Pegmatite Productive Terrains in the Variscan Granite Hosts From Northern and Central Portugal

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ABSTRACT The detection of suboutcropping pegmatite deposits in regions recognizably fertile regarding the occurrence of pegmatites depends upon the optimization of conceptual models which support the interpretation of the regional distribution of pegmatites and the structure of their assemblies. In intra-granitic context is at concern the more conventional cartographic expression of pegmatites in connection with the structuring of granitic cupolas. The establishment of occurrence situations linked to certain lithological units or structural alignments is a pathway for the delimitation of productive research areas. Some productivity situations deduced from geological mapping include: accommodation in preferred structural directions, proximity to mixing-mingling corridors, certain petrographic structuring units that reflect irregularities in terms of flow and fractionation processes, and trends of hydrothermal and supergene alteration of host granitic masses. The detection of these aspects, to regard as exploration guides, can avail itself of remote sensing, as they represent contrasting chromatic lithotypes with sufficient surface continuity.

1 INTRODUCTION

The detection of sub outcropping pegmatite deposits in regions recognizably or hypothetically fertile regarding the occurrence of pegmatites of economic interest, depends upon the optimization of conceptual models which support the interpretation of the regional distribution of pegmatites and the structure of their assemblies.

In intra-granitic context it at concern, the more conventional cartographic expression of pegmatites occurrence in connection with the structuring of granitic domes, often batholitic. The deduction of its potential to generate pegmatites and the levels of emplacement within the granitic columns depends on reconstitution of the functioning of the cupolas and plutonic evolution.

The establishment of occurrence situations in connection with certain structuring lithological units or structural alignments that can be envisioned by the location of known bodies is a pathway for the delimitation of productive research areas, which can, hypothetically be extrapolated and applied to most intra-granitic pegmatite occurrences.

Using geological mapping studies in the surroundings of pegmatitic occurrences in northern and central Portugal, and remote analysis of satellite images, it was possible to discriminate in compartments representing different levels of accommodation, a multitude of significant productivity situations tending for the evidence of hidden pegmatites, which are discussed below.

1.1 Tectonic-orogenic conditioning of the emplacement of pegmatites

In North and Central Portugal most pegmatites appear in a cartographic space more or less coincident with the limits proposed by Lotze (1945) for the Central Iberian Zone (CIZ) of the Variscan Chain. The Central Iberian Pegmatite Belt (CCI) (Leal Gomes & Nunes, 2003) corresponds to the encompassing unit set for the regional distribution of bodies and dykes in the North and Centre of Portugal, which can hold all classes of pegmatites discriminated by Ginsburg *et al.* (1979) (Fig. 1). In this compartment, the regional division - pegmatite field - is the level of organization best suited to structurally discriminate pegmatites (Leal Gomes & Nunes, 2003).

In CCI, the pegmatites are related to granitic intrusions associable to the Variscan Orogeny. Ages are close to those that characterize the granites – 300 Ma (evolution of older granites) and 290 Ma (later granites). The parental plutonites are syn-tectonic two-mica granites and late to post-tectonic biotite granites.

In the final stages of the Variscan orogeny, are defined mega-scale corridors and ductile-brittle shear zones, subject to successive events of reactivation.

Thus, the geometric configuration of the fields is also influenced by horst-graben type displacements and adjustments, associated with major accidents parallel to the Vilariça type lineaments (Fig.1).

The diversity of pegmatites represented here comes from metallogenic specialization of parental granites, magmatic fractionation trends of their more evolved terms and deformational conditions of installation environments (Leal Gomes & Nunes, 2003).

Pegmatites hosted in granites, correspond to miarolitic ceramic pegmatites, related to late to post-tectonic granites regarding the 3rd phase of Variscan deformation (intra-Westphalian, D3). In most cases these are essentially biotite granites, medium to coarse grained sometimes porphyroid.

The sets and pegmatitic bodies acquire irregular shapes, or more regular geometries:

A- Irregular miarolitic or massive bodies - related to diapir like mobilizations.

B- Tabular bodies - related to intrusion into cupolas decompression bands in upper levels of the crust, where there is a prevalence of fragile conditions.

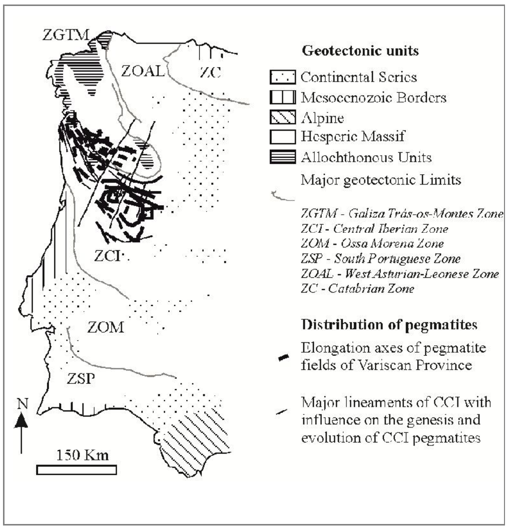

Figure 1 – Position of pegmatite fields in the Central Iberian Pegmatite Belt (CCI). Paleogeographic zonography to the West of the Iberian Peninsula (adapted from Leal Gomes and Nunes, 2003).

Leal Gomes & Nunes (2003) and Guimarães & Leal Gomes (2010), suggest a correlation between the dimensions and shapes of the pegmatite bodies and the chronology of parental granite emplacement.

1.2 Concerned pegmatite fields

The intra-granitic pegmatite fields of CCI, considered most useful for detecting conspicuous pegmatite distribution organizations and relevant compositional properties of host granitic masses, capable of assisting the detection of sub-outcropping pegmatite sets and bodies, and at the same time, able to cover a multitude of significant evidence situations, correspond to the areas of study: Ponte da Barca (Silva, 2002), Chaves (Pereira *et al.*, 1998 and Pereira, 2005), Satão-Aguiar da Beira (Leal Gomes, Trabulo *et al.,* 1995, Guimarães, 2012), Guarda-Belmonte (Silva *et al*., 2006, Ramos, 1998; Correia Neves, 1960).

The location and tectonic-orogenic conditioning of the studied pegmatitic fields and granitic areas are shown in Figure 2.

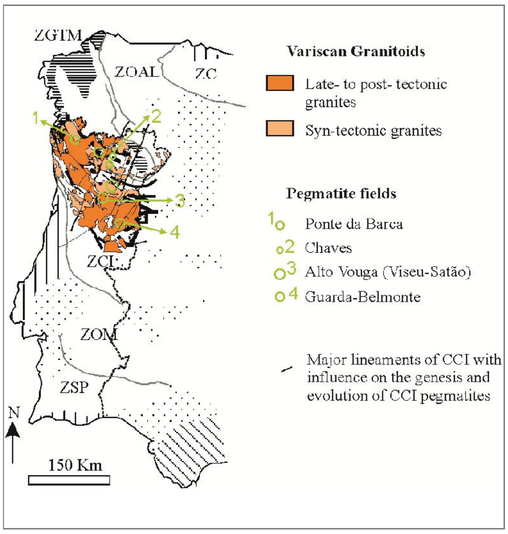

Figure 2 – Identification of areas with studied granitic pegmatite fields. Location in relation to the distribution of syn- and late- to post-tectonic Variscan granites. Legend as in Figure 1.

There, are represented contrasting granitoid types in contact, showing specific aspects of the distribution of genetically related pegmatites.

Overall, these express different levels of exhumation, morphological expression, and structural levels of swarms emplacement. In all cases, pegmatites have cupolar location in relation to the late-tectonic granites.

The contrasts of the pegmatites are manifested in the chemical typology, LCT and NYF, in the paragenetic and morphological diversity and, in respect of specific mineralizations (Table 1).

2 SITUATIONS OF ACCOMODATION AND ENTITIES RELATED TO THE CCI PEGMATITES

Are here contemplated the more consistent geometric organizations of pegmatite bodies in relation with the main brittle-ductile deformation structures, the cartographic expression of pegmatites relative to the host granites and certain related petrographic abnormalities, which are apparent in the studied pegmatite fields of the CCI.

2.1 Structural and geomorphological patterns of pegmatites emplacement

The late-Variscan shear corridors correspond to polycyclic magma feeding systems capable of transmitting the installation of pegmatite magmas, which evolve by gradual and direct "in situ" fractionation. The drainage and accommodation environments are fundamentally transtensive, formulated in ductile-brittle ruptures developed during the consolidation of magmas, or resulting from reactivation of earlier structures, precocious in the structuring of the Iberian Variscan Chain.

In northern and central Portugal, directions NW-SE, NNE-SSW and ENE-WSW (see Fig. 2) and especially their intersections, have decisive influence on pegmatite accommodation and seem to control the alignment of pegmatite bodies.

In the several pegmatite fields considered for study, the more consistent shears have N10-30ºE direction, observing the strict alignment of bodies under this direction. These should represent preferred percolation corridors, and may express paths linking pegmatite bodies. Simultaneously, suggest that the emplacement is related to an episode more or less bounded on the evolution of the regional stress field.

In Chaves (Fig. 2), this direction also plays the role of transmitting post-tectonic magmas, in the last stages of transcurrent deformation, already in uplifting, which should provide the felsic differentiated pegmatite magmas, which evolve from gravitational stratification panels, in successive stages of granitic cupola collapse

- stocksheider pegmatites with endogranite / exogranite complex (Pereira *et al.,* 1998 and Pereira, 2005).

It is also deduced from the analysis of intra-granitic fields, that the pegmatites often have locations near elongated ridges, which are adjacent to continuous lineaments. This topographic location should retract the main structural domains of emplacement in granitic domes.

Table 1 – Emplacement domains and discrimination of morphologies, paragenesis and mineralizations specific to the pegmatites of CCI fields covered in this study.

STUDIED AREAS *	PONTE DA BARCA	CHAVES	ALTO VOUGA		GUARDA-BELMONTE	
Emplacement domains	Intra-granitic	Peri-granitic	Intra-granitic	Peri-granitic	Intra-granitic	
Morphoscopy and morphometry	Irregular bodies (inverted drop and hourglass forms); tabular miarolitic bodies	"Stocksheider" (related to granite cupola colapse)	Irregular bodies (dumbbell, inverted drop, hourglass and spidery forms)	Bodies related to granite cupola collapse and rooted sills	Spidery irregular bodies	Sills
Typology	Miarolitic	Hybrid miarolitic NYF-(LCT)	Hybrid miarolitic	Rare elements (LCT-petalitic)	Hybrid	Rare elements (LCT-lepidolitic)
Paradigmatic pegmatites	Pedra da Moura, Dornas, Mata da Galinheira, Brufe, Carvalheira, Covide	Seixigal	Senhora de Assunção, Vigia, Pestarenga, Corujeira, Vila Longa, Venturinha	Queiriga-Lousadela	Fonte da Cal, Bendada	Alvarrões, Vela, Porto Tomé
Typomorphic accessory paragenesis	- Fe, Mn,Li phosphates + Sphalerite, Arsenopyrite, Pyrite, Pyrrhotite, Ilmenite; - Beryl + Li muscovite + Tantalite + Zircon.	-Fluorapatite +Chlorite+Schorl - Cassiterite +Molibdenite+Tantite; - Fluorapatite+ Phenakite+Bertrandrite+OH-Herderite	Beryl + Li-Fe-Mn-Al phosphates + sulphides + Nb-Ta-Ti-U oxides.	Petalite+Lepidolite+spodumene +topaz+beryl+cassiterite+wolframite+Nb-Ta-Ti oxides + sulphides + sulphosalts + carbonates+ fluorite.	- Beryl + Columbite-tantalite+ Zinwaldite + lollingite + Fe-Mn phosphates	- Lepidolite + topaz + tantalite + cassiterite + polilythionite+ beryl
Mineralization	Ti>Zn>As>(Li) Be>Li>Ta>Nb>Zr	Mg Sn>Mo>Ta>Ti Be>Mo	Be > Nb > Ta > W > Mo > Li>Sn	Li>Be>Sn> Ta>Nb>W>Bi	Be > Nb > Ta > W > Mo > Li>Sn	Li>Ta> Nb>Be>Sn> Cs

* corresponding to pegmatite fields of the CCI. Location in Figure 2.

2.2 "Roof-pendants", "stopped-blocks", and magma mixing corridors (mixing-mingling processes)

The pegmatitic productivity in some sectors appears to be related to contamination processes produced by the interaction of different types of magma, during the rise in the chambers, or resulting from the incorporation of portions of host rock, by collapsing of the chambers roofs.

At issue is the compositional hybridization by mixing with more basic magmas and digestion of polygenic metamorphic rocks, resulting from the transfer of "liquidus" depressors - hygromagmaphile and volatile elements – to the felsic magma, increasing its pegmatite generating potential (Leal Gomes and Nunes, 2003).

The proximity of the contaminated cupola chamber is revealed by the presence of stopped-blocks and roof-pendants. The inclusion or proximity to mixing corridors is revealed by stripes of concentration or proliferation of enclaves. These are common in directions that seem to converge to the pegmatitic bodies or constrain their alignment. They can take mega-scale expression, defining magmatic flow patterns consistent with the trajectories of pegmatitic magmas injection.

Mixing and contamination corridors are especially notable in the area of Ponte da Barca, where the most abundant enclaves, hosted in coarse grain porphyroid granites are hyper-micaceous xenoliths and rounded to ellipsoidal heterogeneous enclaves with meso to melanocratic tendency, fine-grained with or without phenocrysts. Fine to medium grain leucogranitic enclaves may be common in corridors established close to apical contacts between co-magmatic granites.

2.3 Heterogeneities in granitic cupolas and petrographic signatures of apical fractionation and segregation trends

Interface environments between granites, arising or not from cupola differentiation, appear to control the distribution of pegmatite swarms on its periphery.

In the geographical areas discussed herein, the bodies appear to have a well defined relationship with these interfaces between two or more granite.

Moreover, depending on the evolutive complexity of the generator plutonite, are expressed structuring lithologic units in host domes, which reflect irregularities in terms of flow processes and fractionation, showing a greater pegmatitic productivity in their neighborhood.

Some productive transitions on these interfaces could be discriminated and are marked by certain fluidal configurations, petrographic fractionation and segregation trends that are discussed below.

2.3.1 Leucocratic fácies with low granulometry and strong evidence of granitic differentiation

Often pegmatitic bodies are concentrated in areas with strong evidence of granitoid differentiation towards more leucocratic systems.

Transitional terms of fractionation, correspond to fine grained leucogranites and felsic composites of granite with graphic pegmatite with coarse, radial and feathery micaceous intergrowths. The transitional granites can then evolve to pegmatites in bands and pockets, and suffer internal fractionation, potentially generator of zonality.

Lithological masses of this kind are observed in most intra-granitic pegmatite groups studied.

In markedly hyper-aluminous environments, possibly contaminated through contact with metapelitic host rocks, these granites present garnet and cordierite and the fractionated and affiliated, morphologically evolved pegmatites, manifest abundant andalusite and Al phosphates.

2.3.1 Penetrative lineations marked by the fluidal planar alignment of potassic megafeldspars

Lineations corresponding to fluidalities established at low viscosity, assume approximately aureolar and cupular cartographic relation to the surrounding granites. Its attitude, usually accompanies the topography of the apical contact. The distribution of pegmatites is often coincident with the surrounding boundaries of proliferation of these fluidalities which can express upward balloning plumes organization sectioned by erosion (Pereira *et al.*, 2012).

The most typical fluidal aspects, are marked by linear and planar alignment of small potassium feldspar phenocrysts, with very high aspect ratio.

The kinematic interpretation of the geometric arrangement of feldspar phenocrysts may be functional for the establishment of magmatic flow components and reveal paths connecting pegmatite bodies, constrained by the topography of the granitic cupolas. Namely, in Ponte da Barca, granitic masses with fluidalities have sufficient continuity to be useful in pegmatites exploration, observing the mass expansion, and the proliferation of granitic pegmatoid structures and diffuse pegmatitic differentiations in interfaces between different lithologic terms.

2.3.2 Clustering phenomena of K-feldspar megacrysts in the granite host rocks

Agglomerations of K-feldspar megacrysts are also common in granites immediately hosting pegmatites. These are possibly determined by a higher rate of crystallization of the granitic mass, and a relatively higher viscosity or represent cumulated organizations influenced by physical separation in conditions of mobility of liquids. These surfaces with density or rigidity contrast usually manifest vertical tendency sub-parallel to the attitude of some shear zones, suggesting the influence of the D3 stress field on the emplacement of granites and affiliated pegmatites.

In the area of Viseu (Alto Vouga pegmatite field, Fig. 2), these settings are common in the porphyroid facies proximal to some bodies.

2.3.3 "Filter-pressing" phenomena

Often the contact between granitic facies arising from cupola differentiation expresses enrichment in ferromagnesian constituents, mainly biotite. These represent side segregations by removal of felsic constituents by filter-pressing (compare to Weinberg et al., 2001), and have banded and schlierenitic aspect, with coarse grain size. The proximity to fluidal organization units suggests that possibilities of segregation are strongly influenced by the mobility of liquids.

Relationships such as these are contemplated in interfaces between porphyroid granites and fine grained differentiated leucogranites, as for example in Ponte da Barca, where the modal content of biotite in schlierenitic bands with thickness greater than 1 m, may exceed 80%.

Less penetrative schlierenitic aspects are also observed in most granites hosting pegmatites, in the other geographical areas.

2.3.4 "Bubbling" phenomena

The early stages of pegmatitic installation can be characterized by the rise of fluid bubbles in the host granitic cupolas. Result from magmas with culminating enrichment in volatiles that tend quickly to supersaturation at low crystallization rate. The degassing phenomena and mobilization would be facilitated by relatively rapid decompression and cooling of the granite host (e.g. Peretyazhko, 2010).

In a subsequent evolutionary stage of pegmatitic differentiates drainage, bubbles can form pockets morphologically and paragenetically more evolved (Guimarães, 2012 and Leal Gomes & Nunes, 2003).

In the area of Viseu (Fig. 2), the freezing of the ascensional process, resulted in the crystallization of myriads of bubble-like pegmatites with a volume of a few cubic centimeters in a fine grained leucogranite. The spheres and ellipsoids are miarolitic, and distributed below the topographic level of emplacement of Senhora de Assunção pegmatite (Tab.1).

2.4 Patterns of hydrothermal and supergene alteration of productive granitic masses

Trends of yellowing of the granitic mass, caused by supergene leaching of Fe from biotite and garnet crystals, are observed frequently in the vicinity of pegmatitic bodies, particularly in relation to leucogranitic transitional facies. The biotites are discolored and cloritized, occurring consistently the late fixation of Fe in the form of vacuolar replenishments.

Epidotization can also be widespread along major shear structures that control the accommodation of pegmatitic differentiates. In particular, directions N30ºE and ENE-WSW, considered determinant of accommodation and upward mobilization of residual differentiates can, in face of subsequent reactivations, present epidote and influence its concentration in proximal granites and pegmatites.

The most pervasive reddening is typical of the peripheries of mixing corridors, observing in coarse grained porphyroid granitic facies the red shading, both of megacrysts and matrix.

Phenomena of albitisation of granitic host masses are very rare. The fluids that originate replacement units in the later stages of the evolution of pegmatites, not normally extend beyond the contours of the bodies and tabular boxes.

Table 2 –Accommodation situations and entities related to the pegmatites of CCI intra-granitic fields: Ponte da Barca, Chaves, Alto Vouga and Guarda-Belmonte.

PEGMATITE FIELDS / EXPLORATION GUIDES	PONTE DA BARCA	CHAVES	ALTO VOUGA	GUARDA-BELMONTE
Structural and geomorphological patterns	NW-SE to ESE-WNW, N30ºE	N30ºE	N30ºE conjugated with E-W	N20ºE conjugated with E-W
Mixing-mingling processes	Mixing-mingling corridors.		Domains with "magmatic stopping" and "roof-pendants" .	
Heterogeneities in granitic cupolas and petrographic signatures of apical fractionation and segregation trends				
Leucocratic facies with low granulometry and strong evidence of granitic differentiation	Fine-grained leucogranites with garnet and cordierite; pegmatoid leucogranites with coarse, radial and feathery micaceous intergrowths.		Fine-grained leucogranites; graphic leucogranites with coarse, radial and feathery micaceous intergrowths.	Heterogeneous granites with rounded quartz; pegmatoid leucogranites.
Penetrative lineations marked by the fluidal planar alignment of potassic megafeldspars	Linear and plan-linear concentric fluidalities.			
Clustering phenomena of K-feldspar megacrysts			K-feldspar megacrysts agglomerations with vertical trend.	
"Filter-pressing" phenomena	Exuberant shlieren between porphyroid granites and garnet-cordierite bearing leucogranites.		Frequent within porphyroid granites and interfaces with fine-grained leucogranites.	Occasional on the periphery of transitional leucogranites.
"Bubbling" phenomena			Miarolitic bubble-like pegmatites: spheres and ellipsoids with small volume.	
Patterns of hydrothermal and supergene alteration of productive granitic masses	Yellowing and reddening.	Peri-pegmatitic banded albitisation.	Epidotization	Yellowing and reddening

3 REMOTE EXPRESSION IN SATELLITE IMAGES

The lack of consistent physical and chemical contrasts in relation to granitic host rocks, complicates the geophysical and geochemical exploration of intra-granitic pegmatitic bodies.

Lately, remote sensing using satellite imagery is beginning to be explored as a way for the exploration of outcropping bodies (Silva, 2009). The mineralogical characteristics of residual magmatic composites make viable its detection in hyperspectral images.

3.1 Valuation of remote sensing analysis in the context of exploration of hidden pegmatites

When equating the identification of new hidden shallow deposits, geological exploration, especially structural analysis of pegmatites and rocks in its vicinity, seems to be the most sustainable path (Leal Gomes, 2010; Guimarães, 2012). From the organization of attitudes, shapes and internal structures of the deposits and host masses, are deduced three dimensional conceptual models, which can be extrapolated assuming predictive efficacy (Leal Gomes, 2010).

The diversity of situations deduced in this work, support useful models in exploration. These have utility for defining levels of emplacement of pegmatites in the granitic cupolas, and from a conceptual point of view, are in principle usable by remote sensing, as they represent extreme and contrasting chromatic types with sufficient continuity in the surface (length and width). The chromatic thresholds of the contacts (granite) / (pegmatite) or (granite) / (granite with peculiar structuration units) expressed in the prior inventory of productivity situations are the following: fractionated granites with low granulometry and marked felsitic composition, *clear*; segregations and facies resulting from contamination and mixing with high modal expression of mafic ferromagnesian constituents, *dark*; trends of hydrothermal and supergene alteration promote *yellowing*, *reddening* and *greenish* colorations.

Besides the chromatic effect, also the conspicuous structural organization of these targets is usable in conjunction, to the delimitation of favorable areas for exploration.

3.2 Usefulness of processing satellite images for remote evidence of exploration guides

The previous inventory of productivity situations, serves geological exploration of sub-outcropping deposits in strategic and tactical steps.

By providing coherent textural and chromatic contrasts, exploration may resort to remote sensing, existing inclusively possibilities of evidence in constrained spectral images such as those resulting from Landsat.

Methodologically, filtered images subjected to any type of mathematical processing, are more effective and functional in the analysis of the surface. Such analysis has been sustained with the software SPRING (Camara *et al*., 1996); among the most revealing tests are:

- *directional filtering* –for evidence of shear networks and their points of intersection, where are receptioned pegmatitic differentiates.
- *Principal component analysis* – for evidence of anomalous lithological units with important spectral contrast relative to host rocks, which may correspond to exploration guides for pegmatites.
- *Maxver* classification (maximum likelihood algorithm) – for extrapolation to the region of spectral configurations correlated with pegmatites.

Also equates on a next phase, the determination of field spectral parameters representative of the described petrographic entities, using a spectroradiometer.

This survey should reflect a greater diversity of situations and possibilities of remote detection by permitting the establishment of quantitative relationships between pegmatites exploration guides and its expression in satellite images.

It is expected to expand the pegmatitic and related entities spectral database, and ultimately refine and standardize procedures for exploration, through remote sensing, of irregular and tabular bodies situated in intra-granitic context, with operational use analogous to geophysical and geochemical methods.

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