by peritectic melting reaction and the formation of Crd (green dots) and Kfs that appear finally disseminated in the contaminated zones. The arrival of K to the pristine granodiorite shifts the composition of the final contaminated magma to monzogranite.

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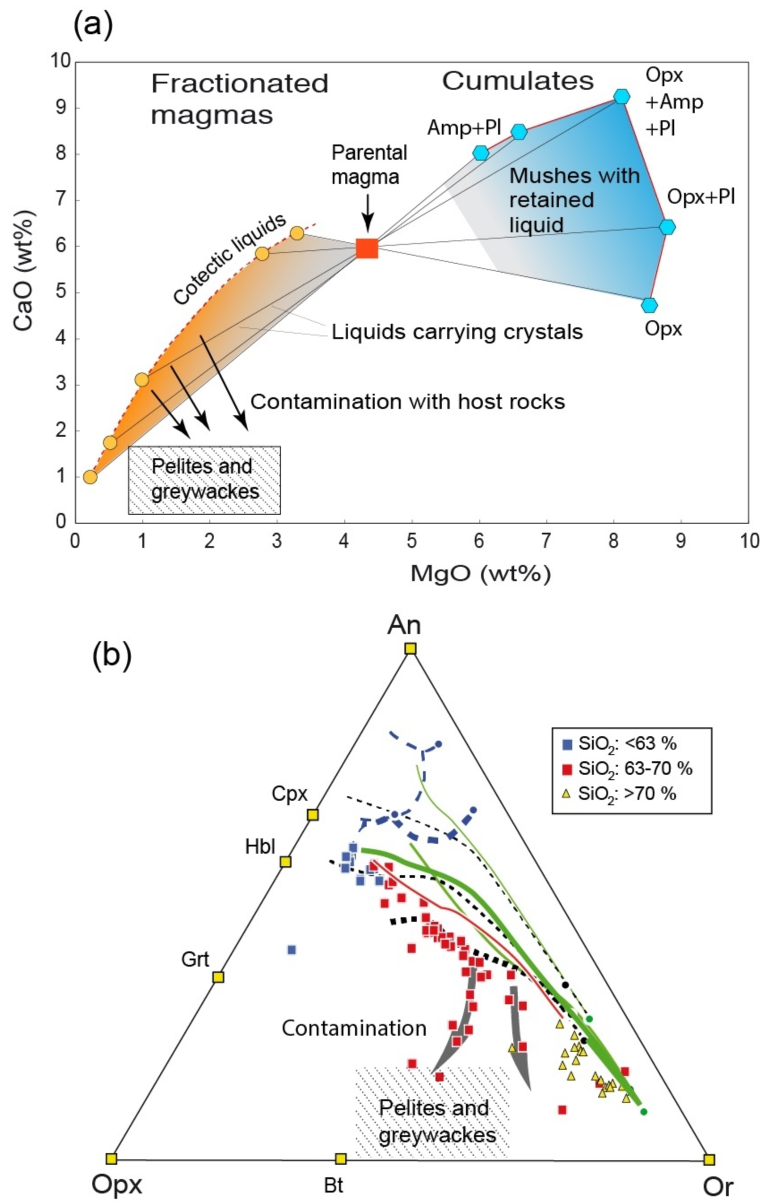

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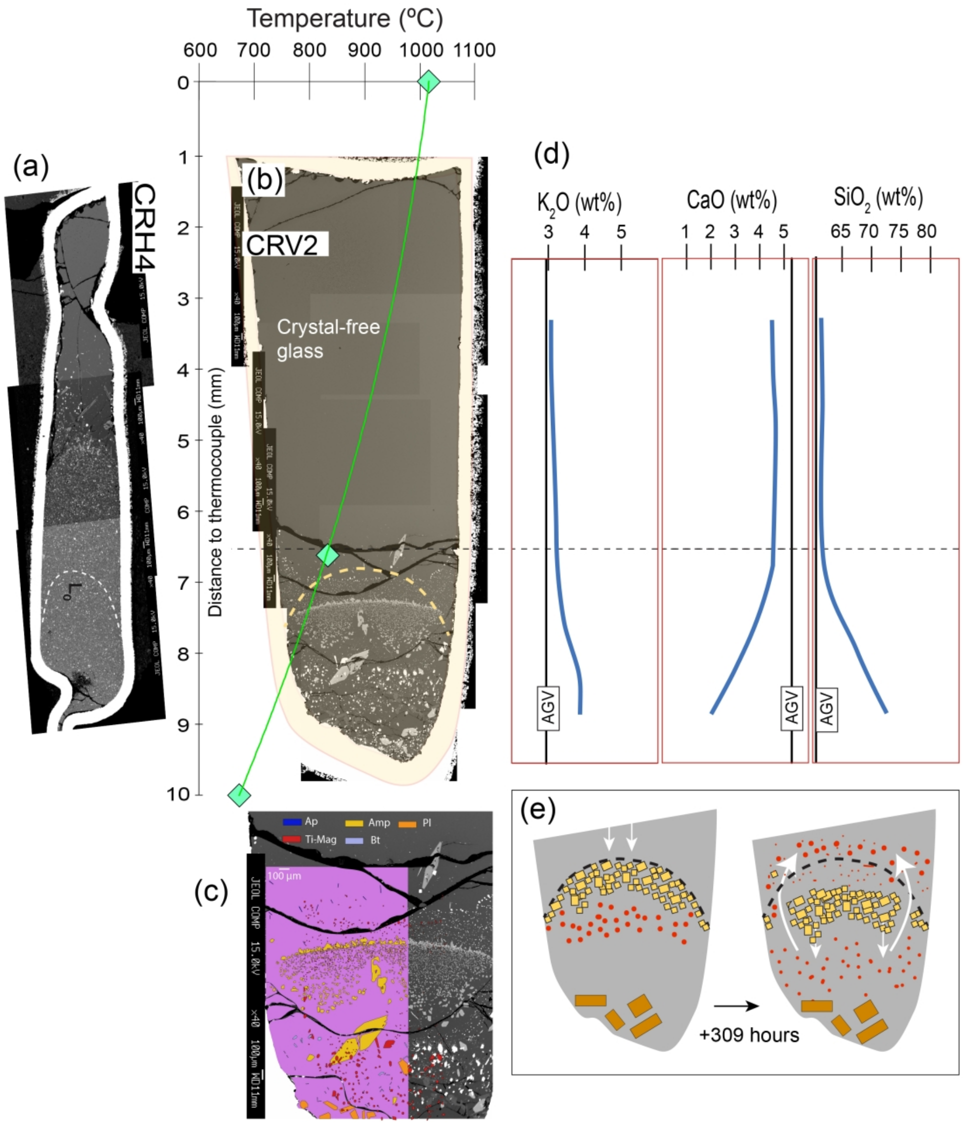

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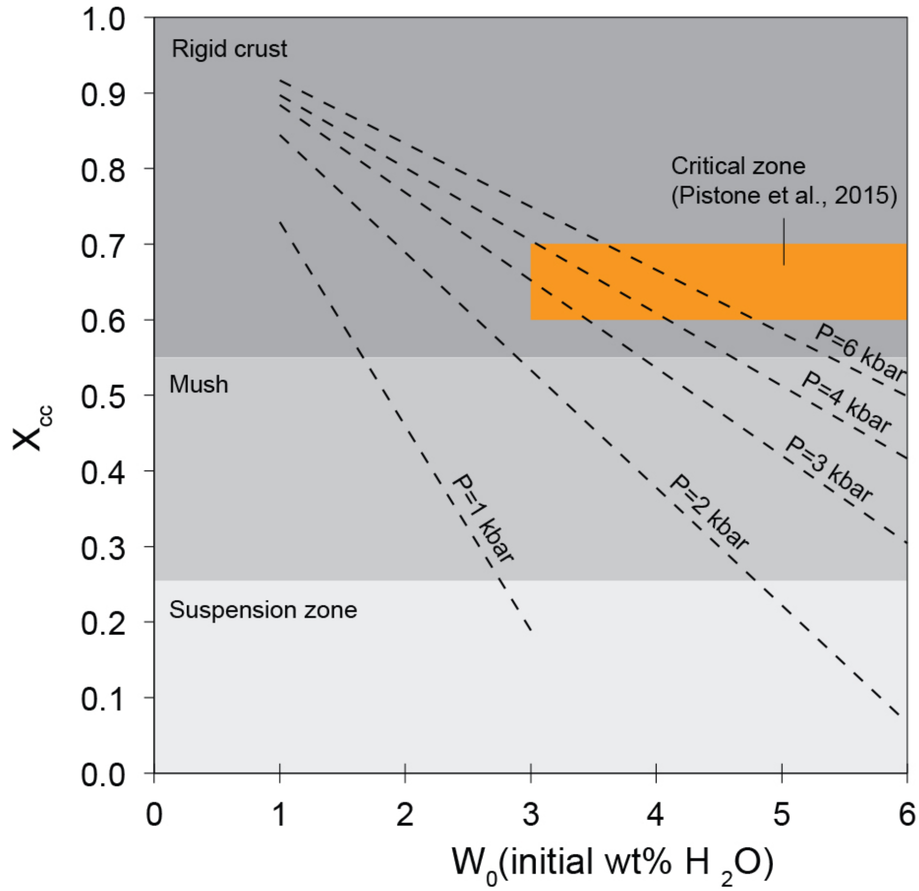

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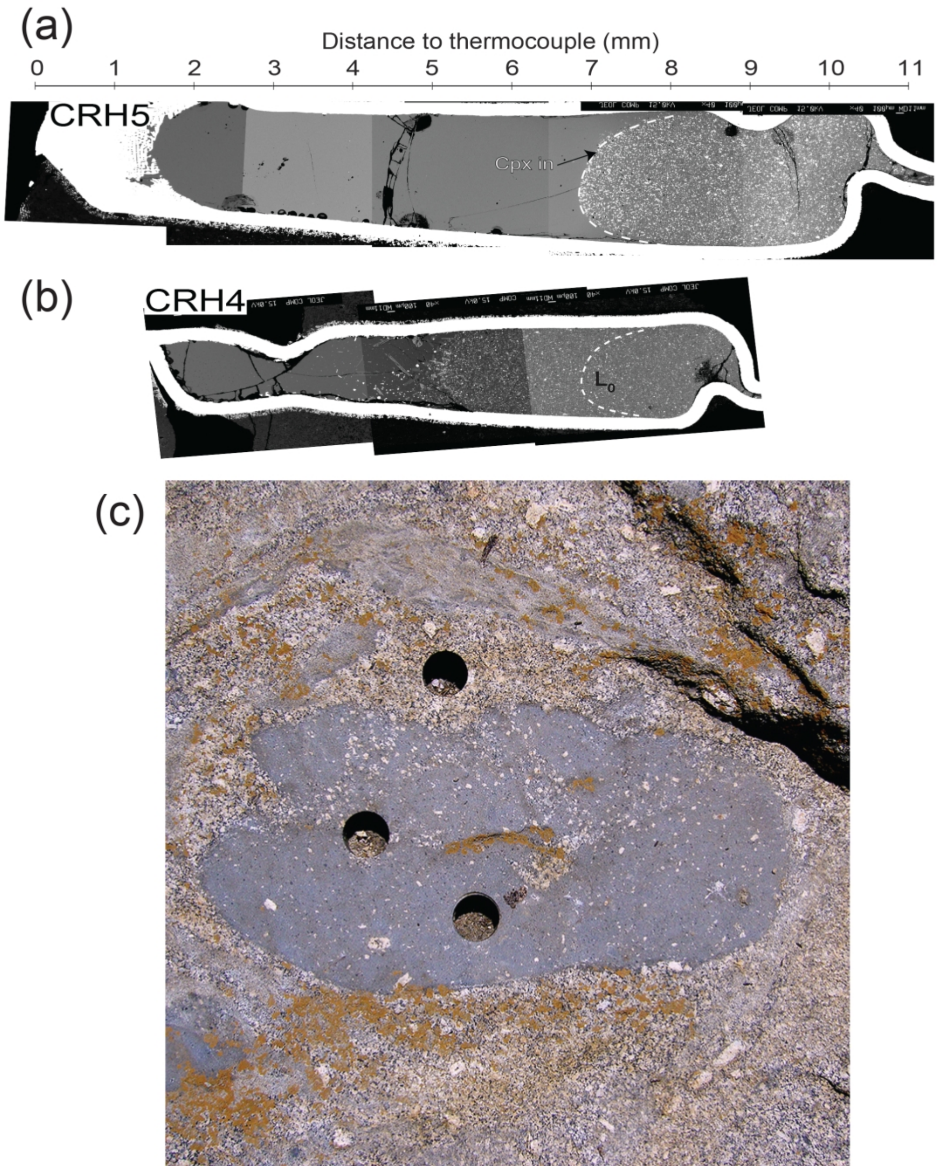

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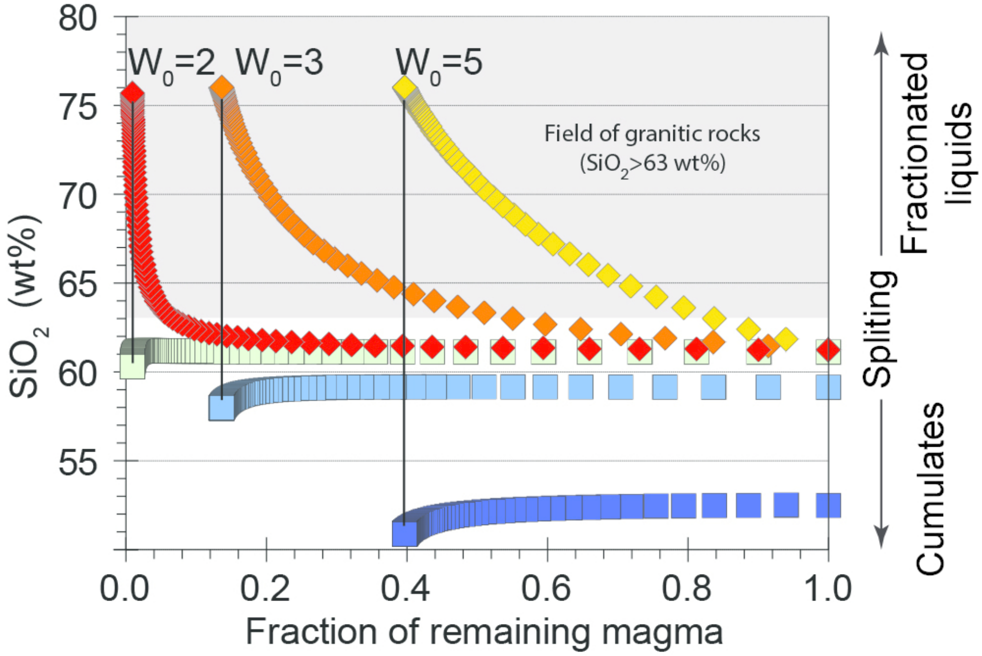

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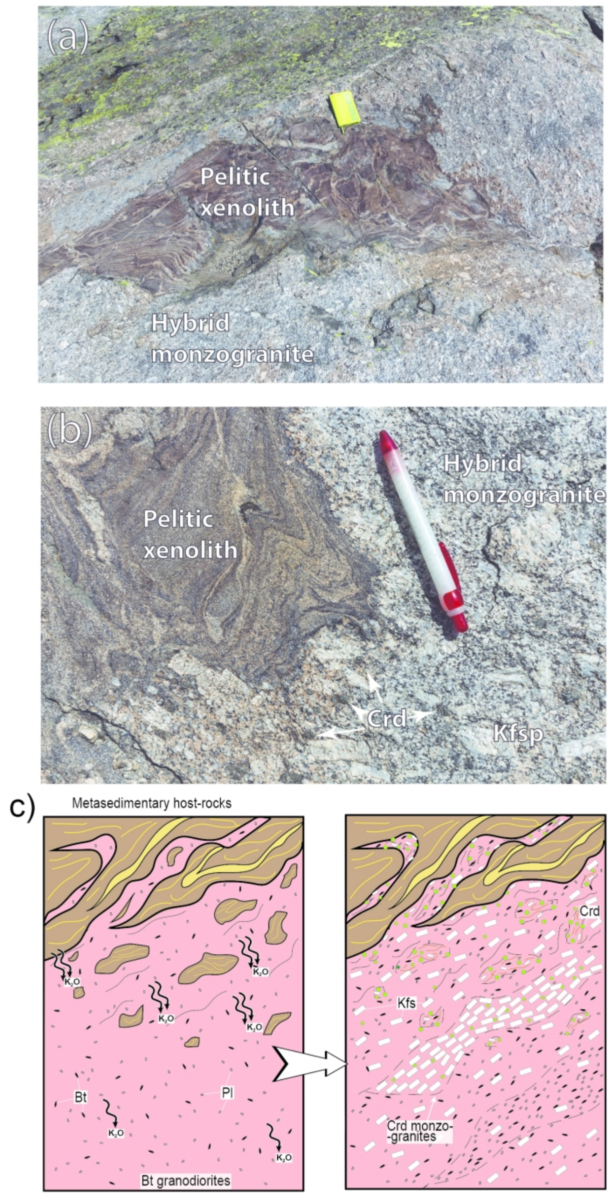

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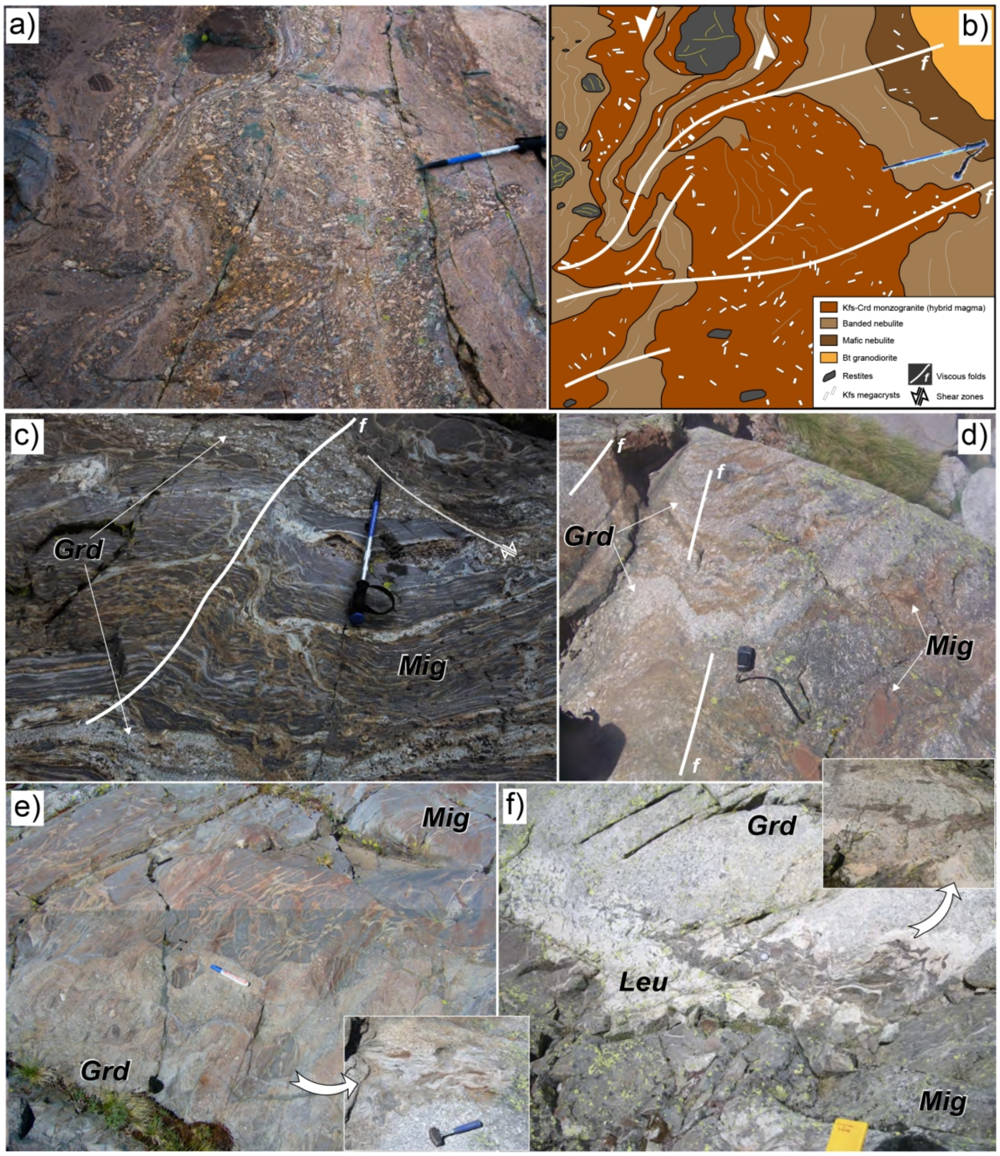

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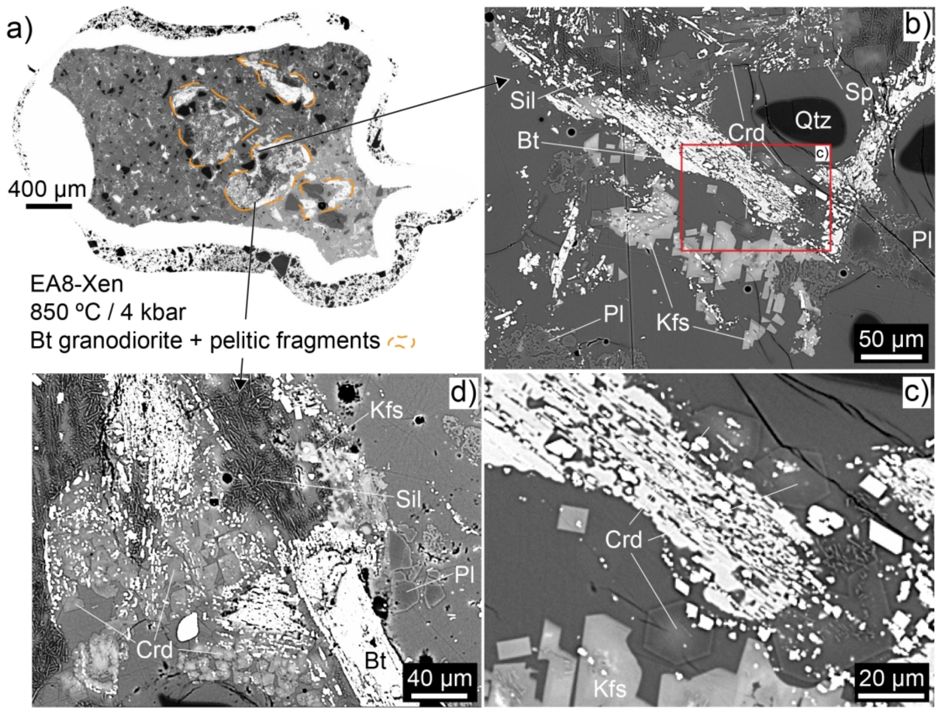

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