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# PROCESSES OF ASSIMILATION IN THE GENESIS OF CORDIERITE LEUCOMONZOGRANITES FROM THE IBERIAN MASSIF: A SHORT REVIEW

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## Abstract

Cordierite monzogranites of the Hercynian Iberian massif have geochemical and textural characteristics that are different from those of the two main recognized families of granitic rocks in the Iberian massif: the peraluminous leucogranites, generally associated with high-grade anatectic zones, and the granodiorites, usually peraluminous and mostly emplaced later. The features of the cordierite monzogranites indicate links to these families. They contain a cordierite-group mineral as the main ferromagnesian phase, have alkali feldspar megacrysts, and commonly show complexly zoned plagioclase. The existence of this intermediate and transitional group of granites constitutes a major problem in granite petrogenesis. A crustal origin has been inferred from previous studies on their genesis; however, a more complex process is invoked to explain their geochemical features, as the major-element composition of these monzogranites does not match the composition of melts obtained experimentally from pelitic metasediments. In addition, the isotopic signatures (Sr–Nd) of these granites do not match those of any known source in the crust where these granites are emplaced. The presence of cordierite as the most characteristic ferromagnesian phase has also to be explained. In this paper, we propose a two-component process of assimilation to explain the origin of this type of granite. After the genesis of peraluminous melts related to an anatectic process, a two-component process of assimilation, involving both country rocks and more mafic mantle-derived material, is proposed in a general model that is based on geochemistry, textures and field relations of cordierite monzogranites, together with isotopic and experimental constraints.

*Keywords*: cordierite, monzogranites, Iberian massif, partial melting, assimilation.

## Sommaire

Les monzogranites à cordiérite du massif ibérique, d'âge hercynien, possèdent des caractéristiques géochimiques et texturales différentes de celles des deux grandes familles de roches granitiques du massif: les leucogranites hyperalumineux, généralement associés aux zones d'anatexie avancée, et les granodiorites, généralement hyperalumineuses et mises en place plus tardivement. Les caractéristiques des monzogranites à cordiérite indiquent des liens à ces deux familles. Dans ces roches, c'est un minéral du groupe de la cordiérite qui est la phase ferromagnésienne principale; elles contiennent aussi des mégacristaux de feldspath alcalin, et un plagioclase à zonation complexe. L'existence de ce groupe intermédiaire et transitionnel de granites soulève un problème pétrogénétique important. Une origine dans la croûte a été supposée suite aux résultats d'études antérieures; toutefois, un processus plus complexe semble indiqué pour expliquer les aspects géochimiques, parce que la composition en termes d'éléments majeurs ne concorde pas avec la composition des liquides obtenus expérimentalement aux dépens de métasédiments métapélitiques. De plus, la signature isotopique (Sr–Nd) de ces monzogranites ne concorde pas avec celle des sources connues dans la croûte où ils sont mis en place. On doit aussi expliquer la présence de cordiérite comme phase ferromagnésienne dominante. Nous proposons un processus d'assimilation à deux composantes pour rendre compte de cette sorte de granite. Après la génération de magmas hyperalumineux au cours d'un processus d'anatexie, nous proposons une assimilation impliquant à la fois les roches encaissantes et des roches plus mafiques dérivées du manteau. Le modèle repose sur les données géochimiques, les textures et les relations de terrain des monzogranites à cordiérite, à la lumière des contraintes isotopiques et expérimentales.

(Traduit par la Rédaction)

*Mots-clés*: cordiérite, monzogranites, massif ibérique, fusion partielle, assimilation.

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## Introduction

The Hercynian massif of the Iberian Peninsula (Spain and Portugal) contains one of the largest and best outcropping domains of granite in the European Hercynides. These features make the Iberian massif suitable for a discussion of contrasting models and hypotheses on the origin of granites (*e.g.*, Villaseca *et al*. 1998). Most of the Iberian intrusive rocks are peraluminous granites to granodiorites that originated during the Hercynian orogeny in Upper Paleozoic times. The main investigators involved in the classification of the Iberian granites (*e.g.*, Schermerhorn 1959, Oen 1958, 1970, Capdevila 1969, Corretgé 1971, Capdevila *et al*. 1973, Martínez 1974, Bea 1975, 1976, Ugidos & Bea 1976, Corretgé *et al*. 1977) distinguish several groups or families using a combination of compositional, mineralogical, and tectonic criteria. These investigators distinguish two types of granites: a) a group of peraluminous leucogranites, generally associated with high-grade anatectic zones, and b) a group of granodiorites, usually peraluminous, that are mostly later in emplacement (Fig. 1). An important contribution to this granite-classification scheme was the introduction by Capdevila *et al*. (1973) and Corretgé *et al*. (1977) of a third group called "série à caractères mixtes ou intermédiaires". Typical rocks of these "mixed-feature granites" are leucocratic cordierite-rich monzogranites that form large epizonal plutons in many different areas of the Iberian massif. This type of granite is the focus of this paper, because the rocks seem to have "contamination" features that make their genesis complex. Note that in this paper, cordierite and Crd refer to "cordierite-group mineral".

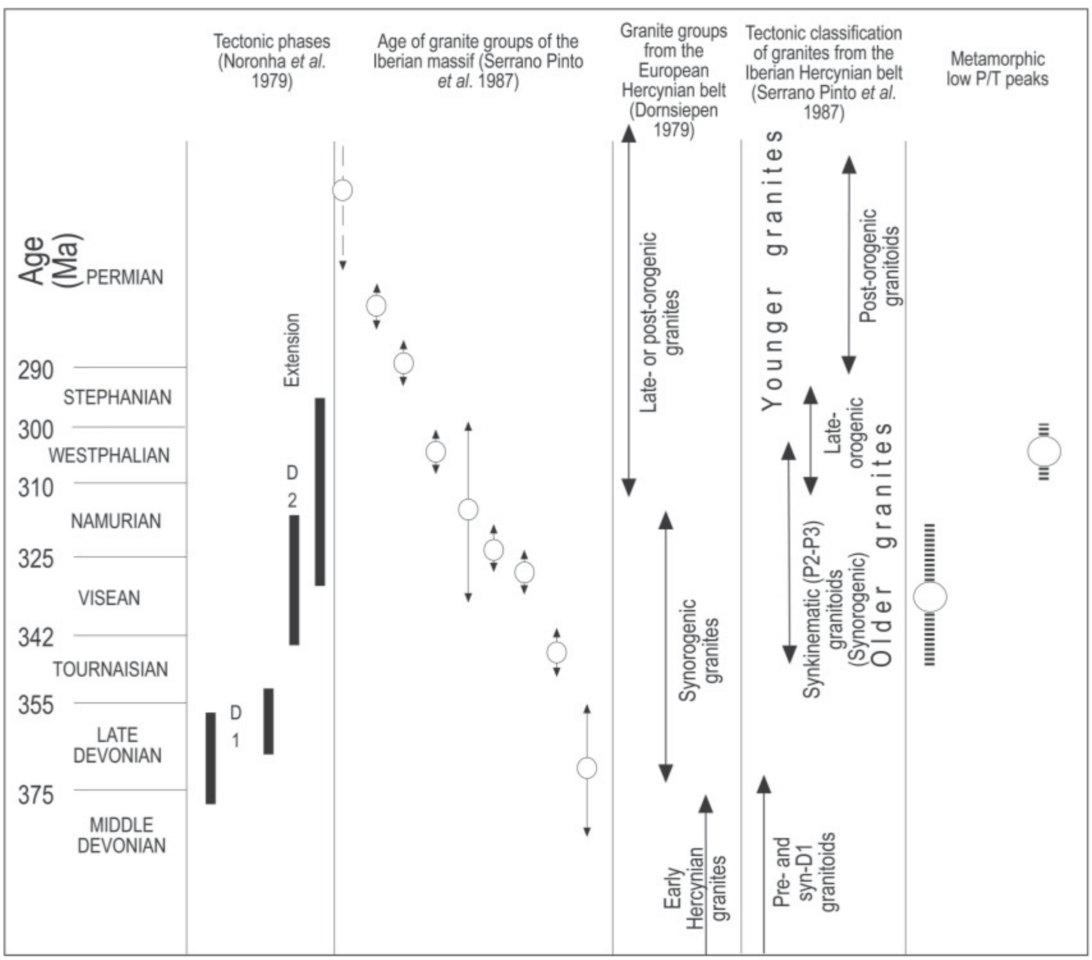


Fig. 1. Age relationships among granites, deformation phases and metamorphic episodes in the Iberian massif.

## Background Information

Petrogenetic models involving anatexis of pelitic gneisses and the origin of peraluminous leucogranites and two-mica granites, early proposed by Capdevila *et al.* (1973) and recently confirmed with isotopic and experimental studies (Moreno-Ventas *et al.* 1995, Beetsma 1995, Castro *et al.* 1999), fail to explain the origin of these mixed-feature granites or cordierite monzogranites. These rocks have been considered as products of assimilation of peraluminous migmatites by the biotite-rich granodiorites (Ugidos 1973, Ugidos & Bea 1976) on the basis of their isotope ratios (Ugidos & Recio 1993).

Furthermore, cordierite monzogranites are not restricted to the Iberian massif. They appear in other orogenic domains (*e.g.*, Clarke 1981, Georget 1986, Roberts & Clemens 1993, Divicenzo *et al.* 1994, Peters & Kamber 1994, Fourcade *et al.* 2001, Rapela *et al.* 2002). The fact that these cordierite monzogranites have features of both typical S-type and some I-type granites, according to the classification scheme of Chappell & White (1974), lies at the heart of the problem and, moreover, it is one of the main causes of criticisms to the straightforward application of the S–I classification in which intermediate or transitional processes are not possible (mafic I-types rarely evolve toward S-type varieties). In the case of Iberian cordierite monzogranites, all the characteristic features point to S-type granites; however, they also have some I-type features without any straightforward genetic relation with this type of granitic rock.

The aim of this paper is to discuss the main problems regarding the generation of the cordierite monzogranites. We focus on three possible components that could be involved from partial melting to magma emplacement: partial melting of mesocrustal rocks, assimilation of country rocks, and contamination from fragments of tonalitic enclaves during ascent and emplacement. In this discussion, we consider some isotopic and experimental data to constrain a petrogenetic model, taking into account possible processes of contamination and hybridization.

## Cordierite Leucomonzogranites from the Iberian Massif

Granites (*s.l.*) occur in all the classical tectonostratigraphic domains of the Iberian massif (Lotze 1945, Julivert *et al.* 1972, Farias *et al.* 1987). The magmatic episode that generated these intrusive bodies extended for approximately 120 Ma, in 10 to 15 Ma pulses (Castro *et al.* 2002a, Bea *et al.* 2004), although most of the plutons concentrate in a smaller intrusive range of 30–40 Ma (330–290 Ma) (Bea *et al.* 1999). The great variety of rocks generated with different ages and petrological characteristics makes their classification difficult (Castro *et al.* 2002a). The classification of the Hercynian Iberian granites is based on their compositional characteristics and their relative ages. Castro *et al.* (2002a) proposed the association of granites in large suites, to avoid the classifications based upon the ages of emplacement into older and younger granites, because the diachronism of the phases of deformation in different geotectonic zones of the massif (Fig. 1). These suites occur in two different domains: Northern and Southern, separated by the Los Pedroches Batholith (Fig. 2). This separation marks the differences in the granite association to the north and south of Los Pedroches, and the possible different sources for the granite series in the two domains. The suite classification proposed by Castro *et al.* (2002a) is as follows: 1) *Suite* 1 or Granodioritic, 2) *Suite* 2 or Monzogranitic (with cordierite), and 3) *Suite* 3 or Peraluminous and leucogranitic.

This classification is close to that proposed by Capdevila *et al.* (1973) and Corretgé *et al.* (1977), in which the previous calc-alkaline series correspond to the granodioritic suite, the previous alkaline series to the Leucogranitic Suite, and the previous "mixed feature" granites to the Monzogranitic Suite. Figure 2 highlights the locations of the Monzogranite Suite. The chemical compositions of the rocks constituting these three suites overlap; no clear-cut distinction thus exists among them. They must be distinguished by detailed field relations and chemical relations within granite members of each suite.

Granites that form the so-called Cordierite Monzogranitic Suite are generally late in relation with the most important episode of deformation and the metamorphic peak, and also in relation to the Granodioritic Suite. This timing is clear in the cases of the Los Pedroches Batholith (Larrea *et al.* 2004), where the different units of the batholith correspond to two different magmatic episodes. The main pulse (granodioritic) is post-D1 Hercynian and pre- or syn-D2. The second pulse, made up of autonomous plutons (cordierite monzogranite type), are clearly post-D1 and syn- and post-D2 (Fig. 1). The granites of this suite commonly form allochthonous zoned plutons. The commonly observed zoning consists in a concentric distribution showing transitions from cordierite granites to two-mica granites. Intrusive aplitic granites complete the sequence.

Examples of cordierite monzogranites in the Iberian massif occur in two different geological situations: as epizonal zoned plutons, and as irregular patches associated with biotite-rich granodiorites with transitional contacts. In both situations, they are similar in petrographic and geochemical features. Zoned plutons are by far the most representative examples of these granites. The best examples are in the Central Extremadura Batholith and the Northern part of Los Pedroches batholith (Alonso Olazabal 2001). The coarser facies with cordierite crystals of up to 6 cm in length occurs in the Cabeza de Araya massif. In the Alcuéscar and Trujillo plutons (Corretgé *et al.* 2004), the cordierite monzogranites locally show transitions to biotite


FIG. 2. Granitoids from the Iberian Massif. Modified map after Castro *et al.* (2002a) contrasting in black the biotite ± cordierite granodiorites and monzogranites (cordierite Monzogranite Suite).

granodiorite in which microgranular enclaves of tonalite composition are normally present. These enclaves are also present, but in lesser amounts, in the cordierite monzogranites. The presence of the tonalitic enclaves, even if they are scarce, is an important feature of the cordierite monzogranites that will provide clues about their genesis (García Moreno 2004, García-Moreno *et al.* 2006).

A relevant observation is the position of cordierite-bearing plutons in relation to the granodiorites of the Los Pedroches batholith (Fig. 2). They cross-cut the granodiorites and are aligned in a trend oblique to the major axis of the batholith (cordierite-bearing plutons are oriented N120–130° cross-cutting the granodioritic plutons, which are oriented N110–115° (Larrea *et al.* 2004). These intrusive relationships are characteristic of the cordierite monzogranites in the Iberian massif: with the exception of the very late granodiorites in the northern part of Iberian massif (Corretgé *et al.* 1990); they are late with respect to the emplacement of granodiorites, though in deeper levels, as the case of the Gredos massif in central Spain (*e.g.*, Bea & Moreno Ventas 1985, Moreno Ventas *et al.* 1995), they show transitions to granodiorites.

The best example of the cordierite monzogranites, based on excellent outcrops and clear facies-relations and zonation, is the Cabeza de Araya massif in the Central Extremadura Batholith (Fig. 2). The Cabeza de Araya rocks have been studied from different points of view, from field relations and petrography by Corretgé (1971) to geophysical and structural studies by Amice (1990) and Vigneresse & Bouchez (1997) and from an experimental petrology point of view by García-Moreno (2004). The Cabeza de Araya granites typically show a zonal disposition, from an external part of cordierite monzogranites to more leucogranitic and two-mica granites (similar to the peraluminous Leucogranite Suite) with less cordierite toward the core of the pluton, and an apical aplitic leucogranitic facies identical to the peraluminous Leucogranitic Suite.

## Petrographic Features

Previous work has emphasized the petrographic peculiarities of the cordierite monzogranites, consisting of: quartz, plagioclase, K-feldspar, ± biotite ± muscovite ± cordierite ± andalusite ± sillimanite ± garnet (Corretgé 1971, Capdevila *et al*. 1973, Ugidos 1973, 1990, Corretgé *et al*. 1977, 2004, Barrera *et al*. 1982, Bea 1982, Brandebourger *et al*. 1983, Corretgé *et al*. 1985, Bea & Moreno-Ventas 1985, and Corretgé *et al*. 2004). The principal features are listed below.

### *Cordierite*

Cordierite is the diagnostic ferromagnesian phase of these granites. It may appear together with biotite. In some monzogranites, cordierite is the only ferromagnesian mineral, appearing as large (2–6 cm across) euhedral crystals (Corretgé 1971). The size of these euhedral crystals is similar to the average grain-size of the granite (Fig. 3). The average composition is $(Mg_{0.8}Fe_{1.2})Al_4Si_5O_{18}$, #Mg range: 0.38–0.50. Thus the characterisic cordierite-group mineral is sekaninaite. Bea (1982) deduced a magmatic origin for cordierite in these granites. The chemical composition of the sekaninaite crystals has been studied in García-Moreno (2004), and they correspond to the compositions of magmatic cordierite according to Pereira & Bea (1994). The interpretation as magmatic cordierite for these monzogranites seems to be evident also according to other studies (Maillet & Clarke 1985, Clarke 1995), although, as will be discussed below, the interpretation of a direct crystallization from any peraluminous melt is not as straightforward as it has been experimentally constrained for the Cabeza de Araya monzogranites (García-Moreno 2004). Moreover, euhedrality is certainly not equivalent to a magmatic origin, according to Erdmann *et al*. (2005).

### *K-feldspar megacrysts*

The presence of K-feldspar megacrysts is one of the salient features of these granites. K-feldspar megacrysts commonly occur in the less differentiated facies of the cordierite monzogranites, in the outer part of the plutons (also with the tonalitic enclaves), whereas they are

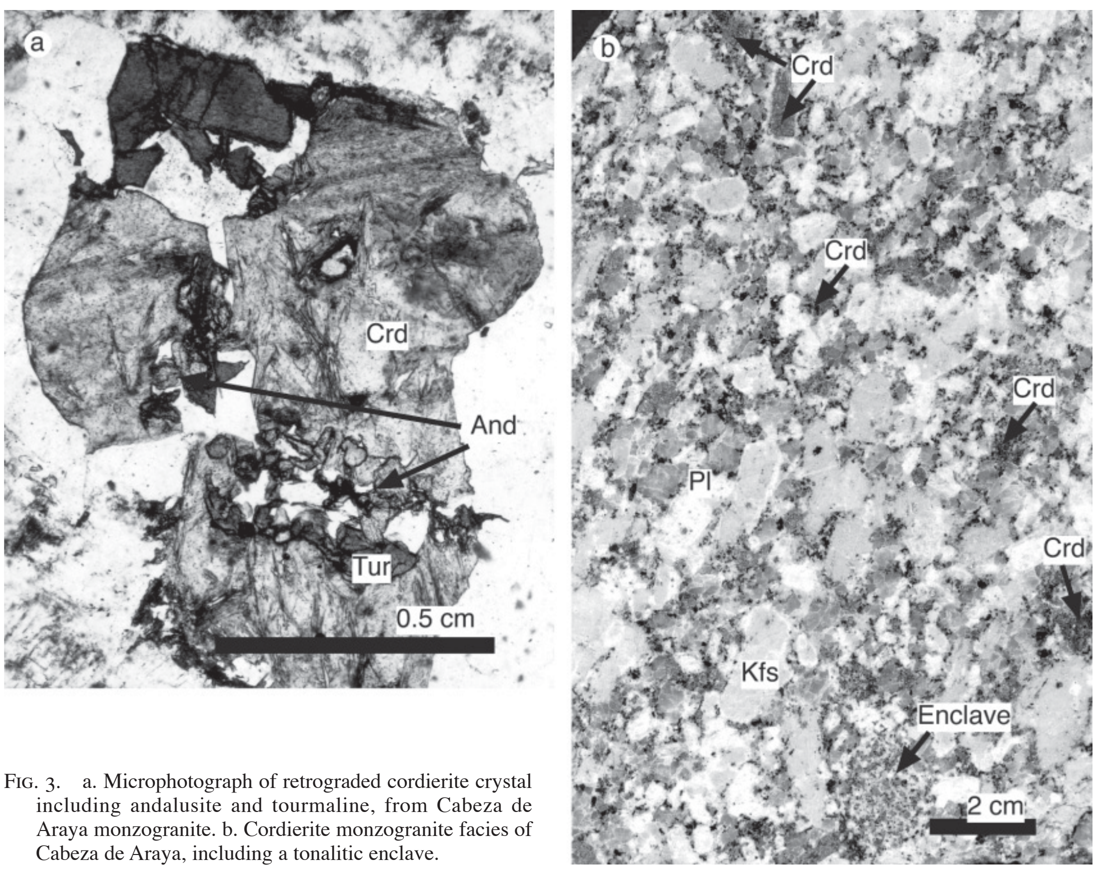


FIG. 3. a. Microphotograph of retrograded cordierite crystal including andalusite and tourmaline, from Cabeza de Araya monzogranite. b. Cordierite monzogranite facies of Cabeza de Araya, including a tonalitic enclave.

absent in the two-mica and aplitic granite facies. Many K-feldspar grains in the cordierite monzogranites have a rapakivi texture, in which the K-feldspar is surrounded by plagioclase that, in the case of Cabeza de Araya, is in the albite range.

*Plagioclase*

In the granites of the Cabeza de Araya massif, plagioclase is Ca-poor (albite–oligoclase) and slightly normally zoned; however, some complexly zoned crystals of plagioclase also occur in the cordierite monzogranites (Castro *et al.* 1999). These crystals have complex patterns of zoning, with multiple resorption-induced surfaces and irregularly corroded cores richer in anorthite compared with the outer rims and the infillings. This type of plagioclase is absent in the peraluminous leucogranites, but it is typical of the biotite-rich granodiorites. The origin of these grains of plagioclase is a matter of debate; there is no agreement about the process that causes the disequilibrium necessary to produce these complex patterns. Changes in the composition of the melt, in the $H_2O$ content, in intensive variables, *etc.* (Hibbard 1981), may be argued as causes of disequilibrium; however, the corroded cores, indicating a rapid growth, are difficult to explain in a plutonic environment unless the liquid was suddenly oversaturated in the plagioclase components.

TABLE 1. GENERAL FEATURES OF GRANITOIDS FROM THE IBERIAN MASSIF

| | Bt-rich granodiorites | Crd-bearing monzogranites | Peraluminous leucogranites and two-mica granites |
|---|---|---|---|
| Relative age | Mostly younger | Mostly younger | Mostly older |
| Relative abundance | > 50% | < 50% | < 20% |
| Occurrence | Allochthonous massifs Associations with gabbroic rocks | Normally in zoned, epizonal plutons | Normally in para-autochthonous massifs, with transitions to migmatites |
| Mineral assemblage | Qtz – Pl – Kfs – Bt ± (Crd) or ± (Hb Px) | Qtz – Kfs – Pl – Crd – Bt ± Ms ± And ± Tur | Qtz –Pl – Kfs ± Bt ± Ms ± Crd |
| Kfs megacrysts | Abundant | Typical | Rare |
| Microgranular enclaves | Typical | Scarce | Absent |
| Ore deposits | Rare (barren granites) | U, W, P | Sn |
| Sr initial ratio* | 0.705 – 0.707 | 0.706 – 0.712 | 0.723 – 0.763 |
| $K_2O/Na_2O$ | > 1 | > 1 | > 1 |
| Al-saturation index A/CNK | ave. 1.09 (0.12) (n = 212) | ave. 1.22 (0.14) (n = 145) | ave. 1.29 (0.17) (n = 255) |

* Data from Moreno-Ventas *et al.* (1995), Castro *et al.* (1999) and Alonso Olazabal (2001). In this context, Crd is meant to signify cordierite-group mineral. In the Crd-bearing monzogranites, the cordierite-group mineral is sekaninaite.

*Andalusite*

Andalusite appears in noticeable amounts, mainly in the coarse-grained, two-mica granites and aplitic granites belonging to the monzogranite series. Andalusite crystals and clusters show many of the textural characteristics described by Clarke *et al.* (2005). Sekaninaite and andalusite can occur together (Fig. 3).

## Geochemical Features

Table 1 summarizes the main petrographic and geochemical features of the cordierite monzogranites compared with other granite series of the Iberian massif. The main geochemical features, in terms of major elements, of these intermediate peraluminous and commonly phosphorus-rich monzogranites (Bea *et al.* 1992) are their intermediate compositions between peraluminous leucogranites and granodiorites (Castro *et al.* 1999, Corretgé *et al.* 2004). Figure 4 shows the A–B multicationic diagram of Debon & Lefort (1983) for the compositions of the most representative cordierite monzogranite family in the Iberian massif, the Cabeza de Araya granitoids. The cordierite monzogranites have more Fe- and Mg-rich compositions (>B) compared with two-mica and aplitic leucogranites, and they are also less aluminous in composition (<A); two-mica and aplitic leucogranites usually have higher andalusite and aluminosilicate contents.

Castro *et al.* (1999) discussed the Sr–Nd isotopic features of cordierite monzogranites and granodiorites from the Iberian massif. They pointed to a juvenile mantle material incorporated into the granitic magmas at the time of melt generation during the genesis of granodiorites and the cordierite monzogranites. Furthermore, cordierite monzogranites have relatively low values of the initial Sr isotope ratio compared with granites from the Leucogranitic Suite: 0.706–0.712 for the cordierite monzogranites *versus* 0.723–0.763 for leucogranites. Granodiorites and mafic enclaves, together with the cordierite monzogranites, produce good Rb–Sr errorchrons and isochrons (*e.g.*, Pinarelli & Rottura 1995, Moreno-Ventas *et al.* 1995, Ibarrola *et al.* 1987, Castro *et al.* 1999). In summary, all the petrographic and geochemical features point to a hybrid origin for the cordierite monzogranites despite the leucocratic character of most of them.

Some petrogenetic models for the cordierite monzogranites are based on major and trace elements to relate the different facies in the cordierite monzogranites. For the Cabeza de Araya granites, Corretgé *et al.* (1985) suggested partial melting of metasedimentary units with a later process of differentiation from a single magma with a common source to produce both the cordierite monzogranites and the two-mica leucogranitic facies.

These authors proposed a separate source and different geochemical characteristics for the strongly peraluminous aplitic leucogranites (identical to the Leucogranitic Suite). Some other investigators of the geochemistry of these rocks have proposed different models for the genesis of cordierite monzogranites. Ugidos (1988) and Ugidos & Recio (1993) proposed the partial melting of metasedimentary rocks and a later process of assimilation of cordierite-bearing country rocks to explain the geochemical features of cordierite monzogranites. These studies, based on the geochemistry of these rocks, can account for many of the observed characteristics of cordierite monzogranites, but some controversies remain unsolved about this special series of granites in the Iberian massif, such as the relatively low values of the initial Sr isotope ratio and the relation with tonalitic enclaves present in the most Ca-, Fe- and Mg-rich members of this series. Some of these controversies have been explained by partial melting experiments at high pressure and temperature. We briefly describe some of the previous experimental results on Iberian granites that can shed light on the genesis of these rocks. Results of these experiments can be reviewed in terms of partial melting, crystallization, assimilation, and dissolution of enclaves, with the aim to understand the possible mechanisms for the genesis of cordierite monzogranites.

## Experimental Petrology

### *Partial melting experiments*

The partial melting experiments intended to shed light in the genesis of Iberian granites were performed on a peraluminous biotite gneiss present as xenoliths in the Tourem anatectic complex (northern Portugal) (Holtz & Johannes 1991). Melts produced by partial melting of these gneissic materials produced a great variety of compositions (with respect to $K_2O$ in particular) depending on the $H_2O$ content of the system.

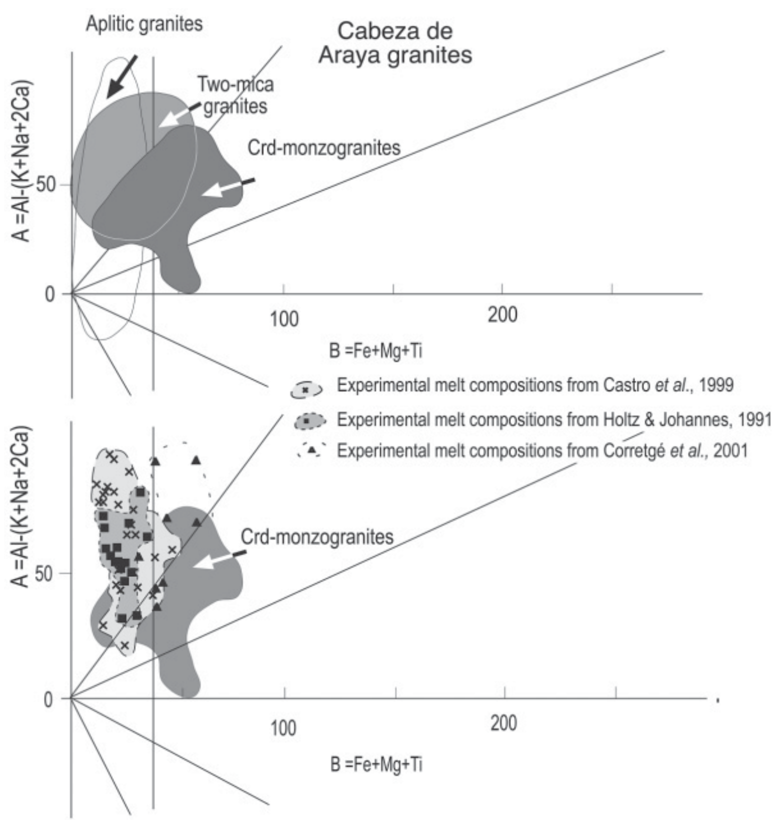


Fig. 4. A–B multicationic diagram (Debon & Le Fort 1983) showing the main facies of Cabeza de Araya (upper part) and the compositions of experimentally produced melt from Holtz & Johannes (1991), Castro *et al*. (1999) and Corretgé *et al*. (2001) compared with the cordierite monzogranite compositions.

Nevertheless, the melt compositions produced are very close to the granite minimum composition and depart from cordierite monzogranite compositions, especially for the less strongly peraluminous and Fe- and Mg-rich end-members of the series, well represented in the Cabeza de Araya massif, as explained above. However, melts produced in those experiments were in equilibrium with cordierite crystals inherited from the cordierite gneiss.

Castro *et al.* (1999, 2000) carried out several series of partial melting experiments using different potential protoliths for the Iberian granites. Results of these experiments, performed under different temperature and pressure conditions and with different $H_2O$ contents, always show melt compositions close to the granite minimum composition for conditions of reasonable pressure and temperature in the anatectic context of the Hercynian orogeny in the Iberian massif (Castro *et al.* 2000). Those compositions, highly peraluminous (A/CNK on average 1.50, range 1.2–1.8) and with relatively low Fe and Mg contents ($0.9 < FeO_t < 1.6$ wt% and $0.04 < MgO < 0.27$ wt%), could be related to the genesis of granites of the Leucogranite Suite, but depart from the cordierite Monzogranite Suite (Fig. 4). However, the process of assimilation of crustal rocks by mantle-derived magmas proposed for the genesis of these suites (Castro *et al.* 1999) cannot account for the strong evidence related to anatectic processes in the cordierite monzogranites.

Corretgé *et al.* (2001) undertook partial melting experiments on a metapelite from the "Equisto-grauváquico" Complex of the Iberian massif. The starting material in those experiments was a spotted hornfels with cordierite and completely devoid of chlorite, representing a rock that has undergone natural partial dehydratation by thermal effects prior to the partial melting event. Results showed melt compositions again close to the granite minimum and highly peraluminous (Fig. 4). Under the conditions investigated, cordierite overgrows relict cores and appears to be in equilibrium with melts. The modeling for the partial melting of the hornfels presented in Corretgé *et al.* (2001) will be discussed below, together with new experimental data using a different hornfels as starting material (unpubl. data). This hornfels represents dehydrated material from the "Esquisto-grauváquico" Complex with the paragenesis: Qtz + Bt + Ms + Crd + Pl. Experiments performed under 3 kbar and 820°C without added $H_2O$ in cold-seal apparatus of the University of Hannover show melt composition closer to the cordierite monzogranites, but still much closer to the granite minimum, with a strong peraluminous character (A/CNK = 1.41 on average) and relatively low Fe and Mg contents ($1.75 < FeO < 2.2$ wt%) and $0.2 < MgO < 0.3$ wt%). The composition of the melts produced under those conditions cannot account for the composition of the more basic compositions of the cordierite monzogranite suite. Again, cordierite crystals are in equilibrium with the melts produced.

Figure 4 shows compositions of melts produced in all the partial melting experiments described in terms of the AB multicationic diagram, compared with compositions of the cordierite monzogranites from Cabeza de Araya.

### *Crystallization experiments*

Crystallization experiments on the most basic rock of the Cabeza de Araya granitoids were performed to investigate the possible origin of cordierite monzogranites (García-Moreno 2004, García-Moreno *et al.*, in prep.). The experiments showed that the chosen composition for the starting material in crystallization experiments (the most basic rock of the Cabeza de Araya granitoids) does not represent a liquidus composition (García-Moreno *et al.* 2003). The phase relations of natural Cabeza de Araya granitoids were not reproduced, especially for cordierite, which failed to crystallize over a wide range of P–T conditions and $H_2O$ contents. Seeds of natural cordierite crystals were added to the starting synthetic glass material to avoid possible problems in nucleation for the crystallization of cordierite, but those seeds dissolved into the melts or showed a mantle of plagioclase in low-pressure (2 kbar) experiments. Natural sekaninaite of the monzogranites studied may be inherited from the source (or assimilated from country rocks) or may grow in equilibrium with a melt whose composition does not correspond with the monzogranite starting composition of these experiments. Cordierite crystals in these monzogranites could be defined as paraxenocrysts in the sense of Erdmann & Clarke (2005), being the result of a peritectic reaction in the anatectic zone and remaining undissolved under later P–T conditions during ascent and emplacement where the melts acquired a more Ca-rich composition by a later process of contamination.

### *Experiments on the dissolution of enclave fragments*

Crystallization experiments cannot explain the origin of the more basic composition of the cordierite monzogranites. Some important aspects of these granitoids, such as the origin of cordierite, together with some textural characteristics and the geochemical features, which point to a mantle-like signature (Sr isotopic ratio), must be explained in terms of a process different than just partial melting of a metasedimentary rock. Although some xenoliths from the lower crust of the French Massif Central (*e.g.*, Downes & Duthou 1988) or of the Spanish Central System (Villaseca *et al.* 1999) show that some residual granulites could match the isotopic values of these granitoids, the relatively low values of the initial Sr isotopic ratio of cordierite monzogranites must be related to some kind of interaction with mantle-derived rocks. The residual granulites are not fertile rocks at the conditions where cordierite monzogranites were generated; the rocks of the middle crust from which these granites must have evolved cannot explain their isotopic relations (García-Moreno *et al.* 2006). A different model to explain the genesis of some cordierite monzogranites in a different geological setting is the one proposed by Fourcade *et al.* (2001) for the Alpine cordierite-bearing granitoids of northern Algeria, in which the cordierite monzogranites are the product of assimilation of pelitic metasediments from the country rock by a metaluminous magma. This model could explain some field observations of cordierite monzogranite relations with granodiorites of the calc-alkaline series, as the case of the Gredos massif in central Spain (*e.g.*, Bea & Moreno-Ventas 1985, Moreno-Ventas *et al.* 1995). However, the (partial) dissolution of enclave fragments model (García-Moreno *et al.* 2006), explained below, together with the assimilation of country rocks, is able to explain not only the field relations of the most important examples of the cordierite monzogranitic suite, *i.e.*, epizonal zoned plutons, but also the main geochemical, textural and isotopic features of these granitoids.

Because the crystallization experiments showed a non-primary pure crustal origin for the cordierite monzogranite compositions, García-Moreno (2004) proposed a process of "contamination" or hybridization of pure anatectic melts as a possible mechanism for the origin of the cordierite monzogranites. Uncontaminated hydrous peraluminous leucogranitic melts could carry fragments of tonalite (as enclaves or dike fragments) in the process of ascent and emplacement. These tonalite fragments could interact with the undersaturated melts in a way similar to the one tested in experiments on the dissolution of enclave fragments (Castro *et al.* 2002b, García-Moreno *et al.* 2006). These authors referred to the process of "enclave dissolution" as partial dissolution of certain phases in the sense of Smith & Brown (1988), as these phases were in equilibrium with a melt prior to the process (at higher pressure). Experiments performed in decompression, simulating ascending magmas, show that from 10 kbar to 4 kbar, at isothermal conditions, enhanced dissolution of the tonalitic enclave into the melt took place, compared with experiments at constant pressure. Furthermore, the composition of the melt changed to higher CaO, FeO and MgO contents as a result of enclave dissolution into the melt. The effect of enclave dissolution during isothermal decompression is related to the change in $H_2O$ solubility values from high to low pressure. At lower pressure, melts are closer to $H_2O$ saturation and will be able to dissolve crystals of the enclave fragment to attain new equilibrium conditions at low pressure (Holtz *et al.* 2001). The tonalitic enclaves that are partially dissolved may have been early or coeval intrusions into the granitic magma or even into the source migmatitic area. If they were coeval, the proposed process is related only to the solid part of the basic magma, otherwise it would be a magma-mixing process. This proposed process can explain some of the most striking features of cordierite monzogranites, but has to work together with another process, as discussed below.

## Discussion: Two-Component Process of Assimilation

The genesis of cordierite monzogranites must be explained in terms of a two-component process of assimilation in the light of the experimental results described and their geochemical characteristics.

We can start considering the process of partial melting of metasedimentary rocks in an anatectic zone for the formation of the initial melts that would generate the peraluminous granitic magma at the origin of the cordierite monzogranites. Results of partial melting experiments indicate favorable conditions for the genesis of these initial melts between 700 and 850°C and pressures of approximately 3 to 6 kbar. According to Castro *et al.* (2000), melt productivity is strongly favored at low P (3.5 ± 0.5 kbar). Anatexis probably took place by decompression associated with crustal thinning and extension, at temperatures invariably below 800°C (Pereira 1993, 1997). Corretgé *et al.* (2001) considered, in their partial melting model, the replacement of the subsolidus association Crd + Bt + Ms by Crd + Opx + Melt. Muscovite probably disappeared in the subsolidus region through the reaction Bt + Ms + Qtz = Crd + Kfs + $H_2O$. This model explains how orthopyroxene, although stable at low pressure, is consumed in a melting reaction, leaving cordierite (paraxenocryst) the surviving mineral in equilibrium with peraluminous melts.

Figure 5c shows that the cordierite monzogranites lie to the AlSi–Crd–Opx side of the low-T eutectic–peritectic *minimum* melting point compositions for the natural rocks. As such, either they represent high degrees of partial melting along cotectic lines, or they represent minimum melts with additions of residual refractory phases such as aluminosilicates, cordierite, and orthopyroxene.

Ugidos & Recio (1993) argued that assimilation of country rocks can be the cause of the derivation of the cordierite monzogranites tending to more Fe- and Mg-rich compositions and probably to an increase in their peraluminous character and departing from the Crd–AlSil cotectic trend (Fig. 5a). But leucogranite minimum melt plus cordierite is not the answer because A/CNK would be too high.

Strontium isotopic values of the cordierite monzogranites, as has been mentioned above, are relatively low with respect to pure anatectic leucogranites. The low values of the initial Sr isotope ratio link the genesis of cordierite monzogranites with more mantle-like material. This link with mantle contamination can be explained by the partial dissolution of tonalitic enclaves, as shown by the experimental results. Dissolution of

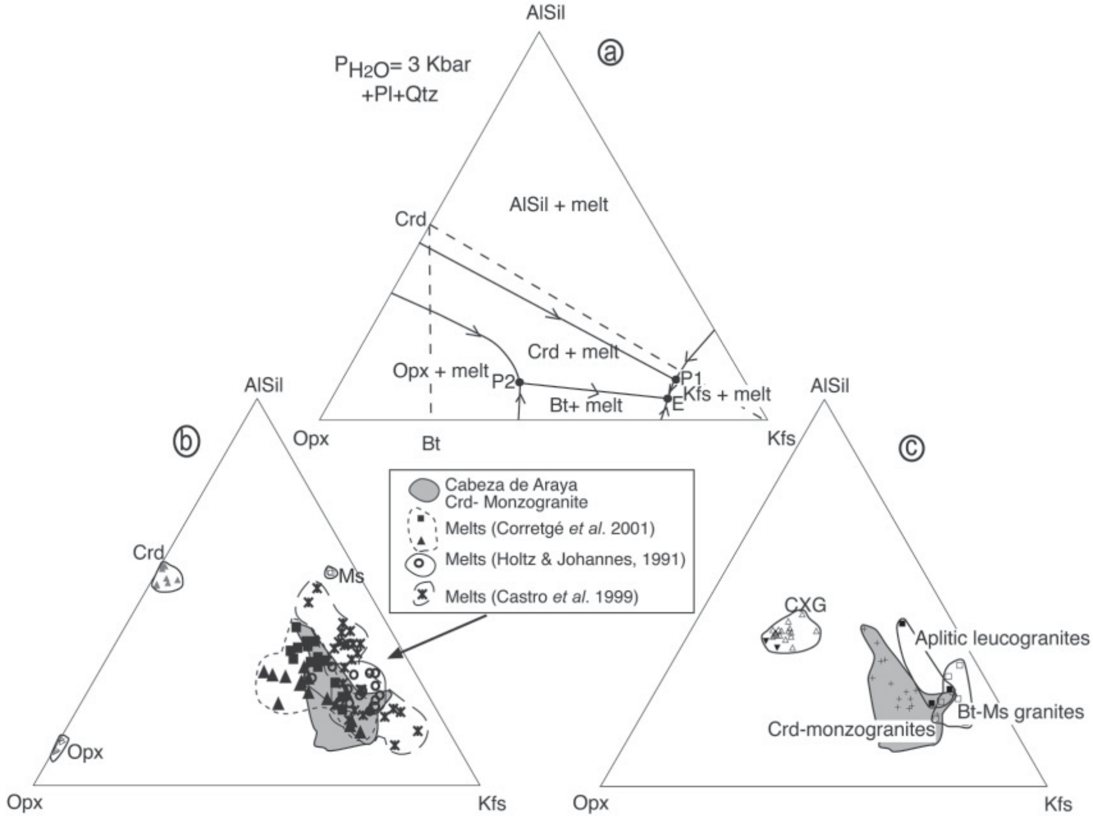


FIG. 5. a. Phase diagram from Dubrovsky (1987) for the AlSil, Opx and Kfs system at 3 kbar with excess of Qtz and Pl with the composition of eutectic (E) and peritectics (P1 and P2). b. Compositions from experimental melts from the studies of Holtz & Johannes (1991), Castro *et al*. (1999) and Corretgé *et al*. (2001). The grey area corresponds to the compositions of cordierite monzogranite from Cabeza de Araya. The data of Holtz & Johannes (1991) correspond to relatively low-temperature melts and are close to the eutectic and peritetic compositions (E and P1 from a). c. Compositions of the main facies of Cabeza de Araya rocks and of the "Complejo Esquisto-grauváquico" rocks (CXG).

plagioclase crystals from tonalitic fragments enclosed in the hydrous peraluminous cordierite-bearing granitic magmas during their ascent can result in the final Sr isotopic compositions of cordierite monzogranites (García-Moreno *et al*. 2006) and the transfer of Ca needed to change the composition of anatectic peraluminous leucogranites to monzogranites (García-Moreno 2004). In addition, the Fe and Mg enrichment needed to explain the most extreme compositions of cordierite monzogranites can be explained by considering partial dissolution of biotite into the hydrous peraluminous melts (some textural evidence is reported in García-Moreno *et al*. 2006). Nevertheless, this process does not exclude the assimilation of cordierite from the country rocks to enhance the Fe and Mg enrichment of these monzogranites. Natural examples of the enclave-dissolution process can be inferred from textural observations in granites. Figure 6 shows natural examples of enclaves in Cabeza de Araya monzogranites. The magmatic enclaves range in size from a few millimeters to decimeters, but rare meter-sized examples occur (Fig. 6a). Figure 6b shows details of the partial disaggregation of a small fragment of an enclave in the monzogranite matrix.

Figure 7 illustrates the double assimilation process, from the country rocks and from the tonalitic enclaves. The model takes into account (see right column) the percentage of tonalitic enclaves, the change in pressure, and $H_2O$-saturation values, always retaining undersaturation in $H_2O$ [$a_{H2O} < 1$]. Starting from the bottom, the model deals first with partial melting of mesocrustal rocks (metasediments from the "Complejo Esquisto-grauváquico") to form a hydrous $H_2O$-undersaturated leucogranitic melt. In the anatectic zone, where this part

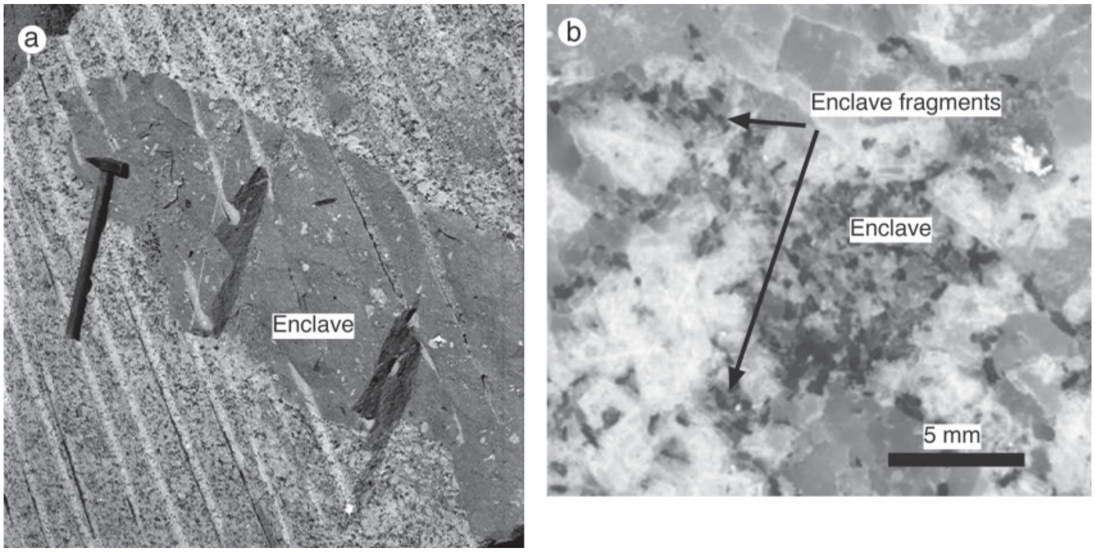


FIG. 6. Macroscopic aspects of tonalitic enclaves in Cabeza de Araya monzogranites. a. Large-scale magmatic enclave. b. Partially digested magmatic enclave.

of the process takes place, there may be some tonalites (basic infracrustal input), but the melts formed do not interact with these more basic rocks. In this first step in the formation of cordierite monzogranites, some cordierite crystals from the source rocks are incorporated in the melt (first assimilation process in Fig. 7) and grow in equilibrium with it, forming cordierite paraxenocrysts. After the partial melting event, during magma ascent, some tonalites are carried up by the magma but still they do not interact with the hydrous $H_2O$-undersaturated leucogranitic melts. However, the first assimilation process and the production of cordierite still go on at this stage. Finally, the second assimilation process starts at shallower levels in the crust, at a stage when decompression occurs and melts become closer to $H_2O$-saturation values. The entrained tonalitic fragments start to partially dissolve, and melts become more Ca-, Fe- and Mg-rich. Partial dissolution of plagioclase crystals from the tonalites lowers the Sr isotopic composition of the final magmas. At this stage, cordierite crystals neither grow nor dissolve into the melts.

## Conclusions

The genesis of leucocratic cordierite monzogranites from the Iberian massif requires the interaction of pure anatectic melts of hydrous leucogranitic compositions with country rocks (or mineral phases from the source region) and tonalitic rocks (or mineral phases from tonalitic intrusions in the source region). It is essential to consider the anatectic process for the origin of these rock series, but a double contamination process is necessary to explain the special features of these rocks, making the cordierite monzogranites product of a triple petrogenetic process in the crust.

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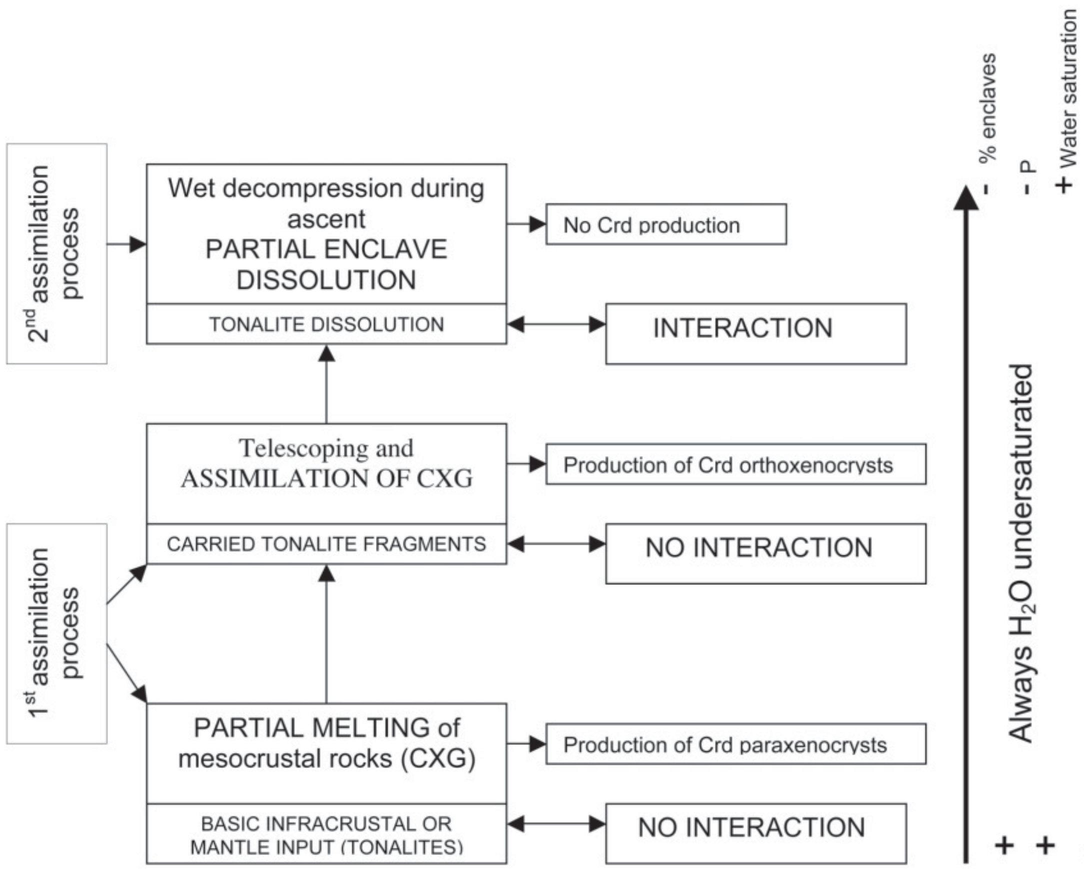


FIG. 7. Flow chart summarizing the proposed petrogenetic model. – to + $H_2O$ saturation refers to melts getting close to $H_2O$ saturation values with decreasing pressure. The model starts at the base of the flow chart upward, from the first assimilation process of country rocks to the second assimilation process during magma ascent and emplacement at upper levels in the crust, where partial dissolution of the tonalitic fragments carried takes place. See explanation in the text. CXG: "Complejo Esquisto-grauváquico" rocks.

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