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Magnetic fabrics in Portuguese Variscan granites: structural markers of the Variscan orogeny

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1. AIMS

This work focuses on the magnetic fabric of **twenty Variscan granitic massifs** (Figure 1), from northern and central of Portugal, and considers the **Anisotropy of Magnetic Susceptibility** (AMS) data obtained in a total of about **750 sampling sites**.

In northern and central of Portugal, **three main Variscan ductile deformation phases** were recognized and described: **D_1, D_2 and D_3**, being **the period of emplacement of granitic magmas generally referenced to D3 (315-310Ma).**

- **D_3 ductile phase** produced **wide amplitude folds with NW-SE subvertical axial plane and subvertical dextral and sinistral ductile shear zones** (Figure 1), forming obtuse angles with the maximum compression direction, **σ_1, NE-SW oriented**.
- The **post-D_3 brittle phase** was responsible for the **development of conjugate faults (NNW-SSE, NNE-SSW and ENE-WSW)**, related to **a N-S late-Variscan maximum compression**.

2. THEORY

The ratio between the **induced magnetization**, *M* (expressed in A/m), and the **magnetizing field**, *H* (expressed in A/m), is the **magnetic susceptibility**, *K* (dimensionless in SI units).

$$K = M / H$$

In polymineralic rocks, the **magnetic susceptibility is the sum of the contribution of all rock-forming minerals**, so it varies with concentration and composition of those mineral phases, which may include diamagnetic, paramagnetic or ferromagnetic *s.l.* species.

- The **Anisotropy of Magnetic Susceptibility defines a symmetric 2nd-rank tensor originated from a symmetric matrix that describes the spatial variation of magnetic susceptibility.** This tensor is expressed by the **magnitude** (eigenvalues) and **orientation** (eigenvectors) of the **maximum** (K_1), **intermediate** (K_2) and **minimum** (K_3) principal axes of magnetic ellipsoid ($K_1 = K_{max} \geq K_2 = K_{int} \geq K_3 = K_{min}$) (Figure 2).

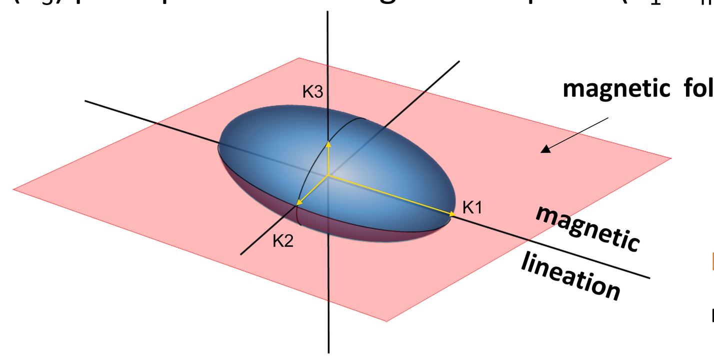


Figure 2. Spatial representation of a prolate magnetic ellipsoid with the representation of the K_1, K_2 and K_3 principal axes.

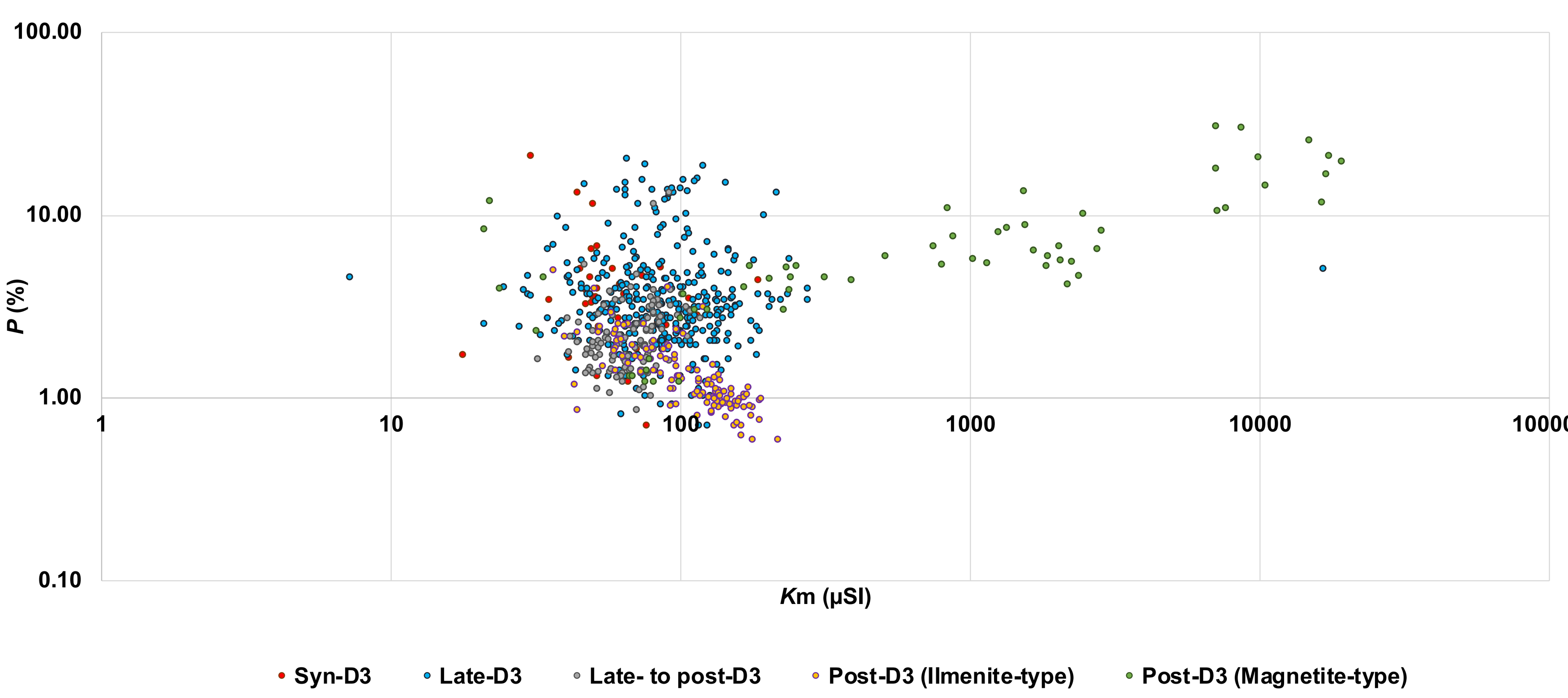
3. "GRANITES AND YET MORE GRANITES"

The studied granites were classified according to field observations and U-Pb dating of their emplacement relative to the D_3 phase .

Granites	Age
Syn-D_3 group composed by two-mica, médium- to coarse-grained, generally porphyritic granites	ca. 320-310 Ma
Late-D_3 group composed by monzogranites, biotite-rich and two-mica granites with medium- to coarse-grained and porphyritic texture	ca. 310-305 Ma
Late- to post-D_3 group composed by two-mica and biotite-rich granites with médium-grained and porphyritic texture	ca. 305-290 Ma
Post-D_3 group is composed by monzogranites and biotite-rich granites with medium-grained and porphyritic texture	ca. < 290 Ma

4. PARAMAGNETIC OR FERROMAGNETIC GRANITES?

- Despite of different petrographic and geochemical characteristics, **K values in the majority of the granites studied range from 20 to 300 × 10^{-6} SI units** corresponding to **reduced- or ilmenite-type granites** (paramagnetic behaviour). The P% is generally lower than 8% which reflect its low deformation patterns.
- The **oxidized-or magnetite-type granites** (ferromagnetic behaviour) **are scarce and are represented by some post-tectonic (or post-D_3) biotite-rich granites with K values ranging from 15 to 20 × 10^{-3} SI units** (Figure 3, green dots), which display **higher P% caused by the presence of magnetite** in the accessory mineral phases.



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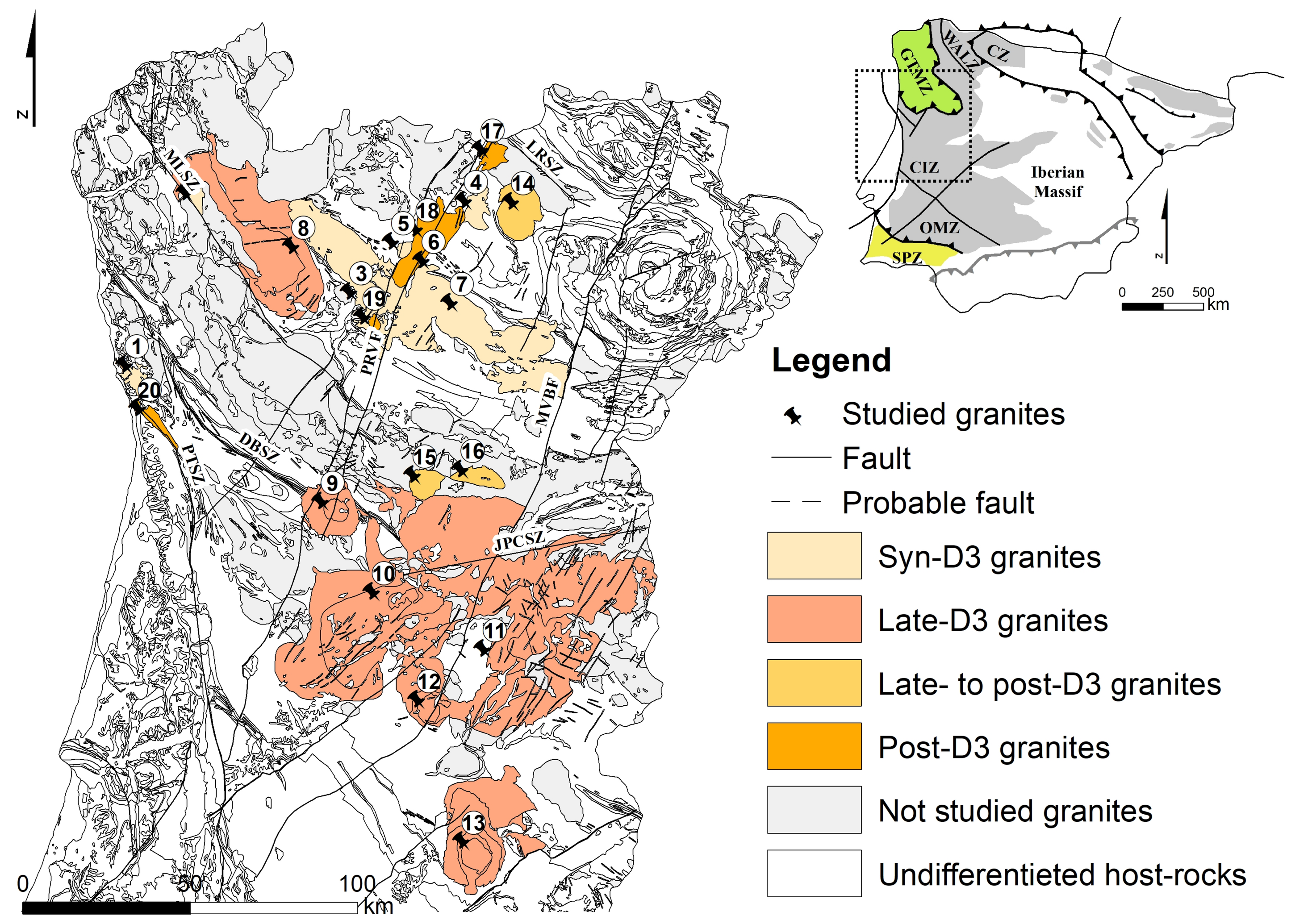

Figure 1. Simplidied geological map of the northern and central of Portugal, highlighting the studied granites subdivided in four groups related to its emplacement during the D_3 ductile phase. **Syn-D_3 granites**, 320-310 Ma: (1) Porto, (2) S. Mamede, (3) Vila Real, (4) Serapicos, (5) Minheu, (6) Lagoa, (7) Gralheira; **Late-D_3 granites**, 310-305 Ma: (8) Vieira do Minho, (9) Castro Daire, (10) Mangualde, (11) Covilhã, (12) Seia, (13) Castelo Branco; **Late- to post-D_3 granites**, 305-290 Ma: (14) Valpaços, (15) Caria, (16) Vila da Ponte; and, **Post-D_3 granites**, < 290 Ma: (17) Águas Frias-Chaves, (18) Vila Pouca de Aguiar, (19) Lamas de Olo, (20) Lavadores-Madalena. **D_3 shear zones:** (MLSZ) Malpica-Lamego Shear Zone, (PTSZ) Porto-Tomar Shear Zone, (DBSZ) Dúrico-Beirão Shear Zone, (JPCSZ) Juzbado-Penalva do Castelo Shear Zone, (LRSZ) Laza-Rebordelo Shear Zone. **Late-D_3 strike-slip faults:** (PRF) Penacova-Régua-Verín Fault, (MVBF) Manteigas-Vilariça-Bragança Fault.

5. MAGNETIC FABRIC

Magnetic fabric gives two types of directional data, **magnetic foliations (plane normal to K_{min})** and **magnetic lineations (trend and plunge of K_{max})** (Figure 2), which provide important information:

- **orientation of the magmatic flow;**
- **relationship between the magma emplacement and tectonics;**
- **stress field** (Figure 4).

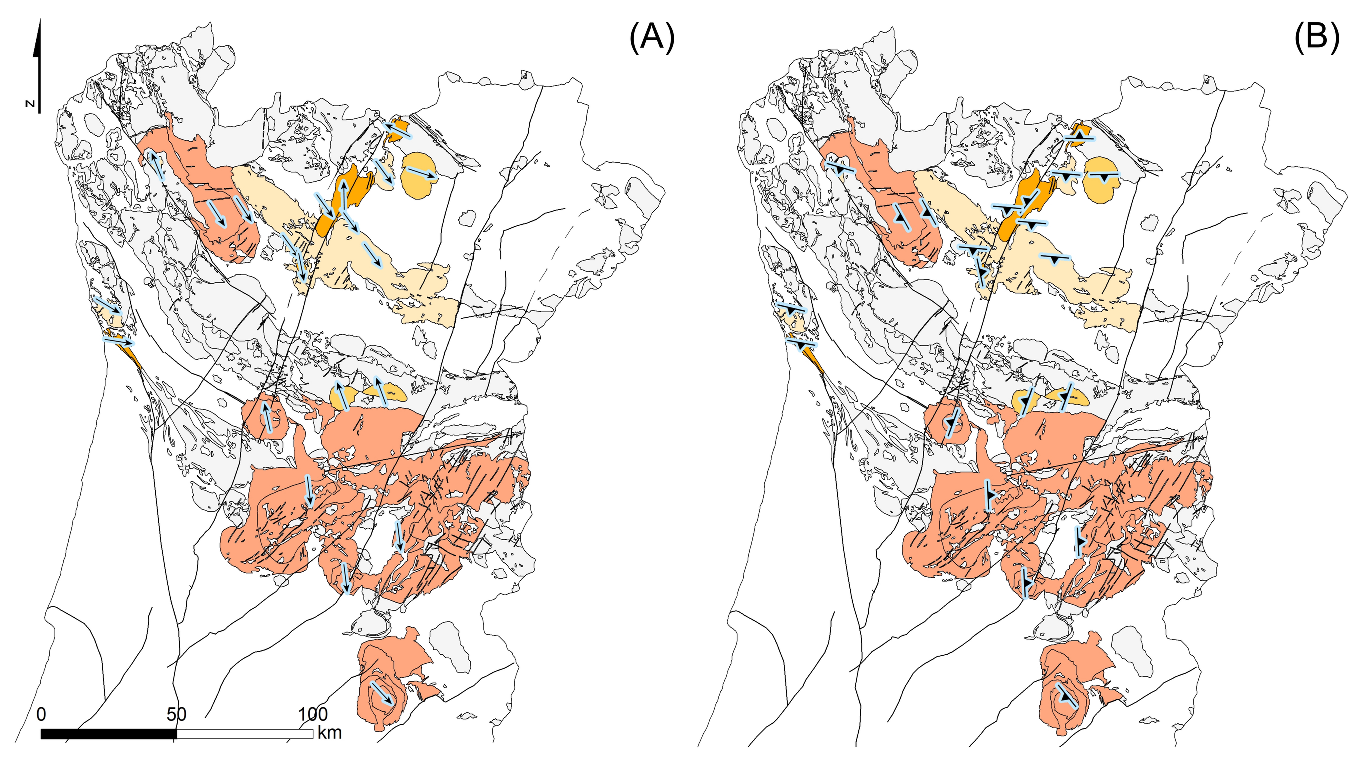

Figure 4. Spatial distribution of directional data obtained in anisotropy of magnetic susceptibility for all granites. (A) Magnetic Lineations; (B) Magnetic Foliations. The symbology represent the average magnetic lineation and foliation obtained in each granite.

6. STRUCTURAL MARKERS OF VARISCAN OROGENY

1. **Syn-D_3 granites** show **magnetic foliations and lineations consistent with the syn-D_3 variscan shear zones *ca.* N110°-120°E**, related to **σ_1 NE-SW oriented**. The **foliations** are, mainly, **subvertical** (> 60º), which may indicate a **high thickness of the granitic body and deep rooting**; on the other hand, the magnetic lineations exhibit variables plunges (Figure 4).
2. **Late-D_3 and late- to post-D_3 granites** are characterized by **foliations and lineations, dominantly NNW-SSE to NNE-SSW oriented** (Figure 4 and 5). The **foliations are subvertical** (> 60º) and the **lineations** have, generally, **soft plunges**.
3. **Post-D_3 granites** have, in general, **magnetic foliations and lineations associated with important regional post-D_3 brittle structures**, which display **NNE-SSW trending** (Figure 4), related to **N-S maximum compression.** The **subhorizontal fabric** may suggest a **small thickness** of the granitic bodies.
4. There is a **dominance of weakly dipping lineations** (slope <60º), **indicating that the feeding zones are deep, which supports the idea of an emplacement at high structural levels.**
5. **The magnetic fabric of different granites materializes the structural anisotropies found during the evolution of the variscan orogeny, and points out the rotation of the maximum compression, σ_1, from D_3 phase to late-to-post D_3 phases.**

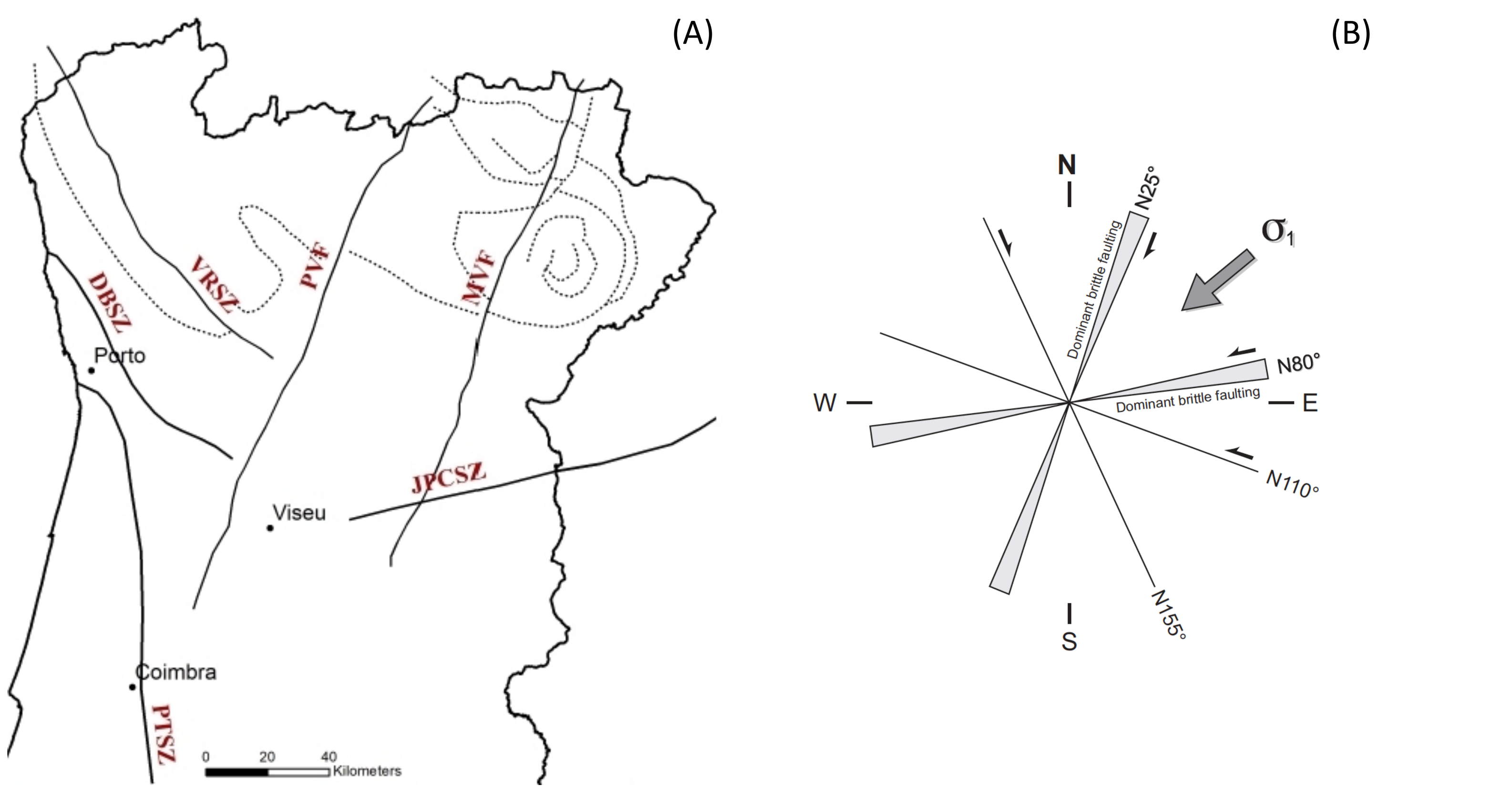

Figure 5. (A) D_3 shear zones and late-D_3 strike-slip faults (see caption Figure 1). (B) Geometry of the D_3 structures according to Marques et al. (2002). Rotation of σ_1, NE-SW oriented during D_3 phase to a N-S in post-D_3 phase.