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Geochemical proxies to granite-related mineral systems using multi-element whole-rock analysis

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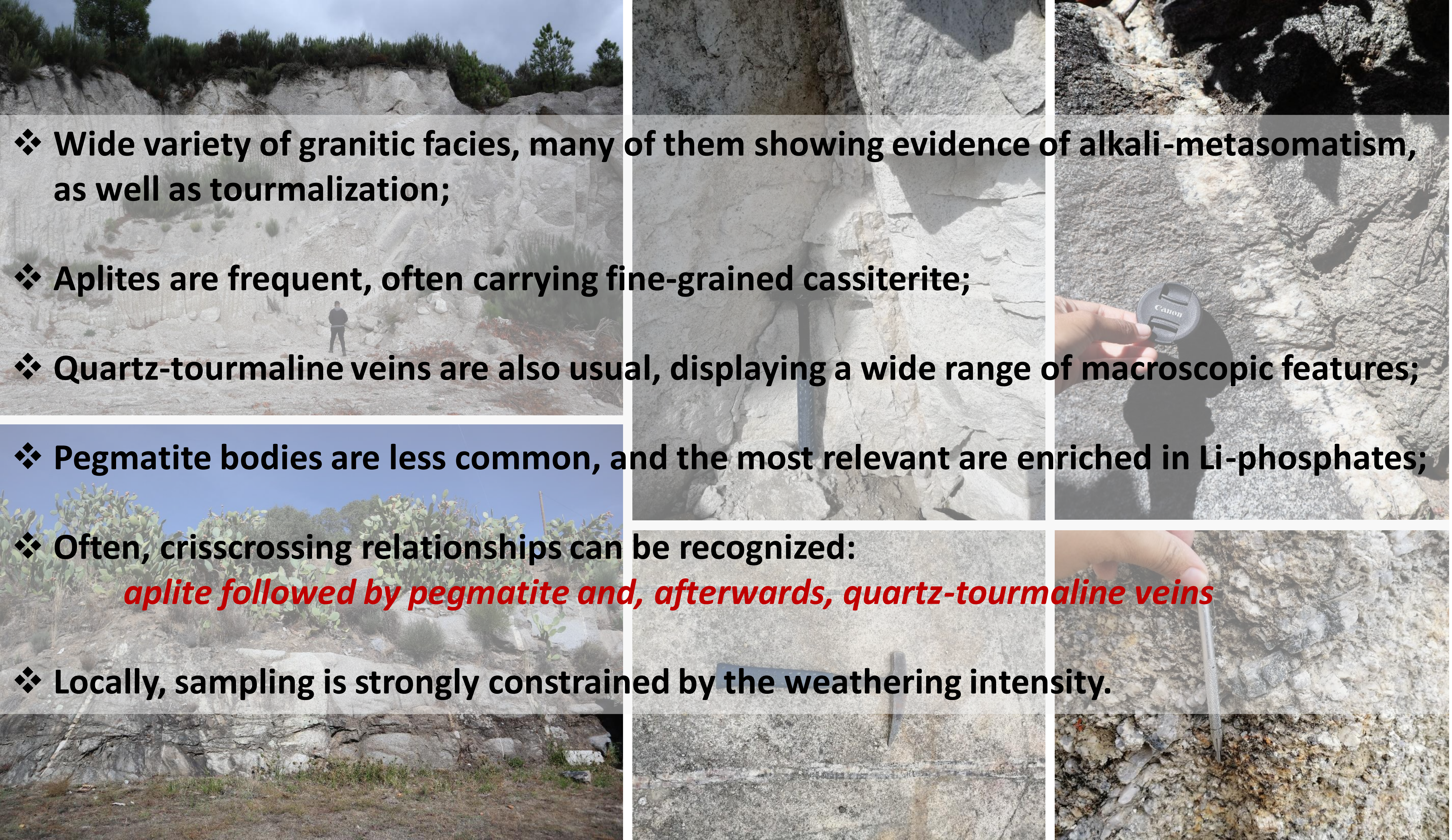
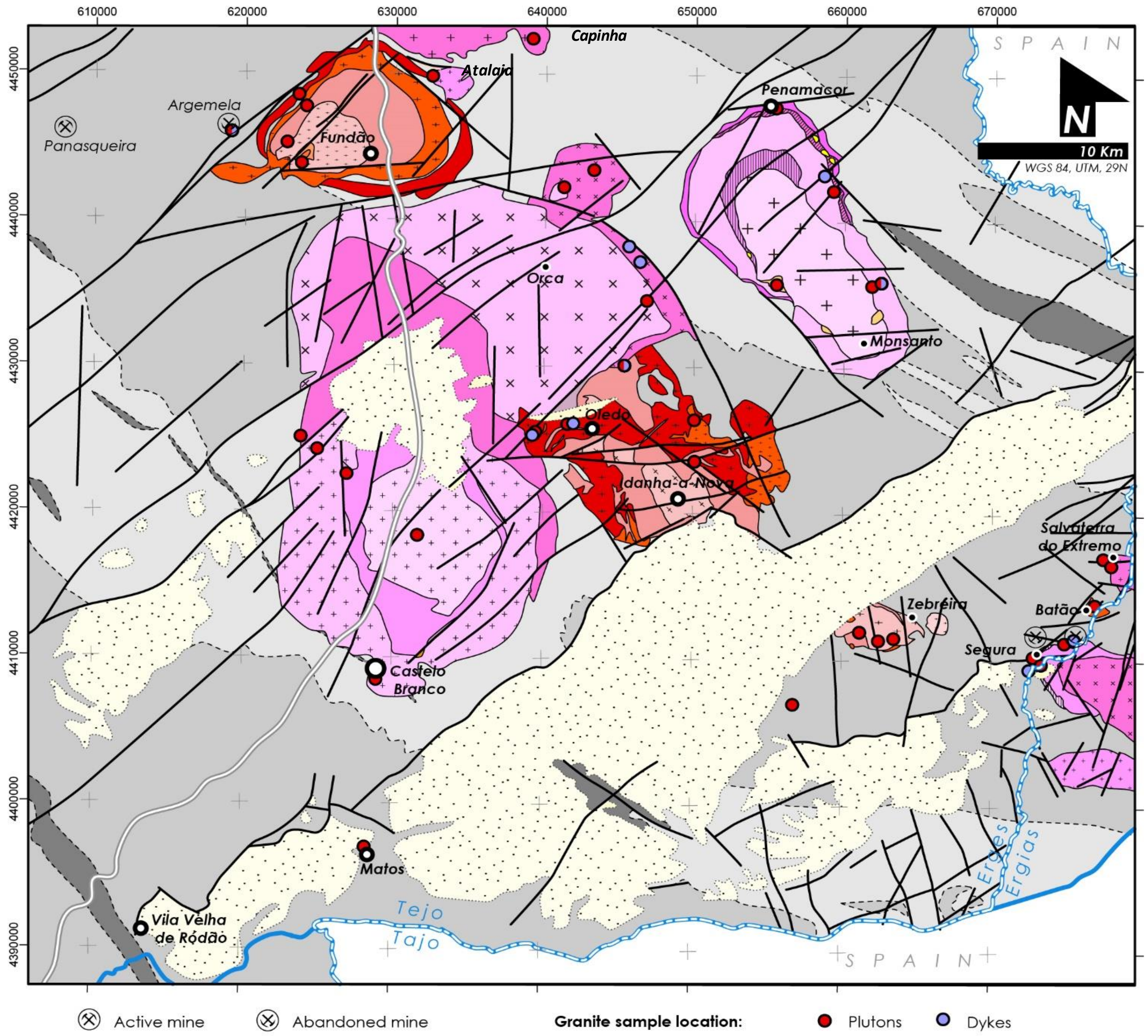


- Wide variety of granitic facies, many of them showing evidence of alkali-metasomatism, as well as tourmalization;
- Aplites are frequent, often carrying fine-grained cassiterite;
- Quartz-tourmaline veins are also usual, displaying a wide range of macroscopic features;
- Pegmatite bodies are less common, and the most relevant are enriched in Li-phosphates;
- Often, crisscrossing relationships can be recognized:

  aplite followed by pegmatite and, afterwards, quartz-tourmaline veins
- Locally, sampling is strongly constrained by the weathering intensity.

Granite-related ore systems

Exclusively associated with Variscan granite suites



Variscan (late Carboniferous) plutons

Pero-Viseu and Capinha

- Coarse- to very coarse-grained, porphyritic granite

Atalaia

- Albite-muscovite granite

Orca

- $G_{Orc}1$: Medium- to fine-grained muscovite granite
- $G_{Orc}2$: Porphyroid biotite-muscovite granite

Castelo Branco

- $G_{CB}1$: Medium- to fine-grained muscovite-biotite granite
- $G_{CB}2$: Medium- to fine-grained porphyritic biotite-muscovite granodiorite
- $G_{CB}3,4$: Medium- to coarse-grained porphyritic biotite-muscovite granite
- $G_{CB}5$: Coarse-grained muscovite-biotite granite

Penamacor-Monsanto

- $G_{PM}1$: Medium- to coarse-grained muscovite-biotite granite
- $G_{PM}2$: Medium-grained muscovite-biotite granite
- $G_{PM}3$: Coarse- to medium-grained porphyritic biotite-muscovite granite
- $G_{PM}4$: Medium-grained porphyritic biotite-muscovite granite
- $G_{PM}5$: Coarse-grained porphyritic muscovite-biotite granite
- $G_{PM}6$: Medium- to coarse-grained porphyritic
- Pegmatite-Aplite dykes swarm

Salvaterra do Extremo

- Medium- to coarse-grained muscovite granite

Segura-Cabeza de Araya

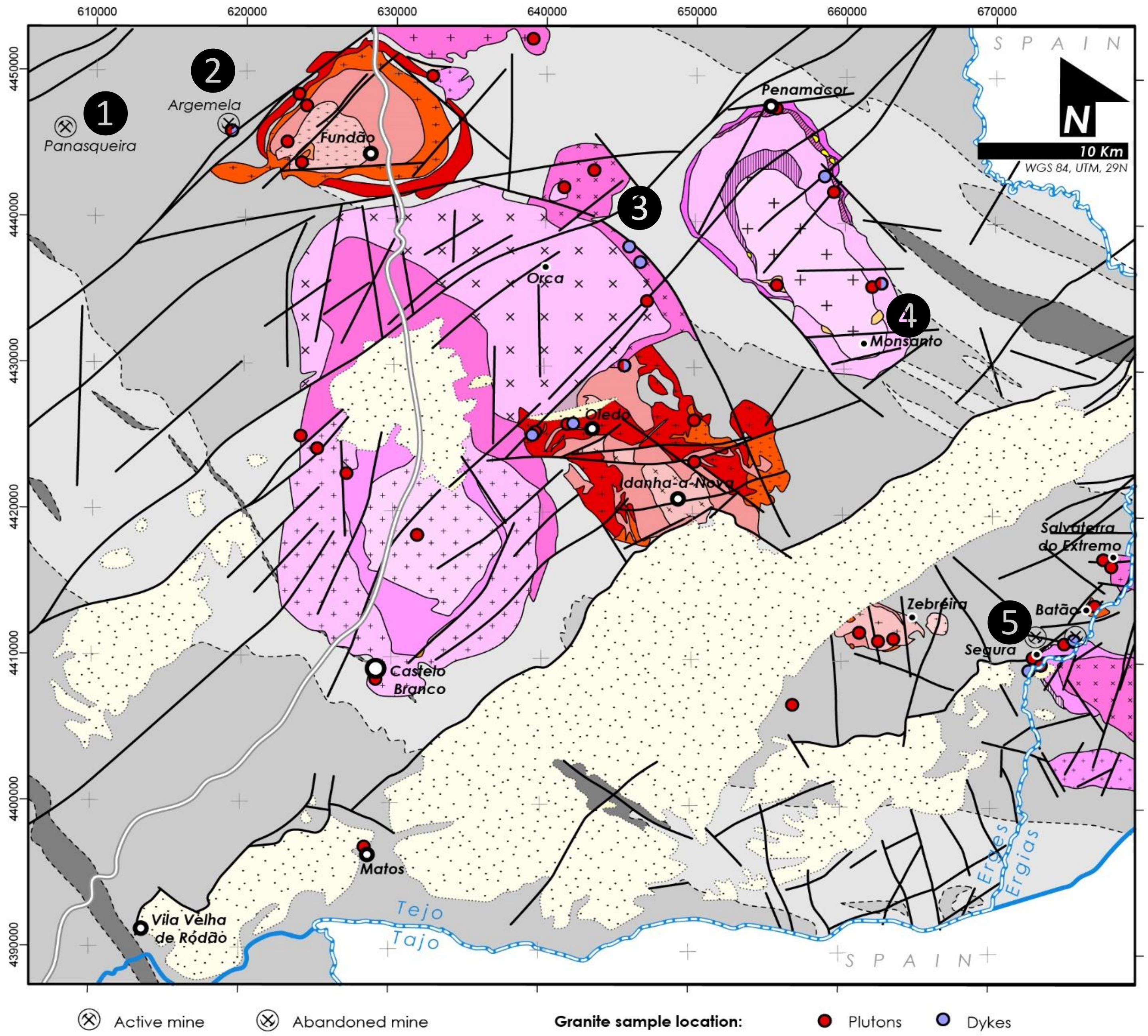
- $G_{SCA}1$: Coarse- to fine-grained muscovite-turmaline granite
- $G_{SCA}2$: Porphyroid two-mica granite
- $G_{SCA}3$: Porphyroid biotite-cordierite granite

Estorniños

- Two-mica porphyroid granite

Main targets studied

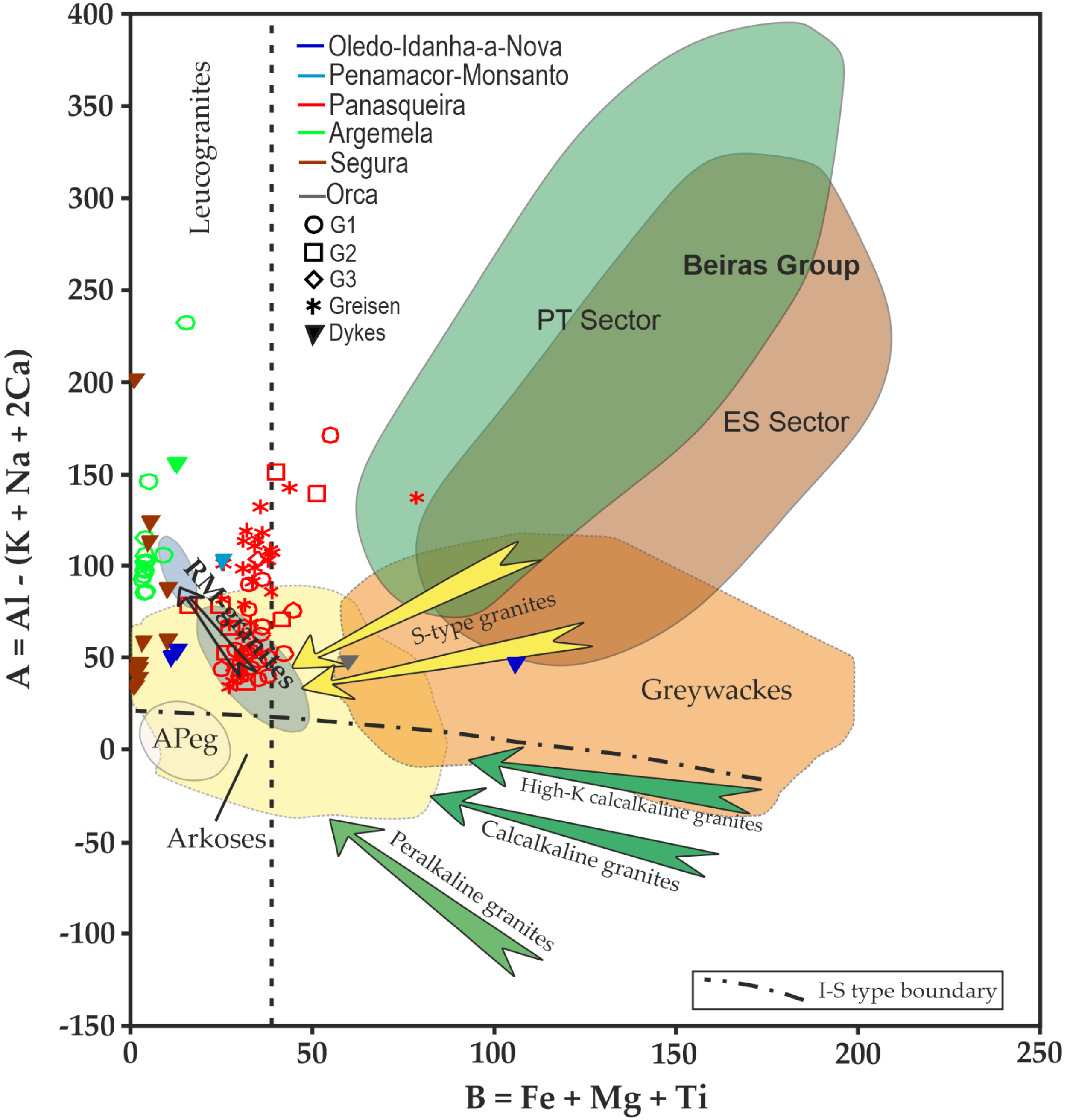
Exclusively associated with Variscan granite suites



1. Panasqueira
   - granites: drill-core samples
   - greisen: underground mining
2. Cabeço de Argemela
   - granites and dykes: key exposures
3. Mata da Rainha (***work in progress***)
   - granites and dykes: key exposures
4. Monsanto-Medelim
   - granites and dykes: key exposures
5. Segura
   - granites and dykes: key exposures

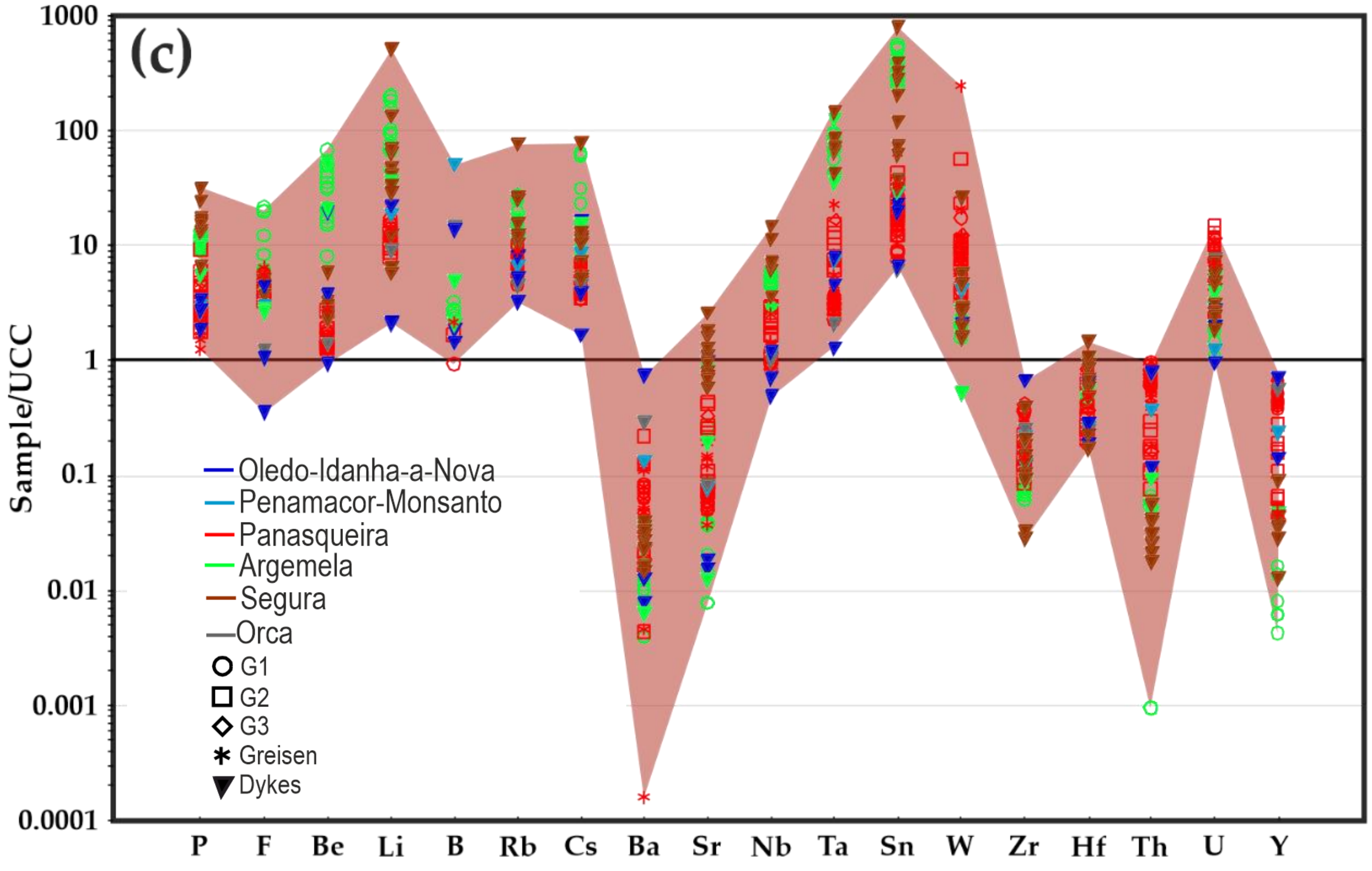
Highly differentiated rocks

- Follow the typical S-type granites fractionation trend;
- Plot in the leucogranites field, near the RMG composition;
- Panasqueira greisen, Argemela RMG and aplite-pegmatite dykes from Argemela and Segura deviate from the general trend.



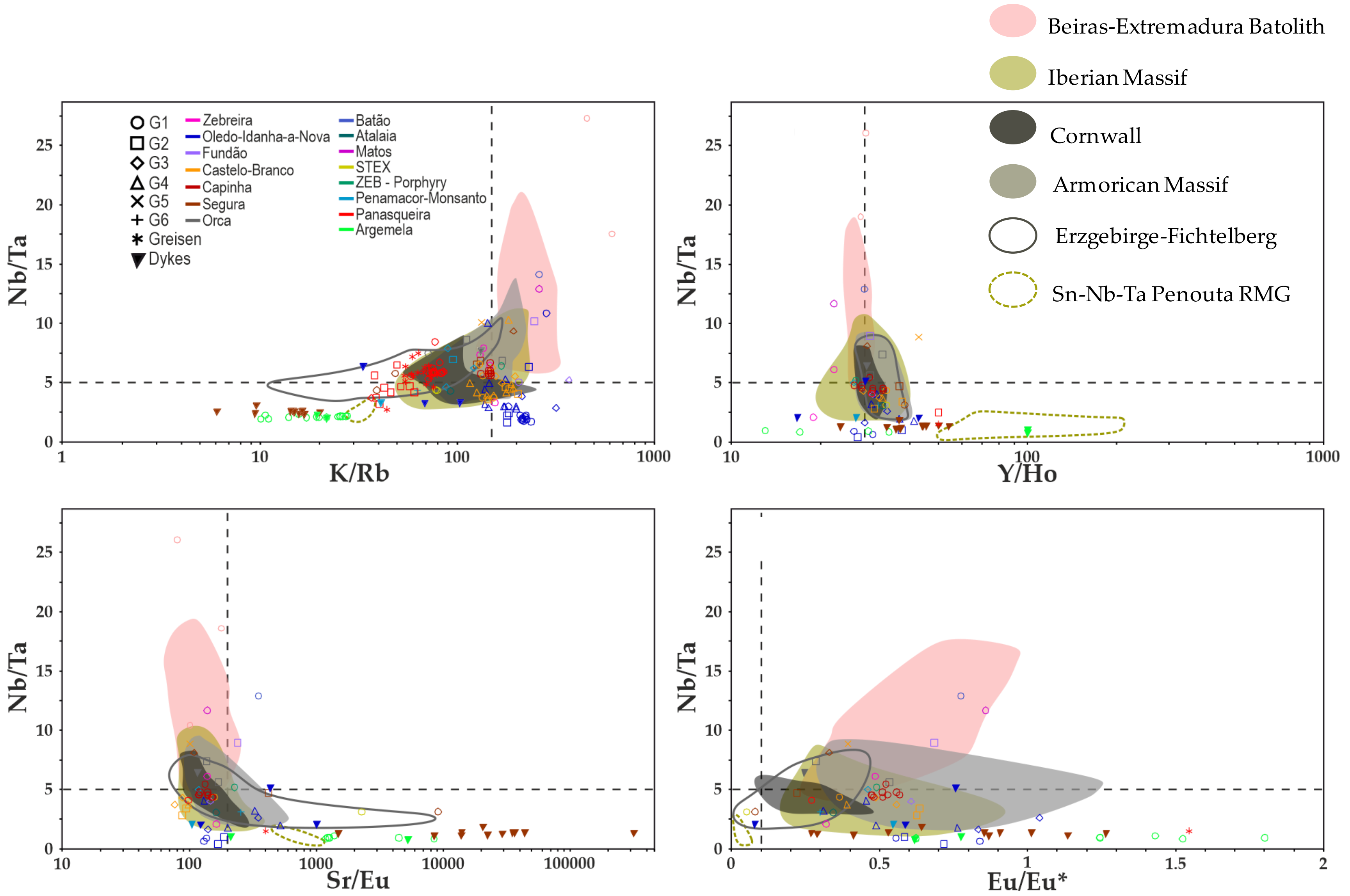
Highly differentiated rocks

- Patterns comparable to Variscan (S-type) granite suites, but:
  - Higher enrichments in **P** (≤ 25×UCC), **F** (≤ 15×UCC), **Be** (≤ 70×UCC), **Li** (≤ 500×UCC), **Ta** (≤ 150×UCC) and **Sn** (≤ 800×UCC).
  - Additional significant enrichment in **Nb** (≤ 20×UCC).



Granite differentiation and metal specialization

- Highly peraluminous Variscan granites and dykes are strongly differentiated and significantly affected by magmatic-hydro-thermal processes.
  - K/Rb < 150
  - Nb/Ta < 5
  - Y/Ho ≠ 28
  - Sr/Eu > 200
  - Eu/Eu* < 0.1
- Good compositional similarity with published data.



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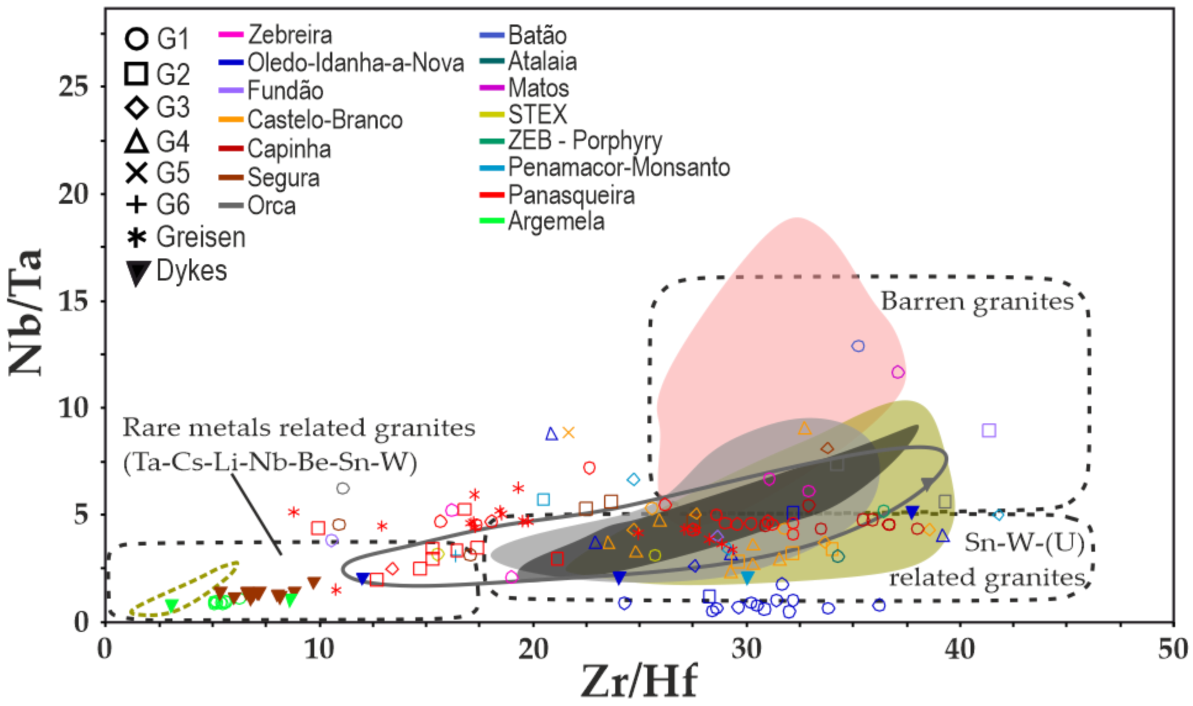
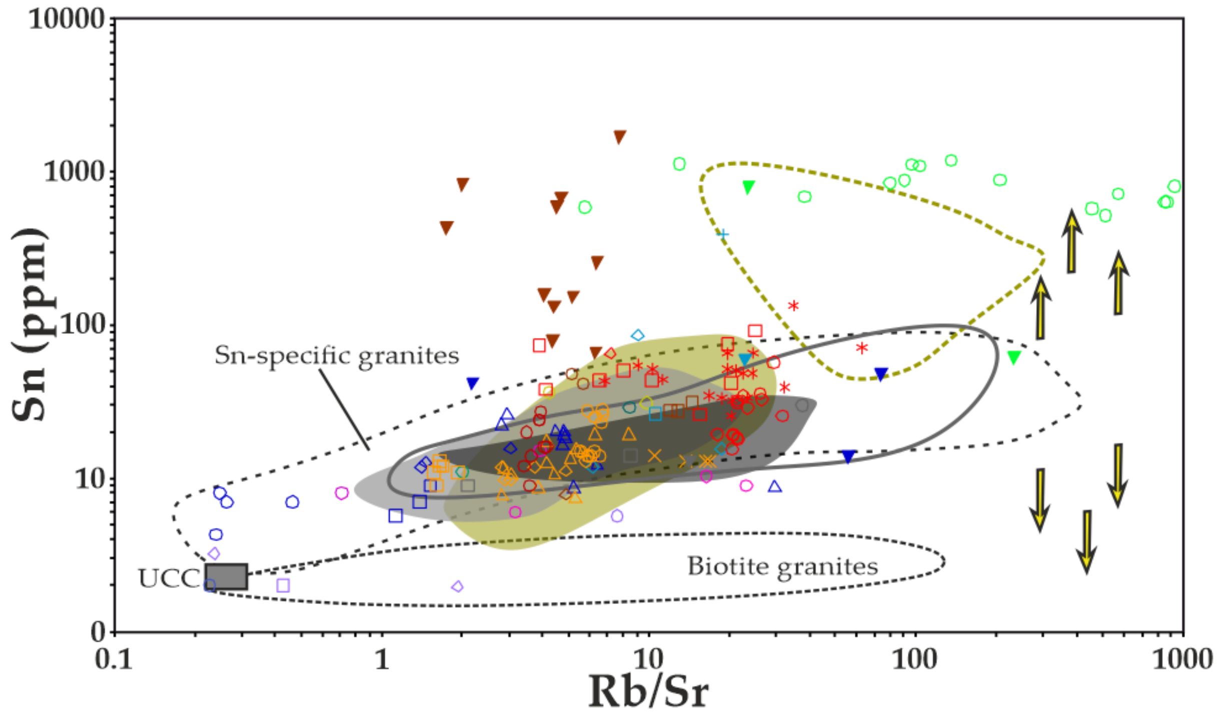


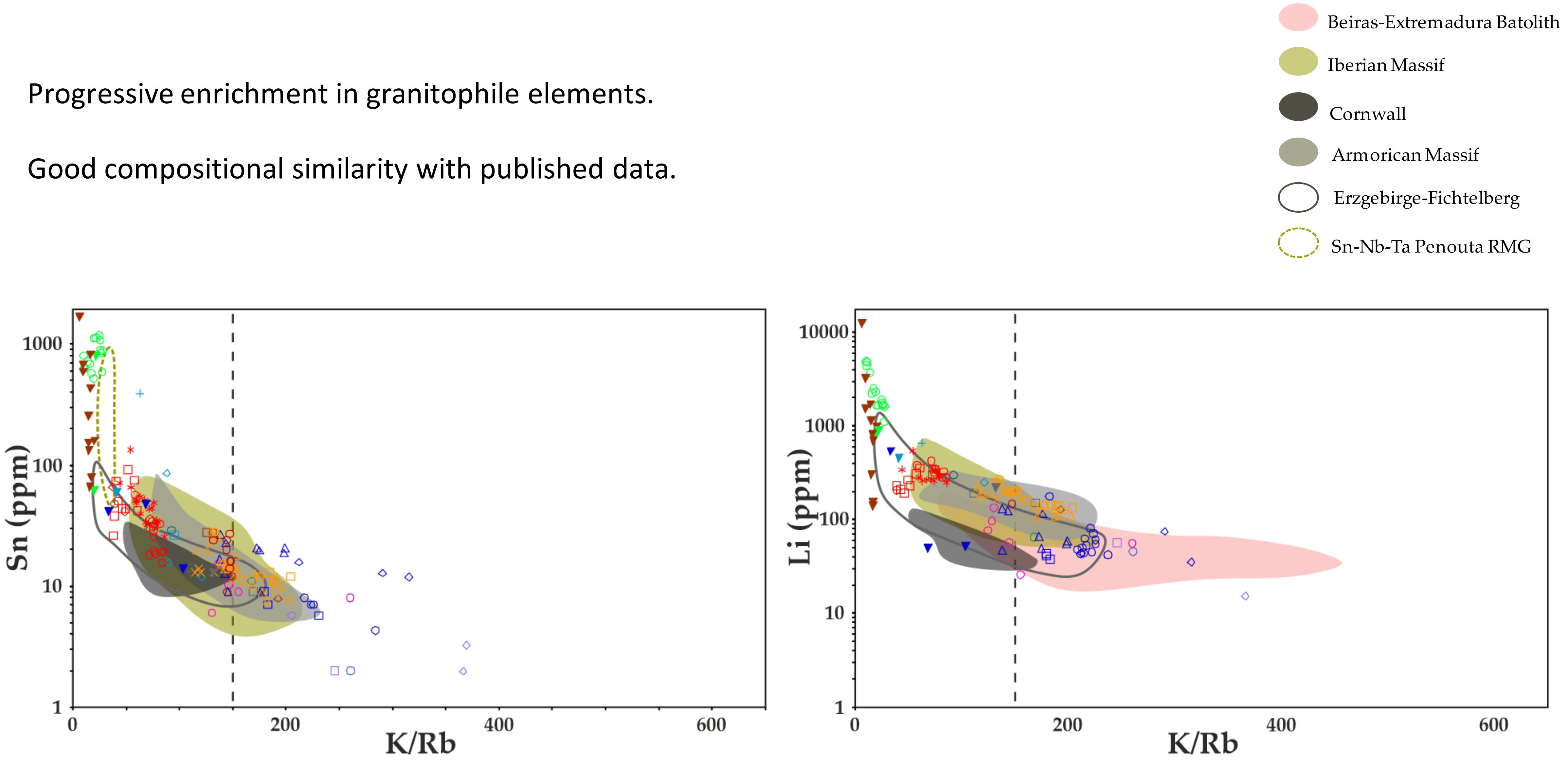
Ballouard et al. 2016



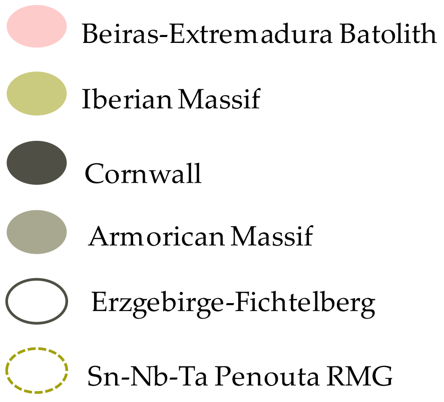
Romer et al. 2020

Granite differentiation and metal specialization

- Progressive enrichment in granitophile elements.
- Good compositional similarity with published data.



Granite differentiation and metal specialization



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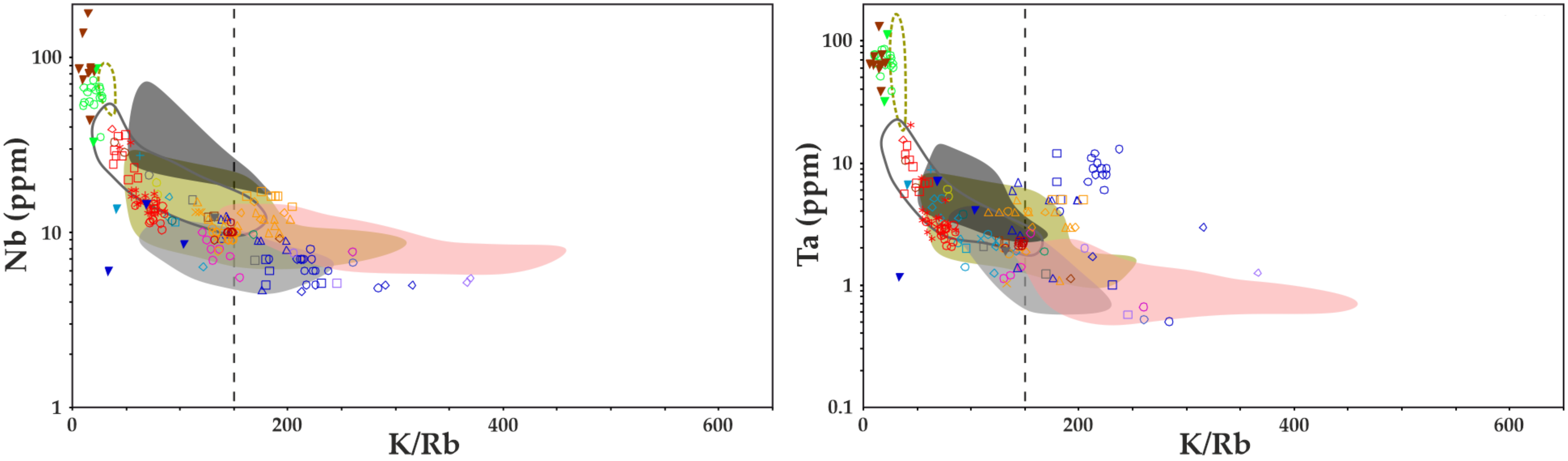


Whole-rock REE contents. *The tetrad effect as possible vector for different types of granite-related mineralization*

minerals

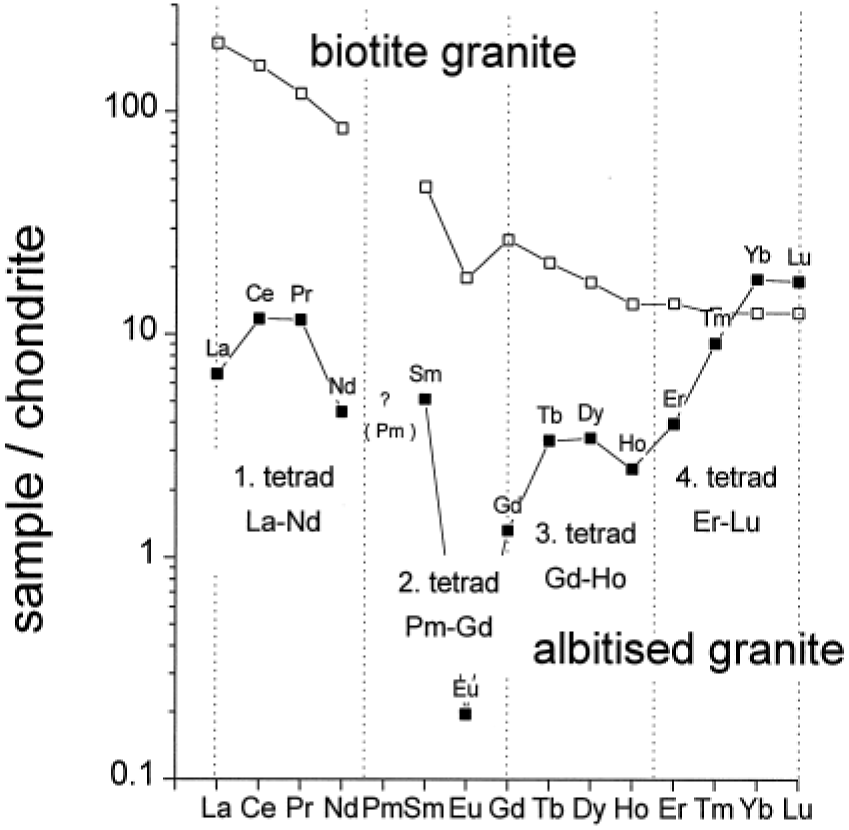
Article

The lanthanide "tetrad effect" as an exploration tool for granite-related rare metal ore systems: examples from the Iberian Variscan belt

Ivo Martins [1,2,*], António Mateus [1,2], Michel Cathelineau [3], Marie Christine Boiron [3], Isabel Ribeiro da Costa [1], Ícaro Dias da Silva [1,2] and Miguel Gaspar [1]

Whole-rock REE contents. *The tetrad effect as possible vector for different types of granite-related mineralization*

- Specific form of REE fractionation:
  - Evidenced by four curved segments – tetrads;
  - Commonly observed in highly evolved felsic magmatic rocks;
  - Two-types of tetrad effect that derive from each other – M-type (convex) and W-type (concave);
  - Degree of tetrad effect ($TE_{1,3}$) can be quantified and is significant when $\mathbf{TE_{1,3} > 1.1}$.



From Irber, 1999

$$t1 = (Ce/Ce^t \times Pr/Pr^t)^{0.5} \quad (1)$$

$$t3 = (Tb/Tb^t \times Dy/Dy^t)^{0.5} \quad (2)$$

with $Ce/Ce^t = Ce_{cn}/(La_{cn}^{2/3} \times Nd_{cn}^{1/3})$

$$Pr/Pr^t = Pr_{cn}/(La_{cn}^{1/3} \times Nd_{cn}^{2/3})$$

$$Tb/Tb^t = Tb_{cn}/(Gd_{cn}^{2/3} \times Ho_{cn}^{1/3})$$

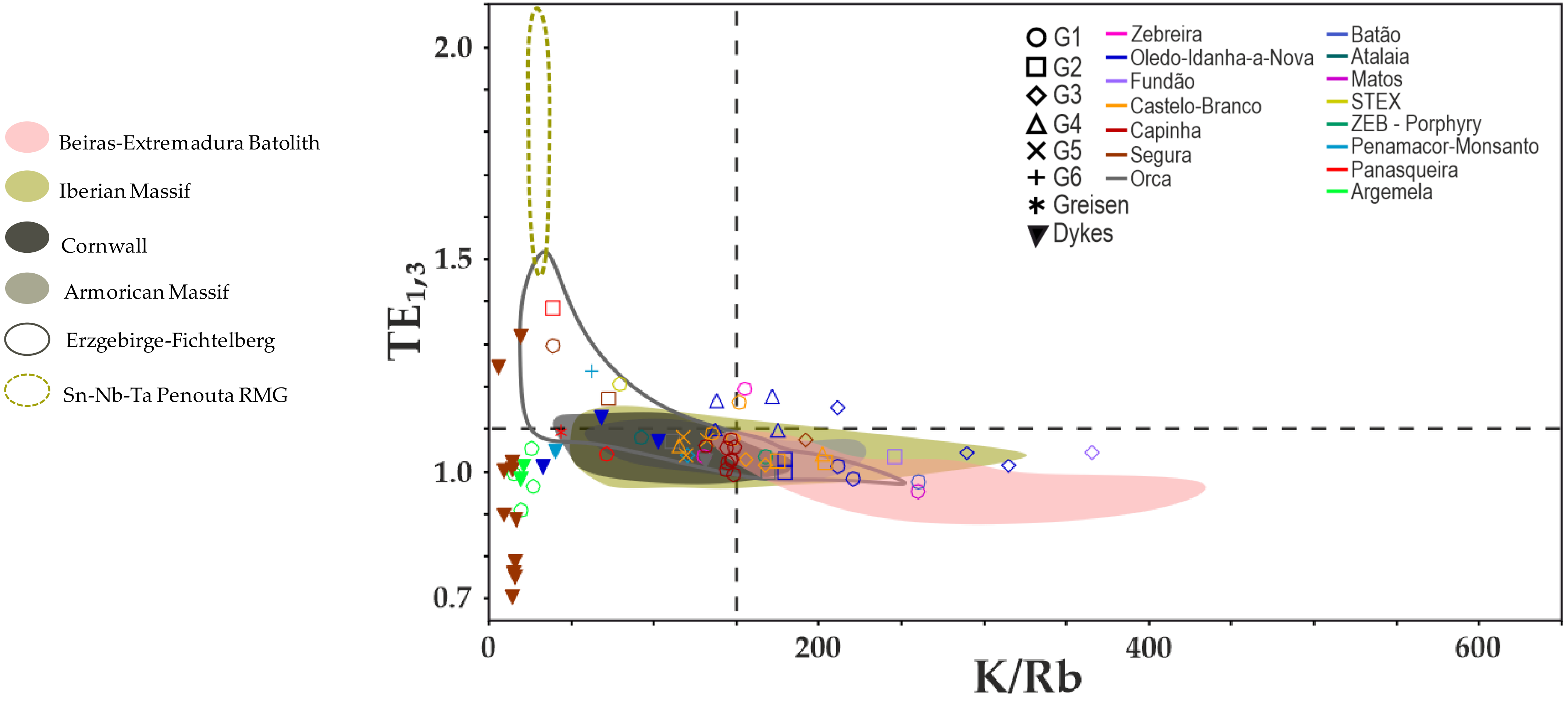
$$Dy/Dy^t = Dy_{cn}/(Gd_{cn}^{1/3} \times Ho_{cn}^{2/3})$$

Ln_{cn} = chondrite-normalized lanthanide concentration

$$\text{degree of the tetrad effect} = TE_{1,3} = (t1 \times t3)^{0.5} \quad (3)$$

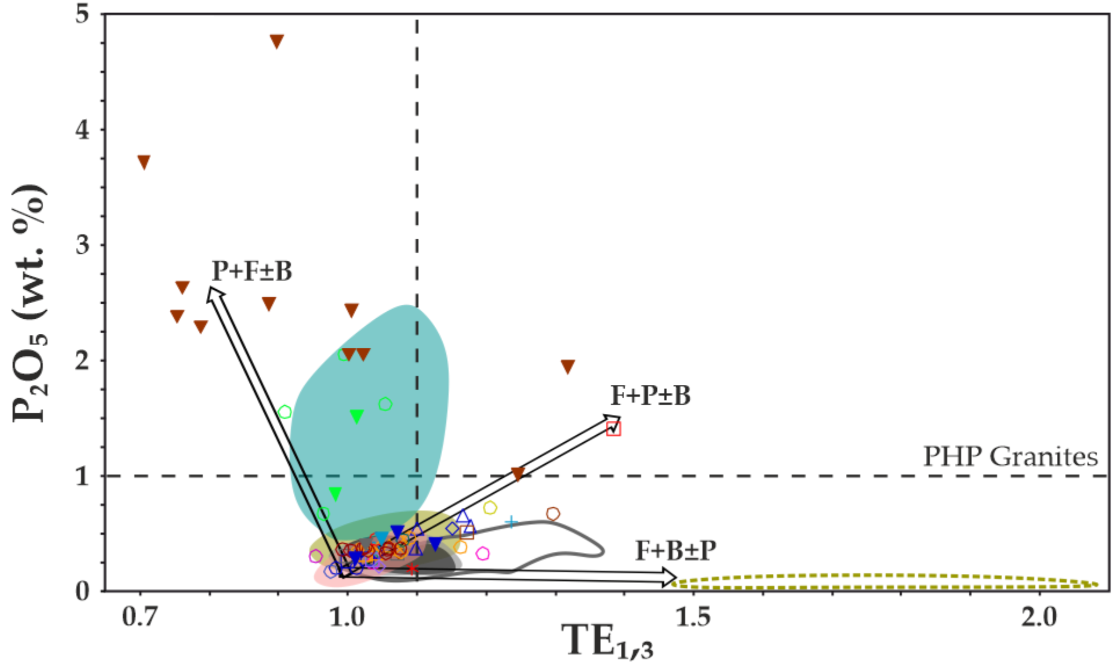
Whole-rock REE contents. ***The tetrad effect as possible vector for different types of granite-related mineralization***

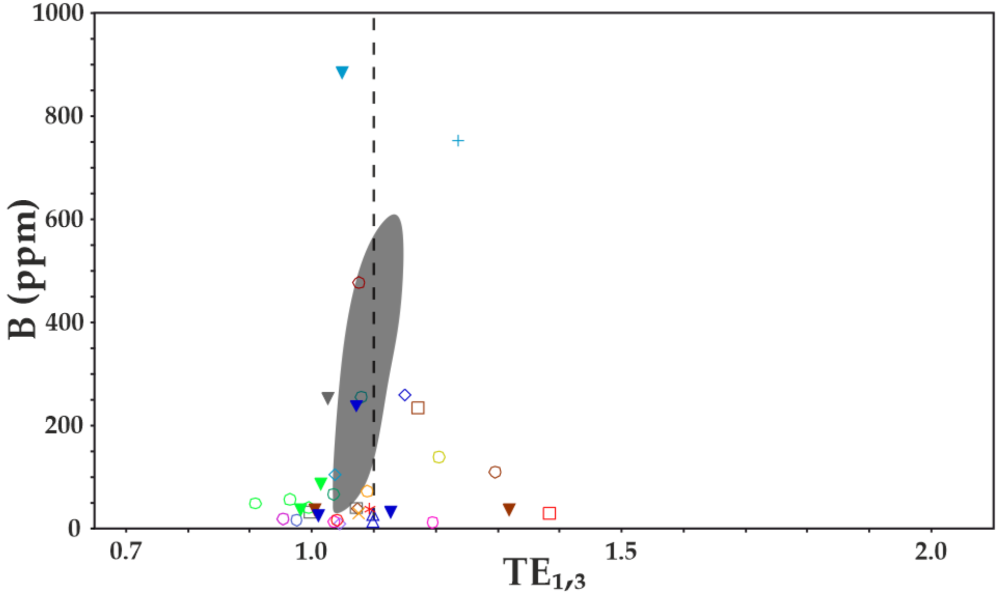
- Increase in $TE_{1,3}$ values tend to co-vary with magmatic differentiation and metal enrichment:
  - Variscan granites showing gradually higher $TE_{1,3}$ values (up to 2.1 – Penouta RMG);
  - Li-phosphate-bearing rocks deviate from this general trend, having no evidence of tetrad effect ($TE_{1,3}$ <1.1).

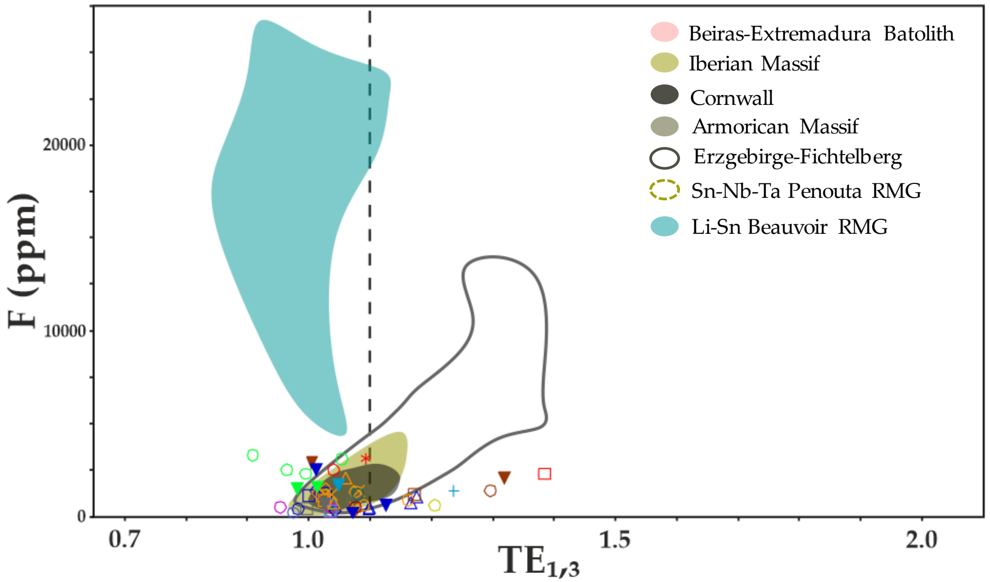


Whole-rock REE contents. ***The tetrad effect as possible vector for different types of granite-related mineralization***

- **$TE_{1,3}$** values can be used to separate:
  - **P+F±B (P>F)** systems related to Li-Sn Peraluminous-High-Phosphorous granites and Li-phosphates-bearing pegmatite dykes ($TE_{1,3}$ <1.1);
  - **F+P±B (F>P)** systems related to W-Sn-Li Peraluminous-High-Phosphorous granites and lepidolite-bearing aplite-pegmatite dykes ($TE_{1,3}$ up to 1.4);
  - **F+B±P (F>B)** systems related to Sn-Ta-Nb Peraluminous-Low-Phosphorous granites ($TE_{1,3}$ up to 2.1);







Geochemical proxies to granite-related mineral systems using multi-element whole-rock analysis

- **Highly differentiated granitic rocks**
  - Whole-rock enrichments in **P, F, Be, Li, Ta, Sn, Nb** (up to 25×, 15×, 70×, 500×, 150×, 800×, and 20×UCC, respectively).
  - K/Rb < 150; Nb/Ta < 5; Y/Ho ≠ 28; Sr/Eu > 200; Eu/Eu* < 0.1; Zr/Hf < 15, as in many other Sn-W(±Li) provinces worldwide.

- **TE1,3 increases and co-varies with magmatic differentiation and metal-enrichment**
  - TE1,3 < 1.1 ⇒ peraluminous-high-phosphorus Li-Sn granite systems
  - TE1,3 > 1.1 ⇒ peraluminous-high-phosphorus granite suites Sn-W-Li (lepidolite) (up to 1.4) and peraluminous-low-phosphorus Sn-Ta-Nb granite systems (up to 2.1)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Thank you for your attention!