

http://doi.org/10.54499/ERA-MIN/0002/2019 https://mostmeg.rd.ciencias.ulisboa.pt/





Modelling the ore potential of peraluminous granite-related systems; implications to mineral exploration strategies.

> António Mateus; Ivo Martins; L. Miguel Gaspar Isabel Ribeiro da Costa; M. Cathelineau; M.-C. Boiron

Geological map of the Góis-Panasqueira-Argemela-Segura strip Penamaco Miranda do Co PORTUGAL Ladoeiro Castelo Branco Ferreira do Zêzere /ila de Rei Vila Velha de 🔬 Cedillo FCT 4 · M Santiago de 16 Instituto Geográfico Nacional, Esri, TomTom, Garring, Foursquare, FAO, RA-MIN Joint Call 2019 (EU Horizon 2020 ERA-MET C http://doi.org/10.54499/ERA-MIN/0002/2019 hund Project ERA-MINZ. Grant american No 737318



Magmatic events represented in the **G-P-A-S strip**

Voluminous Late Cambrian-Ordovician magmatic event (ca. 490-470 Ma) related to extreme thinning of continental margins during a rifting event or a back-arc extension.

HT and LT, deep-seated peraluminous granodiorite and monzogranite suites (ca. 350-335 Ma), conceivably documenting crustal melting increments after initial lithospheric thickening (mostly under the allochthonous /parautochthonous pile).

Calc-alkaline aluminopotassic granodiorites & monzogranites (ca. 320-315 Ma). BDT \approx 13-14 km

Subalkaline aluminopotassic monzogranites & Bt-dominant (HT) γs (ca. 310-305 Ma).

Moderate to strong peraluminous two-mica and Ms-dominant (LT) γs (ca. 300 Ma). BDT ≈10 km

Subalkaline ferropotassic (HT) γ s (ca. 296-290 Ma). BDT \approx 4-5 km

Two main suites, documenting distinct magmatic events



Two main suites, documenting distinct magmatic events





Granite-related ore systems

Exclusively associated with Variscan granite suites

Main targets studied

Panasqueira γ "two-mica": 304±5.8 Ma; 297±1.5 Ma

γ "ms": **294.7±1.7** *Ma* Greisen: **295.5** – **294.8**Ma

2 Cabeço de Argemela

γ : *302.6±0.6 Ma* γ f: *302.9±0.3 Ma* γ f*: *312* – *310* Ma



γ f: 305 – 295 Ma *ms*-lodes: 297.6±1.5 *Ma*

4 Monsanto-Medelim

Peg: 306±1.5 Ma Qz-T: 297.4±1.2 Ma γ (b): 298.9±1.2 Ma γ (bf): 299.08±0.3 Ma γ f: 302 – 301 Ma



γ ms: 305±2 Ma Peg: 303±5 Ma



Basically, 2 out of the 5 main granite suites emplaced during the ca. 320-295 Ma period (Villaseca, 2011; Roda-Robles et al., 2018)

Mineralizing events within the surveyed belt confined to ca. 310-290 Ma, peaking at ≈300 Ma.

...possibly existent but poorly represented Calc-alkaline alumino-potassic (granodiorites and) monzogranites (ca. 320-315 Ma). BDT \approx 13-14 km

Highly peraluminous, Ca-poor, P-rich (bt \pm ms \pm crd \pm and) monzogranites; prevalent metasedimentary sources; ca. 310-300 Ma. Later emplacement (shallow depths) of highly differentiated melts.

P-poor, moderately peraluminous granites, mostly crystallized at 308–299 Ma, coupled with **moderately to low peraluminous granites, with features at the limit between S- and I-type granites.** BDT \approx 10 km. Minor volumes of differentiated melts lately emplaced at shallow depths.

- Not all the Carboniferous granite suites reveal compositions indicative of metal-enrichment processes, nor are they associated with mineralising systems.
- What are the reasons behind the "metal-specialisation" or "metal-fertility", particularly in granite suites with similar emplacement/crystallisation ages?



What do we know:

The Carboniferous granite suites document multistage partial melting of different crustal levels during a relatively short time-span.

Some of these crustal levels also acted as protoliths of the previous Cambrian-Ordovician magmatic event, as suggested by *ɛ*Nd values, Nd TDM model ages and Pb-Pb isotope ratios.

Compositional variation of granite suites is mostly ruled by:

- protolith composition;
- partial melting P-T conditions
- degrees of partial melting and fractional crystallisation; and
- relative abundance of fluxing elements, such as H₂O, F, B, and P

To assess the extent to which these factors contributed to the main compositional attributes of the Carboniferous granite suites, trace element modelling of batch melting and fractional crystallisation was performed using:

• the median and average composition of the Beiras Group pelite and greywacke rocks as the protolith compositions, and these "starting modal abundances"

35% quartz, 30% muscovite, 15% biotite, 10% plagioclase, 5% sillimanite and 5% garnet (metapelite) 40% quartz, 20% plagioclase, 20% biotite, 10% muscovite, 7% garnet and 3% sillimanite (metagreywacke)

- Rb, Ba and Sr to inspect the different degrees of melt differentiation, as these elements preferentially partition to minerals involved in the partial melting and/or fractional crystallisation processes, such as plagioclase, alkali feldspar, biotite and muscovite; and
- Sn, Nb, Ta and Li to appreciate the behaviour of lithophile metals during petrogenesis of felsic melts, which enrichment in granites might be used to evaluate the potential for the generation of granite-related ore deposits



TimeZir
sat(°C)Temperature conditions for the extraction of a granitic melt from its
source assuming no significant fractional crystallisation has occurred

	Cambrian-Ordovician granites											
Facies		Zebreira		OIN-G1		OIN-G2	OIN-G3		Fun	Idão	-	
Sample		G_ZEB#1	G_ZEB#2	GPF	OLX	G_IDN#1	REPA1	REPA2	G_FUN#2	G_FUN#3		
T (°C)		761	765	754	764	755	718	720	742	737		
	Variscan granites											
Facies		CB-G2					SEG	P-M		Orca		
Sample	GIN	GIN2	GIN4	G14	INFX1	INFX2	G_SEG#4	G_MONS#2	P-39	G_STC#1	G_MDCH#1	
T (°C)	824	820	821	818	821	813	767	763	792	759	712	
Facies	Capinha											
Sample		G_CAP#1	1	4	11	15	18	19	Q1	Q2		
T (°C)		750	753	755	749	757	744	749	752	751		

• Samples not recording significant modifications due to late fluid circulation (e.g., Nb/Ta >5 and K/Rb >150)

• Temperature values consistent with partial melting of metasedimentary rocks

Under conditions of increasing temperature on a clockwise P-T-t path, melting of metasediments took place at:

(1) relatively low-T (*ca.* 650 to 750°C) incongruent melting of muscovite in equilibrium with biotite- and sillimanite-bearing restite:

Muscovite + quartz + plagioclase + vapour = sillimanite + melt Muscovite + quartz + plagioclase = alkali feldspar + sillimanite + melt

(2) followed by high-T (*ca*. 800 to 900°C) incongruent melting of biotite in equilibrium with cordierite-, garnet-, and/or orthopyroxene-bearing restite.

Biotite + quartz + plagioclase + sillimanite + vapour = garnet + cordierite + melt

Biotite + quartz + plagioclase + sillimanite = cordierite + orthopyroxene + alkali feldspar + melt



For trace element modelling, it was used:

1) the **batch melting equation**

$$\frac{C_L}{C_0} = \frac{1}{[D(1-F)+F]}$$

2) the Rayleigh fractionation equation

$$\frac{C_L}{C_0} = F^{(D-1)}$$

- *C_L* = weight concentration of a trace element in the melt;
- C₀ = weight concentration of a trace element in the source;
- D = bulk distribution coefficient for residual solids (Batch melting) or the fractionating assemblage (Rayleigh fractionation); and
- F = weight fraction of melt produced (Batch melting) or the fraction of melt remaining (Rayleigh fractionation)

3) the **partition coefficients** compiled from several studies on peraluminous melts

	Qtz	Kfs	PI	Bt	Msc	Grt	Sil
Rb	0.01	0.31	0.02	2.00	0.30	0.01	0.00
Sr	0.00	13.98	6.80	0.38	0.52	0.02	0.00
Ba	0.03	6.00	0.30	3.00	3.70	0.02	0.00
Li	0.05	0.05	0.05	1.65	0.80	0.00	0.00
Be	0.00	0.26	0.10	0.39	1.35	0.00	0.00
Nb	0.00	0.04	0.07	1.96	0.15	0.00	0.00
Sn	0.00	0.05	0.60	2.32	2.14	0.86	0.00
Та	0.00	0.03	0.06	0.16	0.06	1.32	0.00

Modelling was first performed for the low-T muscovite dehydration melting, with 5% to 100% of melt generated (F) and using the median composition of the Beiras Group metasedimentary rocks as the source concentration (C_0). The high-T biotite dehydration melting was then modelled considering the modal abundances of restites from the previous melting as starting materials.

Following Simons et al. (2016), fractional crystallisation processes were modelled for each of the partial melting portions by fractionation of mineral assemblages comprising 50% plagioclase, 23% alkali feldspar, 22% biotite and 5% garnet (incongruent muscovite melting) and 50% alkali feldspar, 25% biotite, 24% plagioclase and 1% cordierite (incongruent biotite melting).



For muscovite dehydration (low-T) melting of metagreywacke

 Rb, Li, Nb, Ta and Sn behave as incompatible; and Ba, Sr as compatible.

For muscovite dehydration (low-T) melting of metapelite

• Rb, Li, Nb, Ta and Sr behave as incompatible; and Ba and Sn as compatible.

The subsequent incongruent biotite melting (high-T) is characterised by:

 incompatible behaviour of Rb, Li, Nb, Sn and Ta and compatibility of Sr and Ba, both of which are more significant for the metapelite protolith.

The compatible and incompatible geochemical behaviours of these elements are maintained and reinforced during fractional crystallisation processes



The most plausible results were obtained for Rb and Sr (± Ba). Accepting the modelling conditions:

- Zebreira, Oledo-Idanha G4, Castelo Branco G1 to G4 and Orca facies conceivably resulted from 5% to 50% low-T partial melting (muscovite dehydration), followed by up to 30% of fractional crystallisation;
- Segura, Penamacor-Monsanto and Salvaterra do Extremo facies involved 5% to 40% of high-T partial melting (biotite dehydration) and up to 10% of fractional crystallisation.

Modelling results for Rb, Sr and Ba do not correlate with the measured contents in most of the Cambrian-Ordovician granitoids, denoting possible contributions from meta-igneous sources (with higher Sr and Ba contents, and lower Rb values), as suggested by the whole-rock isotopic data.





Low-T muscovite dehydration melting

50.00



Partition of Sn between restite and the generated melt is strongly controlled by the relative abundance of micas.

The stability of Sn-bearing phases during incongruent muscovite melting prevents relative Sn-enrichment in the melt and leads to Sn-enrichment in the restite.

During high-T biotite dehydration melting, Sn will be released from the "Sn-sequestering restitic phase" being incorporated into the (more differentiated and enriched) melt.

 fO_2 should also be considered, controlling the stability of Ti-oxides potentially incorporating Sn in the residue. Even in conditions of high-T melting, if Ti-oxides are stable, Sn tends to remain in restite; Sn-specialised granites are normally reduced (ilmenite-type or ferroan granites).

So, there is a **significant deviation** between modelled and measured abundances of Li, Nb, Sn and Ta, even considering the heterogeneity of the Beiras Group.

These discrepancies could result from:

- underestimation of the Nb geochemical compatibility;
- overestimation of Li, Sn and Ta geochemical compatibility; and/or
- magmatic-hydrothermal processes, such as hydro-saline melt immiscibility, metasomatism and/or late interaction with aqueous hydrothermal fluids.

Peraluminous granites recording significant interaction with hydrothermal fluids: Nb/Ta < 5 and K/Rb < 150 (Ballouard et al., 2016)



Improvements of the partial melting and fractional crystallisation modelling considered a complex system, involving interactions between crystals, silicate melts and immiscible aqueous fluids (hydrothermal fluids and hydro-saline melts).

Isobaric Fractional Melting Under Fluid Saturated Conditions

Isobaric Fractional Crystallisation Under Fluid Saturated Conditions

Mass balance approach Spera *et al.* (2007; 10.2138/am.2007.2326)

 $k_{sm,i}$ = solid/melt partition coefficient for element i;

k_{sf,i} = solid/(supercritical) fluid partition coefficient for element i;

 $k_{sm,i} = k_{sf,i} \times k_{fm,i}$ where $k_{fm,i}$ is the fluid/melt partition coefficient for element i;

f_m = melt fraction removed

 $\phi = df_f/df_m = (supercritical)$ fluid fraction generated in each melting increment that will go along with the melt fraction

	В		F	L L	i		Rb		Cs		Nb		Та		Sn	١	N
k _{sm,i}	0.02	k _{sm,i}	0.8	k _{sm,i}	0.09	k _{sm,i}	1.13	k _{sm,i}	0.001	k _{sm,i}	0.203	k _{sm,i}	0.942	k _{sm,i}	0.3	k _{sm,i}	0.4
k _{sf,i}	0.22	k _{sf,i}	2	k _{sf,i}	0.25	k _{sf,i}	0.15	k _{sf,i}	0.01	k _{sf,i}	2.03	k _{sf,i}	3.14	k _{sf,i}	1.88	k _{sf,i}	0.16

No data or quite variable $k_{sm,P}$, $k_{sf,P}$ and $k_{sm,P}$

 $k_{sm,i} \le 0.001$ strongly incompatible elements $0.001 < k_{sm,i} < 1$ incompatible elements $1 \le k_{sm,i} < 3$ compatible elements





f_m

Isobaric Fractional Melting Under Fluid Saturated Conditions

 $f_{f}^{\circ} = 0.01$ (1 wt% H₂O in the source region)

Model 1

• $\phi = -0.20$ (max. 5% of partial melting)

Model 2

• $\phi = -0.10$ (max. 10% of partial melting)

Model 3

• $\phi = -0.05$ (max. 20% of partial melting)

Model 4

• $\phi = -0.02$ (max. 50% of partial melting)

Isobaric Fractional Crystallisation Under Fluid Saturated Conditions

 $C_{s,i}$ / $C^{0}_{m,i}$

C_{s,i} / C⁰_{m,i}

0.001

1.00 0.90 0.80 0.70 0.60 0.50 0.40 0.30 0.20 0.10 0.00

f*_m

- $\phi = -0.04$ (melt having 4 wt% of dissolved H_2O)
- $\phi = -0.15$ (melt having 15 wt% of dissolved H_2O)



+ 0.1





-B

1.00 0.90 0.80 0.70 0.60 0.50 0.40 0.30 0.20 0.10 0.00

f*_m



Biotite | *ongoing work*

Minimum water contents above 6-7 wt% for the magmas, plausibly higher in Variscan suites in comparison to those generated during the Cambrian-Ordovician transition

Implications of modelling results

- 1st stage of variable metal enrichment in initial melts by incompatible crystal-melt fractionation.
- Highly differentiated peraluminous B-rich, F-poor systems will reach water saturation at relative deeper crustal levels in comparison with F- (and possibly P-) dominant melts.
- Late-stage fluid saturation favours W-enrichment, because co-existing aqueous fluid phases will preferentially incorporate W in comparison with Sn.
- Protracted melt fractionation in equilibrium with exsolved fluid phases will further deplete W from the melt.
- W deposition, mostly in quartz-lodes, is controlled by local chemical gradients involving the metasedimentary country rocks, which rule the availability of Fe²⁺, Mn²⁺ (and Ca²⁺):

$$WO_4^{2-} + MCI_n^{2-n} = MWO_4 + nCI_1^{-}$$

 $M = (Fe^{2+}, Mn^{2+}) \text{ or } Ca^{2+}$

 $HWO_{4}^{-} + MCI_{n}^{2-n} = MWO_{4} + H^{+} + nCI^{-}$

Implications of modelling results

• The preferential partition of Sn into the melt phase might lead to SnO₂ oversaturation and cassiterite pp.

 $\log C_{SnO2} = 3.17 - (3.51 \times 10^3 / T)$

Solubility of cassiterite in H₂O-saturated peraluminous melts (in wt%; T in K) Bhalla et al. (2005)

	SnO ₂ (wt%)	Sn (ppm)
800°C	0.79	≈6200
700°C	0.37	≈3650

- Although not preferentially, Sn could also incorporate the fluid phase (along with other metals, namely W).
- In H₂O-saturated peraluminous melts, (very) high Sn fluid concentrations should be expected at high degrees
 of melt differentiation (>0.95). So, the potential for Sn mineralisation is expected to increase with melt
 differentiation in equilibrium with an exsolved fluid.
- Significant cassiterite deposition in magmatic-hydrothermal transition settings should be coeval of secondary muscovite formation (namely in presence of Fluid/Rock ratios >1, favouring the development of greisens):

 $Sn^{II}Cl_{n}^{2-n} + 2H_{2}O = Sn^{IV}O_{2} + 2H^{+} + nCl^{-} + H_{2}$ $3KAlSi_{3}O_{8} + 2H^{+} + 2Cl^{-} = KAl_{3}Si_{3}O_{10}(OH)_{2} + 6SiO_{2} + 2K^{+} + 2Cl^{-}$

T^{zir}sat (°C)

	Variscan granites											
Facies			CB-G2				SEG	P-N	Λ	0	rca	
Sample	GIN	GIN2	GIN4	G14	INFX1	INFX2	G_SEG#4	G_MONS#2	P-39	G_STC#1	G_MDCH#1	
T (°C)	824	820	821	818	821	813	767	763	792	759	712	
Facies						Capi	nha					
Sample		G_CAP#1	1	4	11	15	18	19	Q1	Q2		
T (°C)		750	753	755	749	757	744	749	752	751		

Partial melting involved in primary high-T parental melts (further generating secondary low-T granites by fractionation processes):

Higher temperature conditions (\approx 800 °C) in Sn-related granites than in W-related granites (\approx 750 °C)

• Early batches related to low T muscovite dehydration melts (having W>Sn) followed by high T biotite dehydration (displaying Sn>W)?

Pressure conditions hard to estimate but could be (slightly?) lower in Sn-related granites than in W-related granites

 Increasing of partial melting processes due to depressurisation, triggered by isostatic rebound or orogen collapse at ca. 300 Ma? To conclude:

- The negative εNd_{310 Ma} values (usually between -2 and -6), the high ⁸⁷Sr/⁸⁷Sr_{310 Ma} ratios (typically above 0.706) and the old Nd TDM model ages (mostly ranging from 1.5 to 1.0 Ga) support a prevalent (metasedimentary-)crustal provenance for the melts related to the Carboniferous granites.
- These granite suites show also Pb signatures compatible with a dominant upper crustal Pb derivation without significant juvenile contamination, but the overlap with the Beiras Group metapelites (recalculated for 310 Ma) is limited, thus indicating the contribution of other Pb sources, such as immature metasediments and/or metaigneous protoliths, or even minor supplies of lower crustal reservoirs.
- The possibility of some of these melts resulting from anatexis of protoliths involved in the previous Cambrian-Early Ordovician magmatic event cannot be discarded.



Potential protoliths are compositionally diverse, and "metal-fertility" of melts could be due to:

• mixing of melts produced in different crustal levels with variable metal endowments, thus providing (crustal-derived) hybrid magmas; or

 variable contamination of upper crustal metapelite-related melts by ascent fluids resulting from biotite or amphibole breakdown at higher depths, contributing to concentration enhancements in "mica- or amphibolecompatible elements" (e.g., Na, Li, Rb, Cs, Be, Sn, Nb), besides Th and U.

Both processes could also embrace the variable enrichments in P, B and F that characterise the Variscan granite suites usually related to oreforming systems or displaying signs of mineralisation.



The composition of protoliths involved in partial melting processes, as well as the temperature and degree of melting, in addition to the subsequent fractionation/differentiation, are determining factors but, *per se*, are not enough to explain the development of polymetallic mineralizing systems.

In these cases, (heat and mass) advective processes related to the emplacement/cooling of different volumes of granite at shallow crustal levels (< 5 km) will play a decisive role, mobilizing metals and ligands from country rocks.





https://mostmeg.rd.ciencias.ulisboa.pt/

Thank you for your attention!