# ERA-MIN Joint Call 2019

*MOSTMEG*

*Predictive models for strategic metal rich, granite-related ore systems based on mineral and geochemical fingerprints and footprints.*

Final Project Report

Co-funded by the Horizon 2020 programme
of the European Union

# Contents

# 1. GENERAL INFORMATION

| | |
|---|---|
| **Project acronym** | MOSTMEG |
| **Project title** | *Predictive models for strategic metal rich, granite-related ore systems based on mineral and geochemical fingerprints and footprints* |
| **Project start date (day/month/year)**<br>**Project end date (day/month/year)** | 01/10/2020<br>30/06/2024 |
| **Period covered by the report** | 01/10/2022 – 30/06/2024 |
| **Project website** | https://mostmeg.rd.ciencias.ulisboa.pt/ |
| **Date of submission of the report** | 29/07/2024 |
| **Consortium Coordinator** | *Project Partner 1 – Faculdade de Ciências da Universidade de Lisboa and IDL*<br>*António Manuel Nunes Mateus*<br>*E-mail address: amateus@fc.ul.pt*<br>*female ☐ male X*<br>*Portugal*<br>*Partner type 1: Academia X Large Company ☐SME ☐NGO ☐* |
| **Project Partners (other than Consortium Coordinator)** | *Project Partner 2 – Faculdade de Ciências da Universidade do Porto*<br>*Alexandra Guedes*<br>*E-mail address: aguedes@fc.up.pt*<br>*female X male ☐*<br>*Portugal*<br>*Partner type: Academia X Large Company ☐SME ☐NGO ☐* |
| | *Project Partner 3 – Universidade de Évora, Geociências - HERCULES*<br>*Patrícia Moita*<br>*E-mail address: pmoita@uevora.pt*<br>*female X male ☐*<br>*Portugal*<br>*Partner type: Academia X Large Company ☐SME ☐NGO ☐* |
| | *Project Partner 4 – Laboratório Nacional de Energia e Geologia, I.P.*<br>*Rute Maria Morgado Salgueiro*<br>*E-mail address: rute.salgueiro@lneg.pt*<br>*female X male ☐*<br>*Portugal*<br>*Partner type: Academia X Large Company ☐SME ☐NGO ☐* |
| | *Project Partner 5 – Universidade de Coimbra*<br>*Alcides Pereira*<br>*E-mail address: apereira@dct.uc.pt* |

[1] Academia (universities, other higher education institutions or public research organizations-PRO)

Co-funded by the Horizon 2020 programme
of the European Union

| | |
|---|---|
| | *female ☐ male X*<br>*Portugal*<br>*Partner type: Academia X Large Company ☐SME ☐NGO ☐* |
| | *Project Partner 6 – Instituto de Geociências da Universidade de São Paulo, Departamento de Mineralogia e Geotectónica e Centro de Pesquisas Geocronológicas*<br>*Colombo Celso Gaeta Tassinari*<br>*E-mail address: ccgtassi@usp.br*<br>*female ☐ male X*<br>*Brazil*<br>*Partner type: Academia X Large Company ☐SME ☐NGO ☐* |
| | *Project Partner 7 – CNRS - GeoRessources*<br>*Michel Cathelineau*<br>*E-mail address: michel.cathelineau@univ-lorraine.fr*<br>*female ☐ male X*<br>*France*<br>*Partner type: Academia X Large Company ☐SME ☐NGO ☐* |
| **Final term project summary suitable for web publication** | The Segura-Argemela-Panasqueira-Góis (SAPG) strip, spreading *ca*. 150 km across the Central-Iberian Zone southern domain in Portugal, hosts a wide variety of Sn(-Nb-Ta) and Li(-Sn-Nb-Ta) aplite/pegmatite and Sn-Li, Sn(-W), W-Cu(-Sn) quartz vein types of mineralisation. This feature enables the analysis of factors that rule the development of distinct, although coexisting, granite-related ore systems and the appraisal of mineral exploration vectors to be used in the future.<br><br>The SAPG strip runs over a folded pre-Ordovician metasedimentary succession (Beiras Group, BG) comprising highly mature siliciclastic sediments derived from weathered felsic-intermediate igneous sources related to continental island arcs, and often displaying low to moderate enrichment in Li, Cs, Sn, Bi, Hf, As and Sc. The BG succession is cut by many shear zones (mostly oriented *ca*. E-W and NW-SE) and voluminous (Cambrian-)Lower Ordovician and Carboniferous(-Permian) plutonic rocks, besides different arrays of aplite-pegmatite dykes and quartz lodes. The ore-forming systems are exclusively related to strongly differentiated Carboniferous(-Permian) granite suites, and the critical period for mineralising events ranges from *ca*. 310 to 290 Ma.<br><br>The Carboniferous(-Permian) granite suites include highly peraluminous, calc-alkali to alkali-calcic and magnesian to ferroan rocks, which emplacement were controlled by crustal-scale discontinuities, mostly in the vicinity of (Cambrian-)Lower Ordovician plutons. Parental magmas of these granites resulted from partial melting of diverse protoliths, and the "metal-fertility" might have been achieved through: (i) mixing of melts produced in different crustal levels with variable metal endowment; or (ii) contamination of upper crustal metapelite-related melts by fluids resulting from biotite or amphibole breakdown at higher depths. Both processes also justify the variable enrichment in P, B and F found in granite suites related to ore-forming systems or displaying mineralisation signs. The composition of protoliths involved in partial melting, as well as the temperature (750-800°C for the primary melt batches) and degree of melting (≈5 to 40%), in addition to |

Co-funded by the Horizon 2020 programme of the European Union

| | |
|---|---|
| | subsequent fractionation/differentiation (up to 30%), are determinant factors but, *per se*, do not satisfactorily explain the formation of polymetallic ore systems. In such cases, heat and mass advective processes stimulated by the emplacement of granite bodies at shallow crustal levels are critical, mobilising metals and ligands from country rocks. Indeed, fluid inflow implicated in W-dominant and Sn-dominant quartz lode systems show compositional features resultant from significant interaction with metamorphic rocks, being mostly aqueous solutions with low salinity and a low-density volatile $CO_2$ phase that could be subsequently enriched in $CH_4$ ± $N_2$. The reconstructed P-T-X path for these fluids suggests that pressure conditions differ considerably for W-dominant (2-3 kbar) and Sn-dominant (< 1.5 kbar) mineralising stages, approaching lithostatic pressure in the former and hydrostatic pressure in the latter, evolving in both cases from ca. 400-450°C to 250-300°C. This variation in pressure conditions is most likely related to crustal exhumation at the end of the Variscan orogeny.<br><br>The strongly differentiated and ferroan leucogranites to which the magmatic-hydrothermal ore-forming processes are related show evident enrichment in P, F, Be, Li, Ta, Sn, Nb (on average, up to 25×, 15×, 70×, 500×, 150×, 800×, and 20× the upper continental crust, respectively) and K/Rb < 150; Nb/Ta < 5; Y/Ho ≠ 28; Sr/Eu > 200; Eu/Eu* < 0.1; Zr/Hf < 15; Th/U < 0.5. These features are comparable to those found in many other Sn-W(±Li) provinces worldwide. The lanthanide “tetrad effect” $TE_{1,3}$ is also a discriminant parameter, increasing and co-varying with magmatic differentiation and metal-enrichment. Peraluminous-high-phosphorus Li-Sn granite systems are typified by $TE_{1,3}$ < 1.1, whereas peraluminous-high-phosphorus granite suites related to Sn-W-Li (lepidolite) enrichment display $TE_{1,3}$ up to 1.4, which also differs from the $TE_{1,3}$ values (up to 2.1) depicting peraluminous-low-phosphorus Sn-Ta-Nb granite systems.<br><br>The composition of $TiO_2$-polymorphs, cassiterite, micas (mostly muscovite), tourmaline, and zircon was successfully tested as finger- and footprints to different mineralisation types. The mineral and textural transformations recorded by contact metamorphic aureoles enveloping “fertile” granites were also examined in selected targets to resolve the most promising geochemical vectors towards mineralised domains. Similarly, the abundance and composition of alluvial $TiO_2$-polymorphs, cassiterite, wolframite, and scheelite proved to be useful in the vectoring of mineralising systems. According to the results obtained, future mineral exploration endeavours in the SAPG strip should consider the large and poorly studied areas to the W and SW of the Panasqueira-Argemela systems, along with those to the N-NW of the Lousã-Góis-Vale Pião region. The distal Estorniños granite exo-contact, to the south of Segura, is also a promising area for scheelite mineralisation. |
| **GDPR consent** | I, as coordinator of this project, accept that my name and email address are public at ERA-MIN 2 media channels for dissemination and exploitation purposes.<br><br>yes X no ☐ |

Co-funded by the Horizon 2020 programme of the European Union

# 2. FINAL PROGRESS REPORT

## 2.1 Summary of the project progress and the results obtained at project closure

### 2.1.1 Project overview

The main goal of MOSTMEG project was the development and validation of predictive models for strategic metal rich, granite-related ore systems. To this end, some concepts and exploration strategies were refined through the combination of mineral and geochemical criteria that can be used as pathfinders or vectors to mineralisation. Also, the Segura-Argemela-Panasqueira-Góis (SAPG) strip in Portugal was chosen for study area in face of the co-existence of several W-, Sn- and/or Li-rich geochemical anomalies that support known resources (including world-class deposits) and numerous mineralising occurrences. The conceptual framework used to organise the research tasks in MOSTMEG followed the Mineral Systems Approach, which allowed to figure out the most favourable transient events in the geodynamic evolution able to stimulate the progression of metallogenic processes. In addition, some aspects related to the preservation of ore systems and to the physical dispersion of some ore constituents were assessed by the inspection of heavy minerals in alluvial sediments not subjected to significant transport.

The SAPG strip extends for *ca*. 150 km, from E to W, across the southern domain of the Central-Iberian Zone in Portugal. This strip runs over a folded pre-Ordovician metasedimentary pile cut by many shear zones and voluminous granite plutons, as well as different arrays of barren or Sn(-Nb-Ta) and Li(-Sn-Nb-Ta)-bearing aplite-pegmatites, and Sn-Li, Sn(-W), W-Cu(-Sn)-rich quartz veins. The shear zones, mostly ENE-WSW to ≈ESE-WNW and NNW-SSE to NW-SE, frequently include copious arrays of quartz infillings. According to field observations, these shear zones may control the rising and emplacement of orogenic silicate melts, in many places acting also as a preferred loci for ore-forming processes.

The pre-Ordovician metasedimentary succession, known as the Beiras Group (BG), comprises (flysch-like) siliciclastic units that could be grouped into two main lithostratigraphic formations, the Malpica do Tejo (most likely Ediacaran in age) and Rosmaninhal (late Ediacaran/basal Cambrian?). These rocks were recrystallised under P-T conditions of greenschist metamorphic facies during the Variscan orogenesis and preserve a wide range of (multi-scale) structures that reflect the overprinting of several deformation phases. The multi-element composition of fine-grained metasediments (originally shales/siltstones) is comparable to those typifying highly mature siliciclastic deposits derived from intensely chemically weathered (median CIA value of 75), felsic to intermediate igneous sources related to continental island arcs, revealing low to moderate enrichment in Li, Cs, Sn, Bi, Hf, As and Sc when normalised to the Average

Shale contents. Information provided by whole rock isotopic data corroborates these inferences, showing in addition that: (i) the sources of Pb in these rocks fall within the range of crustal protoliths, despite the signs of a distinct mantle-derived component displayed by some samples from the Malpica do Tejo *Fm.*; (ii) both *Fms.* were supplied by the erosion of crustal rocks, including a noteworthy contribution of felsic (arc-derived) igneous sources; and (ii) the latter sources, younger than 1.2 Ga if the wide range of Nd TDM model ages is considered, are conceivably related to juvenile magmas and should document the dismantling of a Cadomian arc located to the south of the area currently dominated by the BG exposures. Therefore, the contribution of felsic igneous sources might be relevant to the metal endowment potentially provided by metasediments when subjected to physical-chemical conditions favouring their partial melting (if deeper sections of BG are compositionally alike of those currently cropping-out) or hydrothermal leaching (considering just the accessible BG sections hosting the granite bodies) in subsequent stages of geodynamic evolution.

In the SAPG strip, two main suites of plutonic rocks can be distinguished according to their crystallisation ages and compositional features. The first group includes composite plutons and minor intrusions formed in (Cambrian-)Lower Ordovician times (from *ca*. 500 to 480 Ma, locally extending until *ca*. 470 Ma), mostly composed of weakly peraluminous, calcic to calc-alkalic and magnesian granodiorite-tonalite to granite rocks. The second group comprises voluminous monzogranite-granite plutons and derived differentiates, besides several arrays of aplite-pegmatite bodies and occasional porphyry dykes, emplaced during upper Carboniferous (from *ca*. 314 to 303 Ma, sometimes spreading until *ca*. 295 Ma) and displaying high peraluminous, calc-alkali to alkali-calcic and magnesian to ferroan composition. The known ore-forming systems are exclusively related to strongly differentiated and ferroan leucogranites of the second group.

The (Cambrian-)Lower Ordovician granitoids record the emplacement of independent and compositionally different magma batches that reflect different proportions of mixing between melts preserving a "*orogen*" Pb-signature with melts generated in upper crustal levels (under variable degrees of partial melting). As suggested by whole rock Sr, Nd and Pb isotopic data ($0.704 \leq {}^{87}Sr/{}^{86}Sr_{480\ Ma} \leq 0.722$; $-3.048 \leq \varepsilon Nd_{480\ Ma} \leq -2.788$; $18.116 \leq {}^{206}Pb/{}^{204}Pb)_{480Ma} \leq 20.916$; $15.600 \leq {}^{207}Pb/{}^{204}Pb)_{480Ma} \leq 15.777$; $37.792 \leq {}^{208}Pb/{}^{204}Pb)_{480Ma} \leq 40.301$), the formation of these rocks documents a continuum of processes that should have involved partial melting of the lower crust and further magma rising through the crust, assimilating and triggering partial melting of deeper portions of the BG siliciclastic succession.

The Carboniferous(-Permian) magmatic event includes products of multistage partial melting of different crustal levels during a relatively short period, conceivably incorporating contributions of deeper sources, as indicated by whole rock Sr and Nd isotopic data: (i) $0.705 \leq {}^{87}Sr/{}^{86}Sr_{310Ma} \leq 0.716$ in "common" granites, ranging from 0.721 to 0.729 in higher differentiated granites and facies subjected to significant post-emplacement compositional changes, and confined to 0.710-0.712 in late porphyry rocks; (ii) $-6.5 \leq \varepsilon Nd_{310\ Ma} \leq -5.7$ in many granites, but shifting from *ca*. -5 to -2 in some highly differentiated facies, reaching -11.6 in particular aplite dykes and remaining between *ca*. -2.9 and -2.7 in late porphyry rocks. These granite suites show Pb signatures ($17.253 \leq {}^{206}Pb/{}^{204}Pb)_{310Ma} \leq 22.392$; $15.579 \leq {}^{207}Pb/{}^{204}Pb)_{310Ma} \leq 15.870$; $37.905 \leq {}^{208}Pb/{}^{204}Pb)_{310Ma} \leq 38.542$) compatible with a dominant upper crustal Pb derivation without significant juvenile contamination; still, the overlap with BG metapelites is limited, suggesting the contribution of other Pb sources, such as immature metasediments and metaigneous protoliths, or even minor supplies of lower crustal reservoirs. Taking these indications into account, the "metal-fertility" of Carboniferous(-Permian) granites might have been achieved through: (i) mingling of melts produced in different crustal levels with variable metal endowment, thus providing (crustal-derived) hybrid magmas; or (ii) irregular contamination of upper crustal metapelite-related melts by rising fluids resulting from biotite or amphibole breakdown at higher depths, contributing to concentration enhancements in Na, Li, Rb, Cs, Be, Sn, Nb, P, B, F, Th and U. Note also that U/Th > 10 characterise granite plutonic and dyke facies showing signs of mineralisation and effects of mineral/textural changes triggered by mineralising processes.

The geochronological data obtained for the SAPG strip, making use of different techniques, provide evidence for intense and recurrent magmatic activity in some sites. These settings possibly trace crustal domains influenced by large-scale (lithospheric?) structural discontinuities able to control the rising and emplacement of several magma suites. For instance, in the Fundão area, the zoned pluton (from 499±4.7 Ma to 480±5 Ma) was intruded by tonalites at 467±7 Ma and, to the NE, by *ms*-rich granites of Carboniferous age. Similarly, the Zebreira area was subjected to protracted magmatic activity during Ordovician (from ca. 490 Ma – granodiorites – to 463 Ma – *ms*-rich granite), further rejuvenated in late Variscan times (porphyry laccoliths and dykes emplaced at 306 ± 4.6 – 299.9 ± 7.2 Ma). Also, at the Idanha-a-Velha – Oledo pluton, Ordovician (sheared) granodiorites are crossed by Carboniferous (differentiated) granites as dykes or irregular bodies (293.1 ± 1.5 Ma). In addition, the obtained geochronological data reveal that successive granite melts were generated and emplaced during a short time-span in the Carboniferous period, some of them followed by the production of incremental volumes of highly differentiated (and metal-fertile) batches to which several younger aplite-pegmatite swarms are related, and/or separation and further extraction of supercritical fluids, which favoured the late development of some other types of mineralised bodies. Discrimination of various mineralising events throughout the *ca*. 310-290 Ma time window might be possible, separating W-dominant systems from those characterised by the prevalence of Sn and/or Li. However, the validation of this interpretation, impacting on the design of future mineral exploration surveys across the SAPG strip and other similar Variscan orogenic segments, requires additional support.

Heat and mass advective processes stimulated by the emplacement of late Carboniferous granite bodies at shallow crustal levels should play a decisive role in the generation of some mineralisation types, mobilising metals and ligands from country rocks. In fact, the composition of fluids implicated in W-dominant and Sn-dominant quartz lode systems reflects significant chemical interaction with metamorphic rocks; prevailing inflows include aqueous fluids showing low salinity and a low dense volatile $CO_2$ phase that could be subsequently enriched in $CH_4 \pm N_2$. The reconstructed P-T-X path for these fluids shows that pressure conditions were probably close to lithostatic pressure during the W-dominant mineralising stage and mainly hydrostatic pressure during the Sn-dominant mineralising stage, evolving in both cases from ca. 400-450°C to 250-300°C. This implies that W-dominant mineralising systems were developed at depths ≈10 km (2-3 kbar), probably around 310 ± 5 Ma. The hydrostatic pressures inferred for the Sn-dominant mineralising systems indicate shallower levels (*ca*. 3-4 km), conceivably established few million years after (*ca*. 300 ± 5 Ma). This large variation in pressure conditions is ascribed to crustal exhumation at the end of the Variscan orogeny, caused either by an important isostatic rebound event at *ca*. 300 Ma or by a generalised orogenic collapse peaking at the Carboniferous-Permian transition. However, recurrent fluid

Co-funded by the Horizon 2020 programme
of the European Union

inflows during late evolving stages, developed after orogen exhumation and decompression, are crucial for the formation of high-grade/tonnage deposits, such as Panasqueira.

In the SAPG strip, the strongly differentiated and ferroan leucogranites to which the magmatic-hydrothermal ore-forming processes are related show evident enrichment in P, F, Be, Li, Ta, Sn, Nb (on average, up to 25×, 15×, 70×, 500×, 150×, 800×, and 20× the upper continental crust, respectively) and K/Rb < 150; Nb/Ta < 5; Y/Ho ≠ 28; Sr/Eu > 200; Eu/Eu* < 0.1; Zr/Hf < 15; Th/U < 0.5. These criteria are robust enough to assess the mineral exploration potential of a granite-dominated setting, which could be further deepened using the degree of the lanthanide tetrad effect ($TE_{1,3}$). In fact, $TE_{1,3}$ can be considered an exploration vector for different types of granite-related ore systems, especially when considered along with the whole rock $P_2O_5$ concentrations. These combining geochemical features allow us to separate the fertile magmatic-hydrothermal systems into three different groups: (i) Li-Sn, Li-phosphates-bearing granite-related ore systems; (ii) W-Sn-Li, fluor-apatite and lepidolite-bearing granite-related ore systems; and (iii) Sn-Nb-Ta topaz-, tourmaline- and garnet-bearing granite-related ore systems.

The mineral and textural changes recorded by contact metamorphic aureoles enveloping "fertile" granites were also examined in selected targets to resolve the most promising vectors towards mineralised domains. Several mineral criteria, reflecting the replacement of early-grown blasts by pseudomorph aggregates of compositionally variable phyllosilicates (sometimes along with tourmaline), have proven useful in delimiting intense metasomatic haloes related to mineralising processes. These haloes also display specific geochemical signals; for example, concentrations of B, Li, F, Sn, Cs and Rb (W) are exceptionally high in the metasomatised schists enveloping the Cabeço de Argemela granite.

The composition of various minerals in different settings was successfully tested as finger- and footprints to different mineralisation types. The approach covered several families of silicate, phosphate and oxide phases, but studies with a larger spatial scope (*i.e.*, representing a higher number of target-areas) focused mainly on micas (mostly dioctahedral, such as muscovite), tourmaline, zircon and cassiterite. Muscovite in differentiated Carboniferous(-Permian) granites is frequently zoned and its rims incorporate significant amounts of Li, Rb, Cs and Sn, reflecting the involvement of fluids (or magmas) enriched in incompatible elements at the end of the crystallisation of *ms*-rich facies. Tourmaline also displays variable composition when included in granitic (schorlitic with low #Mg [Mg/(Mg+$Fe_T$)] and #Ca [Ca/(Ca+Na+K)]) or metasedimentary (dravitic with higher #Mg and #Ca) rocks, revealing (i) magmatic differentiation trends for composite granites, with progressive decrease in #Mg and #Ca, (ii) compositional variability within metasediments and (iii) mixing lines for each system between tourmaline compositions buffered by metasediments and by magmatic-hydrothermal fluid sources. Zircon denotes open-system behaviour during interaction with late (mineralized) reduced fluids, usually expressed by variable LREE enrichment along with evident fading or elimination of Ce (and Eu) anomaly, in addition to significant increase in U (or Th) and "common" Pb. Across the SAPG strip, cassiterite shows enrichment in Ti, Nb, Ta, Fe, Mn, W, Zr, Hf, Al, Ga, Sc, but their variation among deposits and within each deposit, even at the grain scale, reveals multi-phase and complex mineralising systems. Element ratios, such as Fe/Mn, Nb/Ta, Zr/Hf, Al/Ga, Ti/Al, Hf/Ga, Ti/Zr, and the Ti-(Fe+Mn)-(Nb +Ta) proportions proven to be sensitive to magmatic-hydrothermal ore-forming processes, being therefore useful to discriminate among deposit types, mineralising styles, compositional fluid endmembers, and characteristic mixing trends.

In Segura, the abundance and composition of alluvial $TiO_2$-polymorphs, cassiterite and wolframite anomaly pattern haloes can be correlated with distinct W- and Sn-bearing lodes, interpreted to have different origins and control factors (*e.g.*, structural, lithological, magmatic/hydrothermal, timing), superimposed mostly in the western part of the surveyed area. Also, alluvial scheelite distributions produce anomaly haloes that might assist the design of future mineral exploration surveys, namely across the distal Estorniños granite exo-contact.

Throughout the SAPG strip, besides the brownfield areas surrounding sites subjected to mining in the past, such as those to the north-northwest of the Lousã-Góis-Vale Pião region, other regions must be investigated. This is the case of the large and poorly explored region extending to the west and southwest of the Panasqueira-Argemela systems.

### 2.1.2 Main results achieved in each Work Package

**WP1**

**Re-assessment and harmonisation of the available data, structural analysis and sampling**

(***T1.1 - Data Compilation; T1.2 - Regional and local tectonic/structural constraints; T1.3 - Sampling Surveys***)

**Key geological features of the SAPG strip**

The 1:100,000 scale geological map produced under the scope of MOSTMEG provides a synopsis of the main lithostratigraphic and structural features displayed by the SAPG strip, after a methodical inspection and harmonisation of fragmented information picked in many field minutes and some published records. The joint interpretation of data collected in previous studies and gathered during additional fieldwork shows that:

**1.** The cropping out, pre-Ordovician, sedimentary succession of the Beiras Group is recrystallised under P-T conditions of greenschist metamorphic facies and comprises two lithostratigraphic units, labelled as Malpica do Tejo (MT) and Rosmaninhal (R) Formations (F). The MTF, most likely Ediacaran in age, includes two main siliciclastic members that are distinguished by the relative predominance and thicknesses of middle-coarse grained greywackes over siltstones/pelites. The RF (late Ediacaran/basal Cambrian?) is mostly composed of pelites, but considering the sedimentary facies, this unit can be separated into proximal (p) and distal (d) members. Siltstone layers of variable extension, thickness and grain size are increasingly abundant from the lower to the upper member of the proximal facies ($Rp^1$ and $Rp^2$) and include centimetre-thick discontinuous conglomerate levels in $Rp^2$. The reconstructed cartographic pattern suggests significant lateral facies changes, from ESE to WNW, between $Rp^1$ and Rd. In addition, possible unconformities between MT and $Rp^1$/Rd (intra-Alcudian?) and below $Rp^2$ (basal Cambrian?), as well as the "Toledanic" unconformity at the Cambrian-Ordovician transition, can be inferred.

**2.** The metasedimentary succession is intruded by voluminous plutonic rocks and different arrays of dykes that can be separated by geometry (orientation and shape) and mineral composition. Metasediments and some granitoid facies preserve evidence of heterogeneous strain accommodation, recording the structural rearrangement of multi-scale effects (rock fabrics/foliations, folding, shear and fault zones, quartz veins and other discontinuities) due to the progression of regional deformation phases. The currently available field data does not exclude the possibility of existing pre-Ordovician structures and low-grade metamorphism ($D_n/M_n$). Nonetheless, many of the observed features can be interpreted as miscellaneous effects of early-Variscan (Middle Devonian) deformation and metamorphism ($D_1/M_1$) overprinting pre-existent fabrics generated during the transient rift-to-drift tectonic regime at the end of the Cambrian-Ordovician period and/or to orogenic processes in the Ediacaran (Cadomian orogeny). The later Variscan structures, including NW-SE to WNW-ESE heterogeneous folds and shear zones that cut the post-315 Ma granitoids, correlate well with those typifying the Variscan $D_3/M_3$ regional deformation-metamorphic stage (upper Carboniferous).

**3.** Plutonic rocks can be grouped into two main suites. The first suite includes different rock types (clearly dominated by granodiorites, biotite quartz-diorites and tonalites) which represent the Lower Palaeozoic magmatic event (peaking at the Cambrian-Ordovician transition), concurrent with the extreme continental stretching related to the Rheic Ocean opening. The main plutons in this suite are Batão, Oledo – Idanha-a-Nova, Zebreira and Fundão. The other plutonic suite, mainly composed of monzonitic granites (sometimes porphyroid and often bearing biotite and muscovite) but locally including significant leucogranites, record the multiphase emplacement of melts generated during the Variscan orogenic stages (chiefly throughout late Carboniferous). This suite comprises some of the major exposed plutons (such as Segura, Penamacor-Monsanto, Orca and Castelo Branco), besides the partly and completely concealed granite bodies related to the ore-forming systems of Argemela and Panasqueira, respectively.

**4.** Swarms of subvertical, mesocratic to mafic dykes running from N110°±5° to N121°±5° (mostly fine-grained granodiorites) and N102°±7° (micro-gabbros) occur in several locations, often nearby the Cambrian-Ordovician plutons, the most important exception being the cluster of quartz-diorite/granodiorite dykes labelled as Matos, which also includes a minor laccolith. Subvertical dykes of porphyry tonalites (N148°±5°), porphyry microgranites (N360°±12°) and microgranites (N119°±9°) are also common in the SW part of the study area, particularly in the vicinity of Zebreira where some dykes criss-cross the prevalent granodioritic and biotitic quartz-dioritic facies forming the pluton. Aplite dikes, sometimes occurring along with pegmatites, are mostly confined to the periphery of the Orca and Penamacor-Monsanto plutons, and to the metasedimentary envelope of the Segura granites, displaying a wide range of directions (although dominantly between NE-SW and ENE-WSW) and dips (from subvertical to low-angle, <40°, usually to the NW-WNW). Around the Oledo – Idanha-a-Nova pluton, but mainly on its western border, rhyolitic dykes can also be observed besides those of aplitic and microgranitic nature. All these rocks trace the protracted magmatic activity in the region during the Lower and Upper Palaeozoic periods, concurrently or after to the multistage crustal emplacement of silicate melts related to the development of the plutons mentioned above. Nonetheless, convincing mineralisation signs are confined to the aplite/pegmatite arrays recognised near Monsanto, Segura and Argemela, notwithstanding the geochemical indications provided by some aplite bodies sampled elsewhere.

**5.** Many subvertical shear zones cut across the study area, mostly running ENE-WSW to ≈ESE-WNW and NNW-SSE to NW-SE, as observed throughout the Variscan orogen. Considering the macroscopic features displayed by these structural corridors, and their kinematics and spatial orientation, a straightforward comparison with the so-called syn-$D_1$ and syn-$D_3$ Variscan shear zone systems can be made. In general, the nucleation/development of these shear zones is related to strain partitioning within metasedimentary successions or along with their contacts with the Cambrian-Ordovician granitoids (at some stage in $D_1$) and thermo-mechanical contrasts with country rocks during the multiphase emplacement and cooling of Variscan granite bodies (roughly during $D_3$). So, the main shear zones are: (i) important crustal-scale structures that might have influenced the rising and emplacement of orogenic silicate melts, as verified for several dyke swarms; (ii) critical conduits for long-lasting crustal fluid flow, concomitant of strain accommodation, as indicated by copious arrays of quartz infillings, occasionally also bearing other accessory mineral phases such as sulphides and gold; and (iii) central to the development of a wide range of subsidiary structures which might have acted as preferred loci for lode ore-forming processes of magmatic-hydrothermal nature, like those recognised in Mata da Rainha. The leading family of shear-related, subvertical quartz infillings runs N67°±16°. Subsequent reactivation of several shear zone segments in Late-Variscan and Alpine times led to fault zones included in the regional network of strike-slip fault systems which, in the study area, are represented mainly by those oriented N42°±10°. The tectonic inheritance and recurrent reactivation of several families of shear/fault zones explain also the late development of brecciated quartz-rich infillings mineralised with barite and galena (N113°±11°) near Segura.

**Concise notes on the detailed field surveys carried out in selected areas**

Complementing the 1:100,000 scale geological map of the SAPG strip, four areas were selected for detailed studies: Segura, Medelim, Mata da Rainha and Argemela-Fundão.

**1.** Fieldwork and detailed geological mapping (1:5,000) carried out in the Segura area was the basis for an extensive database on the swarms of Li-bearing aplite and pegmatite dykes, and a complete revision of the exposed granite and metasedimentary (Malpica do Tejo *Fm.*) facies, and the contact metamorphic aureole associated with the Segura-Cabeza de Ayara pluton. These data represent a fundamental background to support an integrative (multi-scale) interpretation of the geochemical and mineralogical information gathered in the mineralised systems encircling the granite batholith, and of the late transformations experienced by the spotted schists forming the contact metamorphic aureole.

**2.** The Medelim area encloses an anomalously Sn-rich (*ca*. 400 ppm) coarse-grained, *ms*-rich granite that intrudes the border facies of the Penamacor-Monsanto granite body. This *ms*-rich granite comprises a fine-grained leucogranite facies within which a dense swarm of aplite dykes was also delimited during geological mapping at 1:1,000 scale.

**3.** The Mata da Rainha area presents different types of old mining works, the most important of which are the Sn-W quartz lodes subjected to underground mining during the World War II period. The exploited quartz lodes are largely hosted by strongly altered (tourmaline-enriched) spotted schists (Rosmaninhal *Fm.*) near a leucogranite facies locally transformed into a greisen. The geological mapping (1:5,000) allowed the recognition of different granite facies and several clusters of tourmaline-rich aplite dykes, frequently coupled with quartz-tourmaline veins in the granite and metasediments, some of them subjected to artisanal mining in the past. The field survey also demonstrated that shear zones, mostly running NW-SE and ENE-WSW, affect some core-border granite facies transitions and many granite-metasediment contacts, influencing the development of several families of quartz- (and quartz-tourmaline?) veins; these structures are criss-crossed and displaced by late, NE-SW-trending Late-Variscan strike-slip fault zones.

**4.** The Argemela-Fundão area was subjected to multi-scale geological surveys, and the general inspection at 1:25,000 scale was complemented by detailed mapping in critical domains selecting the scales (1:5,000 to 1:1,000) in accordance with the information density. The geological mapping of the N-NW subsector of Argemela-Fundão area (between Telhado, Barco and Cabeço de Argemela) allowed the recognition of different arrays of dykes intruding the BG metasediments (Malpica do Tejo *Fm*.), besides several arrays of quartz lodes and other structures, namely ENE-WSW shear corridors with left-handed kinematics, some of them preserving evidence of multiple reactivation events. Significantly, some of these shear zones separate blocks that comprise metasediments variably affected by contact metamorphism, possibly denoting the influence of primary composition on andalusite/cordierite? blastesis, besides differences on the proximity to a granite batholith in depth. The mineral blasts in these spotted schists are notably retrogressed, but there are no evident signs of biotite or tourmaline, as recognised at Pedra Alta and Cabeço de Argemela.

**5.** At Pedra Alta (included in the Li-Sn permit recently assigned to the PANNN Company), the accessible parts of the old mining works preserve different families of quartz veins, which geometry and spatial orientation is consistent with data reported in previous studies. However, according to our observations, the dominant quartz veins, that may carry disseminated cassiterite (and wolframite?), post-date an early system of quartz veins affected by boudinage and occasional folding; and these are the main structures that incorporate phosphate phases, at least in the examined rock exposures. The interference patterns generated by the overlapping of these different quartz vein arrays are geometrically complex but can be unravelled in many sections of the open pit.

**6.** At Cabeço de Argemela, a general inspection of the granite contacts and their surrounds was carried out, revealing several groups of aplite dykes, some of them deformed and some others emplaced lately, crisscrossing all the reference markers in country rocks, although being affected by discrete quartz veins and fractures showing quartz-tourmaline infillings. Metasediments show multiple generations of quartz lodes, some of them carrying phosphate minerals, currently replaced by secondary mineral assemblages. In metasedimentary domains nearby the quarry, some quartz infillings of NW-SE dextral shears were tentatively exploited in the past, locally coming with deformed aplite bodies that are intersected by quartz veins carrying accessory amounts of phosphate minerals.

**7.** Three main groups of veins can be identified in the Cabeço de Argemela granite, the most important of which comprising quartz, albite, and amblygonite, and preceding the development of fine quartz lodes carrying minor amounts of disseminated cassiterite, wolframite and different sulphides. Sporadically, metasomatic fronts resembling pseudo-dykes are preserved, being intersected by discrete quartz veinlets. The systematic measurement of all these features allowed the characterisation of their geometry and spatial orientation, showing that straightforward comparisons between Cabeço de Argemela and Pedra Alta should be avoided because some vein sets in the latter site preserve evidence of a long evolution, suggesting spatial superposition of effects due to diachronic mineralising events.

Co-funded by the Horizon 2020 programme
of the European Union

**8.** The geological mapping of the Argemela-Fundão S-SE subsector revealed many structural features not included in published maps and compelled to several refinements of geological contacts; this field survey enabled also the identification of different granitoid facies, most of them forming dykes that crisscross the main rings of the Fundão pluton. The performed study allowed to deepen the current knowledge on the geochemical characteristics displayed by the granitoid facies forming the southwestern extension of the Fundão pluton.

## WP2

### Vectoring the Metal Endowment and the Critical Timing for Triggering the Mineralization

(***T2.1 - Crustal protoliths for "productive/fertile" granite melts; T2.2 - Temporal development of "fertile" granite melts and related mineralization***)

### Geochemical features of BG metasediments; are they relevant to regional metal endowment?

Compositional characteristics of BG metasediments (Malpica do Tejo and Rosmaninhal *Fms*.) were appraised using extensive multi-element analyses obtained for 98 samples, complemented with published data for 169 samples from the Panasqueira area and compared with results of 140 samples reported for equivalent units in Spain. Intending to lessen the scattering potentially caused by inherent heterogeneities displayed by greywacke-like facies, the sampling considered only fine-grained metasediments, mostly pelites. The multi-element whole rock geochemical data obtained show that:

**1.** BG pelites, often mixed with siltstones, are characterised by median concentrations of major (and some minor) elements comparable to those typifying fine-grained and highly mature siliciclastic sediments derived from intensely chemical weathered (median CIA value of 75) felsic to intermediate igneous sources related to continental island arcs. The most significant minor elements are Ba (511 ppm), F (449 ppm), Zr (196 ppm), V (152 ppm), Rb (113 ppm), Cr (101 ppm), Zn (101 ppm), along with trace amounts of B (94 ppm), Li (66 ppm), Ce (61 ppm), Sr (58 ppm), Ni (42 ppm), Cu (32 ppm), Y (29 ppm), La (28 ppm), Ga (22 ppm), Sc (19 ppm), Pb (14 ppm), Nb (12 ppm) and Th (10 ppm). The Average Shale-normalised patterns are characterised by positive anomalies of Li, Cs, Sn, Hf, Bi, As and Sc, and negative anomalies of Mg, Mn, Ca, S, F, Sr, Nb, Ta, W, Th, U, Y, Ni, Mo, Cd, Cu, Pb, Ge and Ag, similar to those reported in literature for lateral equivalent metasedimentary successions in Spain. Nonetheless, the higher $Na_2O$ and CaO concentrations (often up to 3 wt% and 1 wt%, respectively) in the Spanish sector, and their negative correlation with $Al_2O_3$ contents, should reflect a mineral assemblage with a higher abundance of plagioclase that possibly signs a closer spatial relation with source regions.

**2.** The whole rock isotopic data gathered for the same samples confirm: (i) the inferences based on multi-elemental geochemistry about the main sources involved in the formation of the BG sediments; and (ii) the usefulness of geochemical criteria to distinguish the Malpica do Tejo and Rosmaninhal *Fm*s., the latter being more radiogenic, though isotopically closer to the upper member of the former formation. Indeed, initial $^{87}Sr/^{86}Sr$ calculated for an age of 560 Ma yielded median values of 0.703 for both members of the Malpica do Tejo *Fm*, somewhat below the interval that characterises the Rosmaninhal members (0.706 to 0.711). Furthermore, the lower and upper members of Malpica do Tejo *Fm* show median $\varepsilon Nd_{560\,Ma}$ values of -3.321 and -2.458, respectively, contrasting with the median $\varepsilon Nd_{560\ Ma}$ values estimated for the lower and upper members of the Rosmaninhal *Fm.* (-1.977 and -2.277, respectively), which clearly deviate from the value estimated for the distal member of the latter formation (-2.689). The Nd TDM model ages estimated for the Malpica do Tejo and Rosmaninhal *Fms.* range from 1.40 to 1.68 Ga and their median values are: 1.62 and 1.55 Ga for the lower and upper members of the Malpica do Tejo *Fm*, respectively; and 1.48, 1.51 and 1.55 Ga for the lower, upper, and distal members of the Rosmaninhal *Fm.*, respectively. In addition, most of the isotopic Pb-Pb ratios calculated for 560 Ma show minor differences, and the sources of Pb fall within the range of crustal protoliths, despite the signs of a distinct mantle-derived component displayed by some samples from the Malpica do Tejo *Fm*.

**3.** Considering the Sm-Nd isotopic data, sediments forming the Malpica do Tejo and Rosmaninhal *Fms.* were supplied by erosion of crustal rocks, including a noteworthy contribution of felsic (arc-derived) igneous sources. The latter sources, younger than 1.2 Ga if the wide range of Nd TDM model ages is considered, may be related to juvenile magmas and should document the dismantling of a Cadomian arc located to the south (present coordinates) of the area currently dominated by the BG exposures. As documented in other studies, the BG metasediments are isotopically distinct from those forming the Douro Group and the Série Negra, to the N and S of the surveyed area, respectively. The differences cannot be explained in terms of metamorphic grade and/or anatexis in some layers of these metasedimentary sequences, suggesting that: (i) basins retaining the Beiras and Douro Groups were geographically or temporally separated and supplied by different source regions; and (ii) older crustal rocks coupled with minor contributions of juvenile magmas represent the main provenances of Série Negra, justifying their lower $\varepsilon$Nd values ($-5.5 < \varepsilon Nd_{560} < -11.4$) and older Nd TDM model ages (1.6 < Nd TDM < 1.9 Ga).

**4.** Contribution of felsic (arc-derived) igneous sources is relevant to the metal endowment potentially provided by the BG metasediments in subsequent stages of geodynamic evolution. The influence might be significant when adequate physical-chemical conditions are achieved: (i) to support the partial melting of BG metasediments, if deeper sections of the sedimentary pile are compositionally alike of those currently cropping-out; or (ii) to boost the hydrothermal leaching of BG metasediments, if accessible sections hosting the granite bodies are considered.

**Compositional attributes of granite suites; implications to metallogenic processes.**

The compositional characteristics of the exposed granite suites were assessed by whole rock multi-element analysis of 130 samples representing different granitoid facies, aplite-pegmatite bodies and porphyry dykes, subsequently compared with 192 whole rock analyses compiled from published data. Additionally, 33 samples were selected for multi-system isotopic analyses.

**1.** The (Cambrian)-Lower Ordovician plutons are mainly composed of weakly peraluminous I-type (mean ASI value of 1.1), biotite/biotite>muscovite tonalite to granodiorite rocks. These facies have moderate contents of $SiO_2$ (mean value of 68 wt%), total alkalis ($Na_2O+K_2O$ mean value of 6.85 wt%) and a mean Fe* ratio [$(FeO_{(t)}/(FeO_{(t)}+MgO)$] of 0.66. These rocks display compositional features alike of calcic to calc-alkalic series and magnesian granites, showing condensed differentiation trends from diorite to normal granite compositions. Regarding their isotopic signature, it should be noted that: (i) $^{87}Sr/^{86}Sr_{480\ Ma}$ values are 0.706 for Batão, 0.704-0.709 for Fundão, 0.704-0.711 for Matos, 0.707-0.708 for Zebreira, and 0.722 for the Idanha-a-Nova – Oledo leucogranite; (ii) $\varepsilon Nd_{480\ Ma}$ values are positive (4.783) for one of the granitoid facies

Co-funded by the Horizon 2020 programme
of the European Union

forming the Fundão pluton and for two of the dykes from Idanha-a-Nova – Oledo (0.756 and 1.008); (iii) granitoid rocks from Matos, Batão and Fundão, show $\varepsilon Nd_{480\,Ma}$ values between -0.331 and -1.485, whereas those from Zebreira and the two-mica granite from Idanha-a-Nova – Oledo display $\varepsilon Nd_{480\,Ma}$ values extending from -3.048 to -2.788; (iv) Nd TDM model ages define two main groups, the older comprising the two-mica granite from Idanha-a-Nova – Oledo (*ca*.1.50 Ga) and the granitoids from Zebreira (*ca*. 1.40 to 1.50 Ga); (v) younger TDM model ages characterise the Batão tonalite (1.24 Ga), the granitoids from Matos (1.27 to 1.33 Ga), the dykes from Idanha-a-Nova – Oledo (1.15 to 1.33 Ga) and the granitoids from Fundão (0.82 to 1.24 Ga); (vi) Pb-Pb isotopic ratios calculated for an age of 480 Ma spread between the "*orogen*" and "*upper crustal*" reference curves of the plumbo-tectonic model, but the slight overlapping with BG metapelites (recalculated for 480 Ma) suggests that protoliths isotopically distinct from those metasediments might have been involved in the crustal melting processes (the main deviations are documented for the granitoids from Zebreira and the two-mica granite from Idanha-a-Nova – Oledo, all displaying negative $\varepsilon Nd_{480\,Ma}$ values and older TDM model ages).

**2.** In face of their geochemical features, the (Cambrian-)Lower Ordovician granitoids should be related to independent magma batches which compositional differences reflect different proportions of mixing between melts that preserve a "*orogenic*" Pb-signature with melts generated in upper crustal levels (with variable degrees of partial melting). Considering that the "*orogen*" Pb-reservoir denotes recycling and extraction of Pb from the other three main reservoirs involved in the plumbo-tectonic model (mantle, lower and upper crust), this inference is consistent with the proposal of Castro et al. (2020)[2] for the formation of granodiorite/tonalite plutons and minor intrusions during Cambrian-Ordovician times. This proposal considers: (i) the emplacement of sanukitoid magmas at the lower crust, transferring the heat and releasing water during their crystallisation; (ii) subsequent partial melting of the lower crust, which includes the roots of the calc-alkaline Cadomian arc; and (iii) further magma rising through the crust, assimilating and/or triggering partial melting of metasediments (deeper portions of the BG siliciclastic succession).

**3.** Samples representing the Carboniferous(-Permian) plutons are highly peraluminous S-type (median ASI value of 1.26), muscovite>biotite / biotite>muscovite monzogranite to granite rocks that exhibit high median values of $SiO_2$ (73 wt%), median total alkalis (8.12 wt%) and a median Fe* ratio of 0.8. The compositional attributes of these rocks match those typifying calc-alkalic to alkali-calcic series and magnesian to ferroan granites developed in syn-collisional settings, often recording strongly differentiation paths. The Upper Continental Crust-normalised multi-element patterns for these rocks are characterised by positive anomalies of Li, B, Rb, Cs, Be, F, Nb, Ta, Sn, W and U, and negative anomalies of Ba, Sr, Y, Zr, Hf and Th, usually much more distinct than those in patterns typifying the (Cambrian-)Lower Ordovician granitoid suites. The "common" granites in Carboniferous(-Permian) plutons show $0.705 \leq {}^{87}Sr/{}^{86}Sr_{310\,Ma} \leq 0.716$), deviating from the isotopic values of facies recording higher differentiation degrees and/or post-emplacement compositional changes ($0.721 \leq {}^{87}Sr/{}^{86}Sr_{310\,Ma} \leq 0.729$), and late porphyry rocks ($0.710 \leq {}^{87}Sr/{}^{86}Sr_{310\,Ma} \leq 0.712$). The estimated $\varepsilon Nd_{310\,Ma}$: (i) vary between ca. -6.5 and -5.7 for granite samples collected at Capinha, Salvaterra do Extremo, Medelim, Orca and Fundão, as well as for aplite

[2] Castro A., Pereira M.F., Rodríguez C., Fernández C. and de la Rosa J.D. (2020) Atypical peri-Gondwanan granodiorite–tonalite magmatism from Southern Iberia. Origin of magmas and implications, *Lithos* 372–373, 105684.

Co-funded by the Horizon 2020 programme
of the European Union

dykes from Argemela and Panasqueira; (ii) range from ca. -5 to -3 for samples from Segura (granite inner facies), Monsanto (granite and pegmatite), Castelo Branco (differentiated granite), Panasqueira (two-mica granite) and Argemela (differentiated/modified granite); (iii) change between -2.9 and -2.7 in late porphyry rocks; (iv) is around -2 for the *ms*-rich granite border facies of Segura; and (v) stands at -11.6 for one of the aplite dykes sampled in Argemela. The Pb-Pb isotopic ratios calculated for an age of 310 Ma spread often between the "*orogen*" and "*upper crustal*" reference curves of the plumbo-tectonic model, but for many samples display evident increase in $(^{207}Pb/^{204}Pb)_{310\ Ma}$ and $(^{206}Pb/^{204}Pb)_{310\ Ma}$ ratios, above 15.6 and 20, respectively; the overlap with the Pb-Pb isotopic value of BG metapelites (recalculated for 310 Ma) is limited.

**4.** The first group of $\varepsilon Nd_{310\ Ma}$ values (ca. -6.5 to -5.7) indicates a prevalent crustal origin of the melts involved in the Carboniferous magmatic event, also consistent with the obtained range for $^{87}Sr/^{86}Sr_{310\ Ma}$ values. The moderate negative $\varepsilon Nd_{310\ Ma}$ values suggest that other protoliths than metapelites should be considered in partial melting processes, namely immature meta-sedimentary rocks (such as meta-greywackes) and/or meta-igneous sources. In addition, a higher compositional heterogeneity of the crustal source region, possibly involving minor contributions of deeper sources (including those related to lower crust partial melting), might explain the shift of $\varepsilon Nd_{310\ Ma}$ values (ca. -5 to -3) characterising the second group of granite samples. Similarly, the late porphyry rocks sampled at Zebreira ($\varepsilon Nd_{310\ Ma} \approx -2.8$) might be related to melts produced in lower crustal sources, although significantly contaminated with pelitic-derived components during their subsequent ascent in the crust, as suggested by their $^{87}Sr/^{86}Sr_{310\ Ma}$ signature (≈ 0.711). Following the same reasoning, the aplite dyke in Argemela with the lowest $\varepsilon Nd_{310\ Ma}$ value (-11.6) must represent magma batches generated by partial melting of middle to lower crustal sources with a dominant pelitic composition ($^{87}Sr/^{86}Sr_{310\ Ma} = 0.713$). These interpretations, consistent with the Pb-Pb isotopic scattering, are also compatible with the estimated Nd TDM model ages, which: (i) is around 2 Ga for the Argemela aplite dyke with the lowest $\varepsilon Nd_{310\ Ma}$ value; (ii) range from *ca*. 1.6 to 1.5 Ga for the Capinha, Salvaterra do Extremo, Medelim, Orca, Fundão and Panasqueira granites, as well as for the aplite dykes from Argemela and Panasqueira; (iii) vary between *ca*. 1.4 and 1.3 Ga for samples from Segura (granite inner facies), Monsanto (granite and pegmatite), Castelo Branco (differentiated granite), and Argemela (differentiated/ modified granite); (iii) stays about 1.3 Ga for the late porphyry rocks; and (iv) is around 1.2 Ga for the *ms*-rich granite border facies of Segura. Consequently, the Carboniferous(-Permian) magmatic event represented in the SAPG strip documents multi-stage partial melting of different crustal levels, some of those probably acting also as protoliths of the previous (Cambrian-)Lower Ordovician magmatic event.

**5.** Considering the geochemical indications, the Carboniferous(-Permian) granite suites are clearly more fertile than those of (Cambrian-)Lower Ordovician age. Among the former suites, the strongly differentiated and ferroan leucogranites represent the most promising targets. Tin contents are considerably higher (≈400 ppm) in a late leucogranite facies (Medelim) of the Penamacor-Monsanto pluton, rising to ≈1000 ppm in the Argemela leucogranite. These metal grades co-vary positively with F concentrations, which largely exceed 1000 ppm and 2000 ppm in the Medelim and Argemela leucogranites, respectively. Tungsten contents ranging from 10 to 20 ppm were measured in samples of granite facies from Orca, Castelo Branco, Panasqueira and Argemela; these values were exceeded in the two analysed samples representing the Capinha granite (20-30 ppm W). Significant Li contents (100-500

Co-funded by the Horizon 2020 programme
of the European Union

ppm, occasionally up to ≈700 ppm) characterise the granites from Castelo Branco, Segura, Panasqueira, Penamacor-Monsanto, Orca and Capinha. Most Argemela leucogranites are still more Li-rich with values up to ≈5000 ppm Li.

**Time windows for the emplacement of granite suites and progression of ore-forming processes**

At the MOSTMEG onset, geochronology data on granitic rocks scattered across the SAPG strip was confined to: (i) TIMS U-Pb zircon and monazite ages for some facies of the Segura, Idanha-a-Nova – Oledo and Castelo Branco plutons; (ii) K-Ar in biotite extracted from granitoids of Zebreira and Fundão plutons; and (iii) several age determinations for the Panasqueira system using different methods and minerals. Considering this background, it was decided to obtain geochronological information with SHRIMP U-Pb zircon dating in samples representing: (i) the granitoids of Zebreira, Fundão, Batão, and Matos; (ii) the granite facies of Salvaterra do Extremo, Capinha, Penamacor-Monsanto, Orca, Argemela and Panasqueira; (iii) the highly differentiated facies of Segura pluton and nearby aplite-pegmatite dykes; and (ii) the late porphyry dykes and laccoliths of Furão and Marcelina, in the Zebreira area. This approach was further complemented with other techniques due to: (i) the extreme difficulty, or even impossibility, to obtain zircon concentrates in various highly differentiated or compositionally modified granite facies from, *e.g.*, Panasqueira, Argemela, and Medelim; (ii) the abundance of inherited zircon populations in many granite facies; (iii) the insufficient zircon overgrowth encircling inherited cores or late rims with adequate thickness but containing too much uranium; (iv) the profusion of discordant data; and (v) the limitations posed by the use of TEMORA standard in SHRIMP measurements (natural zircon with low to "normal" U content), possibly not so suitable for dating high-U zircons as those usually present in many of the sampled plutonic and dyke granite facies. To overcome these difficulties and better constrain the temporal development of "fertile" granite melts and related mineralisation in the SAPG strip, the LA-ICP-MS U-Pb zircon analysis was used to estimate the age of the cordierite facies of the Cabeza de Araya batholith (Piedras Albas Quarry, the core domain of the Segura pluton) and the Estorniños two-mica granite. Additionally, K-Ar and Ar-Ar ages of mica (mostly muscovite) were gathered for 28 samples collected in different sites. Note that K-Ar ages are roughly equivalent to the whole age (WMA) using the Ar-Ar technique when plateau ages cannot be obtained on the whole spectra. The main advantage of dating mica with these two techniques results in the estimation of the granite/aplite/pegmatite minimal age, when the use of other approaches, such as U-Pb in zircon, is impossible or generates unlikely results from the geological point of view. A summary of the obtained geochronological results shows that:

**1.** The (Cambrian-)Lower Ordovician magmatic activity across the SAPG strip must have persisted from *ca.* 500 to 470 Ma, as recorded by the Batão (500 ± 6 Ma), Fundão (499 ± 5 to 467 ± 7 Ma), Idanha-a-Nova – Oledo (489 ± 4.5 to 478.3 ± 1.1 Ma) and Zebreira (488.1 ± 3.4 to 468.4 ± 5.4 Ma) plutons, along with the swarm of mesocratic dykes and laccoliths labelled as Matos, for which a tentative age of 479 Ma was estimated. These SHRIMP U-Pb zircon ages are slightly older than the WMA Ar-Ar estimates for muscovite in granodiorite from Zebreira (461.4 ± 3.2 Ma, comparable to the total fusion age of 460.9 ± 2.2 Ma) and, all together, reveal strong consistency with the protracted tectono-thermal event at the stretched Gondwana margin that preceded the opening of the Rheic Ocean, as widely documented in literature for Iberia Variscides and other segments of the Variscan Orogen.

**2.** Some settings were subjected to intense and recurrent magmatic activity, possibly indicating crustal domains influenced by large-scale (lithospheric?) structural discontinuities able to control the rising and emplacement of several magma suites. For instance, the Zebreira area was subjected to protracted magmatic activity during Ordovician (from ca. 490 Ma – granodiorites – to 463 Ma – *ms*-rich granite), further rejuvenated in Late Variscan times (porphyry laccoliths and dykes emplaced at 306 ± 4.6 – 299.9 ± 7.2 Ma). Also, at the Idanha-a-Velha – Oledo pluton, Ordovician (sheared) granodiorites are crossed by Carboniferous (293.1 ± 1.5 Ma) granite dykes and irregular bodies, which include biotite yielding very consistent Ar-Ar WMAs at 290.2 ± 2 Ma and 289.3 ± 0.5 Ma.

**3.** The Carboniferous(-Permian) magmatic activity across the SAPG strip is recorded by the emplacement/crystallisation of several composite plutons for which the obtained U-Pb zircon ages indicate a peaking time between ca. 314 and 300 Ma. Condensing the geochronological data for the composite plutons, we have: (i) Castelo Branco, from 310.1 ± 0.8 Ma to 309.0 ± 1.1 Ma; (ii) Orca, from 310 ± 3 Ma to 304 ± 3 Ma, the latter dating complemented with Ar-Ar muscovite (plateau) ages of 291.0 ± 2.1 Ma and 291.4 ± 0.5 Ma; (iii) Penamacor-Monsanto, from 311.2 ± 2.8 Ma to 308 ± 3 Ma, recording as well an Ar/Ar muscovite (plateau) age of 304.6±1.5 Ma and an Ar/Ar biotite WMA of 299.2 ± 1.6 Ma; and (iv) Segura-Piedras Albas (Cabeza de Araya batholith), from 309.8 ± 1.4 Ma to 305 ± 2 Ma. Similar SHRIMP U-Pb zircon ages were obtained for the *bt*-rich Capinha granite (314 ± 3 Ma), the two-mica Estorniños granite (303.7 ± 2.1 Ma) and the (drilled) two-mica Panasqueira granite (304 ± 5.8 Ma), besides the porphyry laccoliths (306 ± 4.6 Ma) and dykes (299.9 ± 7.2 Ma) cropping out in the Zebreira area. Therefore, successive granite melts were generated and emplaced during a relatively short time span in the Carboniferous period. The extraction of some of these melts were followed by: (i) the production of incremental volumes of highly differentiated (and metal-fertile) batches to which several younger aplite-pegmatite swarms are related; and/or (ii) the separation and further removal of supercritical fluids, which favoured the late development of other mineralisation types.

**4.** The best estimation for the timing of mineralisation events in the SAPG strip is *ca*. 310-290 Ma. This time window includes Concordia ages obtained for the pegmatite dykes of Monsanto (308 ± 3 Ma) and the Li-rich aplite/pegmatite lodes of Segura (303.6 ± 5.8 Ma), along with the strongly differentiated (usually muscovite rich) leucogranites found in several locations. These SHRIMP U-Pb zircon ages are supplemented with Ar-Ar (WMs or plateau) ages yielded by muscovite from: (i) pegmatite and aplite bodies at the outer border of the Orca pluton (305.4 ± 0.5 Ma and 296.7 ± 1.8 Ma, respectively); (ii) a thin selvage in a late quartz-tourmaline vein at Mata da Rainha (297.5 ± 2.0 Ma); (iii) a pegmatite dyke at Monsanto (306.1 ± 1.5 Ma), which is older than the muscovite collected in the quartz-tourmaline vein (297.4 ± 1.6 Ma) cutting the metasomatised granite (294.6 ± 1.5 Ma) and the pegmatite; (iv) the evolved granite facies at Medelim (301.7 ± 0.4 Ma), slightly older than muscovite in the outermost facies of the pluton (298.9 ± 0.4 Ma) and in a nearby aplite vein (299.1 ± 0.2 Ma); (v) a deformed, and controlled by a regional shear zone, aplite dyke at Argemela (310.9 ± 0.3 Ma); (vi) an amblygonite-bearing quartz vein at Cabeço de Argemela (308.3 ± 1.9 Ma); (vii) the modified granite facies at Cabeço de Argemela (302.6 ± 0.6 Ma and 302.9 ± 0.3 Ma); and (viii) the two granite facies picked in well logs at Panasqueira (297.1 ± 1.5 Ma and 294.7 ± 1.7 Ma), besides a greisen sample collected in the underground mining works (295.2 ± 0.3 Ma). The LA-ICP-MS U-Pb dating of cassiterite also fall in the *ca*. 310-290 Ma period and, despite some deviations from the results provided by other techniques, the ages gathered for several Sn-ores across the

Co-funded by the Horizon 2020 programme
of the European Union

SAPG strip are: 296 ± 0.98 Ma (Góis, Sandinho); 297 ± 1.4 Ma (Panasqueira, topaz-rich lodes in the SW domain of the mine); 311 ± 1.9 (Cabeço de Argemela, quartz vein of group III); 311 ± 1.4 (Pedra Alta, Argemela); 286 ± 1.4 (Capinha); 292 ± 0.9 Ma (Mata da Rainha) and 309 ± 1.2 Ma (Cerro Queimado, Segura).

## WP3

### Relevant Processes for Metal Concentration and Deposition at the Ore System Scale

(*T3.1 - Rare metal enrichment in (aplito-)pegmatite systems; T3.2 - High-grade, (magmatic-)hydrothermal ore systems; T3.3 - Mineral assemblages potentially enriched in valuable by-products*)

### Controls of "metal-specialisation" or "metal-fertility" in granite suites

As profusely documented in literature, the compositional variation of crustal-derived granite suites can be regulated by several causes, namely the protolith composition, partial melting conditions, degrees of partial melting and fractional crystallisation and relative abundance of fluxing elements, such as $H_2O$, F, B, and P. To assess the extent to which these processes contributed to the main compositional attributes of the sampled granitoid/ granite/aplite suites across the SAPG strip, trace element modelling of batch melting and fractional crystallisation was performed. Modelling improvements were further implemented, considering a complex system characterised by interactions between crystals, silicate melts and immiscible hydro-saline melts or hydrothermal fluids. These approaches were useful to understand the reasons behind the "metal-specialisation" or "metal-fertility" in granite suites, especially in those with similar emplacement/crystallisation ages. In this regard it should be remembered that not all the Carboniferous granite suites in the SAPG strip reveal compositions indicative of metal-enrichment processes, nor are they associated with mineralising systems. The assumptions and calculation procedures used, as well as the main results achieved, can be shortened as follows:

**1.** The nature of the main protoliths involved in partial melting processes was appraised in view of the $Al_2O3/TiO_2$ vs. $CaO/Na_2O$ and the Rb/Sr vs Rb/Ba ratios from whole rock geochemical data. Most of the Cambrian-Ordovician granitoid rocks plot within the greywacke/igneous source compositional field, except the more fractionated facies of the Zebreira, Oledo-Idanha-a-Nova and Fundão plutons, which fall into the metapelite-derived melting compositional field together with all the Carboniferous granite suites. These results, consistent with indications provided by multi-system isotopic data, suggest that partial melting modelling could use as first approach the modal mineral abundances for metagreywackes and metapelites, their main difference being their relative abundance in micas and feldspars. Based on the whole-rock geochemical composition of the BG metasediments, the modal abundances for starting metapelite and metagreywacke materials considered in the modelling procedure were 35% quartz, 30% muscovite, 15% biotite, 10% plagioclase, 5% sillimanite and 5% garnet, and 40% quartz, 20% plagioclase, 20% biotite, 10% muscovite, 7% sillimanite and 3% sillimanite, respectively.

**2.** Zircon saturation temperature ($T_{zirsat}$) was calculated, confining the temperature conditions for the melt extraction from its source if no significant fractional crystallisation has occurred. Before, the whole rock Pb and Ba concentrations were used to separate primary low-T from secondary low-T granites, fractionated from a higher-T parental magma, wherein the latter show Pb < 30 ppm and Ba < 200 ppm. On

Co-funded by the Horizon 2020 programme of the European Union

this basis: (i) the melting temperatures for the Zebreira, Fundão, Segura, Penamacor-Monsanto, Orca and Capinha plutons only considered results from a few number of samples, because the remaining ones should represent secondary low-T granites; and (ii) many of the facies forming the Castelo Branco pluton were not used in the $T_{zirsat}$ appraisals since they should have resulted from the fractional crystallisation of CB-G2. Samples from the Salvaterra do Extremo pluton must also represent secondary low-T granites as their Pb and Ba contents stand below the detection limits of the analytical methods used. The $T_{zirsat}$ estimates indicate higher crystallisation temperatures (> 750°C) for the (Cambrian-)Lower Ordovician granodiorites, biotitic quartz-diorites and tonalities, as well as for several Carboniferous monzo-granite and granite facies from Castelo Branco and Penamacor-Monsanto plutons. The lowest crystallisation temperatures were obtained for the Panasqueira (750 – 650°C) and Argemela (660 – 615°C) granites.

**3.** Trace element modelling of batch (partial) melting and Rayleigh fractionation was performed using: (i) the conventional equations and the elemental partition coefficients compiled from several studies for peraluminous melts; (ii) the median and average composition of BG pelite and greywacke rocks as the protolith compositions; (iii) a clockwise metamorphic P-T-t path, where the relatively low-T (*ca*. 650 to 750°C) incongruent melting of muscovite in equilibrium with biotite- and sillimanite-bearing restite is followed by high-T (*ca*. 800 to 900°C) incongruent melting of biotite in equilibrium with cordierite-, garnet-, and/or orthopyroxene-bearing restite; (iv) the behaviour of Rb, Ba and Sr to inspect different degrees of melt differentiation, as these elements are preferentially partitioned to mineral phases involved in the partial melting and/or fractional crystallisation processes, such as plagioclase, alkali feldspar, biotite and muscovite; and (v) the 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, as widely documented in literature.

**4.** Modelled Rb and Sr contents, occasionally along with those of Ba, are comparable with the concentration values obtained for these elements in many granitoid facies cropping out in the Segura-Panasqueira area. Accepting the modelling conditions: (i) 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; (ii) the 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. Higher deviations between modelled and measured element concentrations characterise some other (Cambrian-) Lower 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.

**5.** Modelled and observed abundances of Li, Nb, Sn and Ta deviate significantly, even considering the compositional heterogeneity of the metasedimentary sequences. These discrepancies could result from (i) the underestimation of Nb compatibility and overestimation of the Li, Sn and Ta compatibility and/or (ii) the non-evaluation of the influence of other plausible processes, such as hydro-saline melt immiscibility, high-T alkaline metasomatism and/or late interaction with aqueous hydrothermal fluids. In fact, using the Nb/Ta and K/Rb ratios to separate peraluminous granites affected by magmatic-hydrothermal transformations (<5 and <150, respectively), one may conclude that the majority of the analysed granitoid facies should have been subjected to some kind of compositional readjustment, leading to a progressive enrichment in lithophile elements such as Li, Nb, Sn and Ta. Such a trend is consistent with indications provided by Nb/Ta and Zr/Th ratios, which show in addition that many of the analysed Carboniferous(-Permian) granite suites spread over the empirical field of Sn-W(-U)-related granites and transition to that of rare metals (Ta-Cs-Li-Nb-Be-Sn-W) related granites, where the Argemela leucogranites plot.

**6.** Improved models of partial melting and fractional crystallisation in complex systems were assessed, following the mass-balance approach reported in literature[3] for "*Isobaric Fractional Melting Under Fluid Saturated Conditions*" and "*Isobaric Fractional Crystallisation Under Fluid Saturated Conditions*" and using as reference the key elements B, F, Li, Rb, Cs, Nb, Ta, Sn and W. Results from this approach show that: (i) initial melts will be variably enriched in different metals due to incompatible crystal-melt fractionation; (ii) 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; (iii) late-stage fluid saturation favours W-enrichment, because co-existing aqueous fluid phases will preferentially incorporate W in comparison with Sn; and (v) protracted melt fractionation in equilibrium with exsolved fluid phases will further deplete W from the melt. Accordingly, W deposition, mostly in quartz-lodes, should be controlled by local chemical gradients involving the metasedimentary country rocks, which rule the availability of $Fe^{2+}$, $Mn^{2+}$ (and $Ca^{2+}$). The preferential partition of Sn into the melt phase might lead to $SnO_2$ oversaturation and cassiterite precipitation. However, the possibility of incorporate part of the available Sn in the fluid phase greatly limits its saturation in melt, thus leading to variable levels of Sn enrichment (along with other metals, such as W) in fluid components co-existent with melt fractions. Modelling results also show that (very) high Sn-contents in fluid should be expected at high degrees of melt differentiation (> 0.95) in $H_2O$-saturated peraluminous melts; the range of $H_2O$ wt% values for which this behaviour is documented is compatible with information inferred from biotite composition, indicating minimum water contents above 6-7 wt% for the magmas, plausibly higher in Carboniferous(-Permian) suites in comparison to those generated during the Cambrian-Ordovician transition. So, the potential for Sn mineralisation is expected to increase with melt differentiation in equilibrium with an exsolved fluid, and noteworthy cassiterite deposition in magmatic-hydrothermal transition settings should be coeval of secondary muscovite growth, namely in presence of high (> 1) fluid/rock ratios favouring greisen formation.

**7.** As indicated by whole rock multi-element and multi-system isotopic data, parental magmas of granite suites in the SAPG strip resulted from partial melting of diverse protoliths, and their "metal-fertility" might have been achieved via: (i) mingling of melts produced in different crustal levels with variable metal endowment; or (ii) contamination of upper crustal metapelite-related melts by fluids resulting from biotite or amphibole breakdown at higher depths, contributing to concentration enhancements in Na, Li, Rb, Cs, Be, Sn, Nb, P, B, F, Th and U. Both processes justify also the variable enrichment in P, B and F found in granite suites related to ore-forming systems or displaying mineralisation signs. The composition of protoliths involved in partial melting processes, as well as the temperature (750-800°C for the primary melt batches) and degree of melting (≈5 to 40%), in addition to the subsequent fractionation/ differentiation (up to 30%), are determinant factors but, *per se*, do not satisfactorily explain the formation

[3] Spera FJ, Bohrson WA, Till CB, Ghiorso, MS (2007) Partitioning of trace elements among coexisting crystals, melt, and supercritical fluid during isobaric crystallization and melting" *American Mineralogist* 92 (11-12), 1881-1898.

Co-funded by the Horizon 2020 programme
of the European Union

of polymetallic ore systems. In such cases, heat and mass advective processes stimulated by the emplacement/cooling of different granite bodies at shallow crustal levels (< 5 km) should play a decisive role, mobilising metals and ligands from country rocks.

### Fluid evolution and PTX-t path in long-lived, magmatic-hydrothermal mineralising systems

A series of representative quartz veins found in different structural arrays affecting BG rocks in a larger number of places (highly deformed and folded by $D_n$ and $D_{n+1}$ phases, along or crosscutting the $S_n$ and $S_{n+1}$ foliations) were prepared for fluid inclusion (FI) studies. The objective was to get data on regional fluids trapped in quartz aggregates, whatever the early history of these mineral infillings, as they could be micro-fractured and healed during brittle episodes concurrent of the main mineralising events across the SAPG strip. The early history of the quartz is generally lost, but the idea was to examine a potential trap for post-$D_{n+1}$ fluid circulations. Around 30 thick sections were prepared and comprehensively examined under magnifications between ×200 and ×1000. Results were well below what was expected because FIs are, in most samples, very tiny (around or less than 5 μm) and very difficult to study or interpret as several processes of necking and deformation have entirely obliterated the FI record. In other words, quartz veins did not act as satisfactory traps for fluids during the last stages of Variscan evolution, synchronous of granite intrusions and formation of the main ore-forming systems. Thus, FI studies were confined to samples representing mineralised structures in Segura, Mata da Rainha, Pedra Alta and Vale Pião, complementing published information on this issue gathered for the Cabeço de Argemela and Panasqueira. Of the results obtained, the following stand out:

**1.** Several FI types are preserved in quartz aggregates forming the Segura Li-rich aplite-pegmatite bodies: (i) Lw-c and Lc-w, isolated or in clusters, and Vc-w and Vc occurring in clusters and fluid inclusion planes (FIP); (ii) Lw-c, Lw-m, isolated or developing clusters; and (iii) Vm-w and Vm in clusters and FIP. The volatile phase composition of fluids is dominantly constituted by $CO_2$ (58 to 89 mol%) with minor amounts of $CH_4$ (3 to 22 mol%) and $N_2$ (5 to 24 mol%), or mainly composed of $CH_4$ (51-82 mol%) with amounts of $N_2$ between 18-49 mol%, excluding those in Lw-c FI. Except for the $CO_2$-($CH_4$-$N_2$)-rich vapours (Vc FI) and the $CH_4$-vapours (Vm FI) the main fluid component is water (89.3 to 95.5 mol%), along with minor $CO_2$, $CH_4$, $N_2$ and salt. Despite these results, it should be noted that, in all the examined samples, most FI are either decrepitated or occur as late FIP dominated by mono-phase methane or carbon dioxide-rich inclusions of low density. Therefore, it is challenging to place precisely the few bi-phase fluid inclusions in the sequence of fluid events; they are probably earlier than mono-phase low density volatile dominated inclusions. The significance of the trapped fluids in these quartz aggregates is, at present, difficult to establish. Inclusions might correspond to relatively late fluid trapping after a phase of tectonic deformation, postdating the aplite-pegmatite emplacement, during which most primary FI have been destroyed. The presence of both aqueous carbonic fluids and methane-rich low-density fluids may indicate that both late fluids were still equilibrated with host metamorphic rocks when they percolated the aplite-pegmatite bodies.

**2.** Two types of quartz vein mineralisation are known in the Segura region: (i) mined Sn-lodes, located at *ca*. 1 km NW of the westernmost tip of the Segura granite, and (ii) lodes with dominant arsenopyrite (± stannite ± chalcopyrite ± bismuth phases) and wolframite, which have been explored but with no significant mining works. In quartz coming along with arsenopyrite, FI are slight with 6-7 wt.% eq. NaCl salinities and a vapour phase dominated by nitrogen (80-90 mole %) and methane, devoid of $CO_2$; the homogenisation temperatures of these FI are around 270-300°C. In stannite-bearing quartz, two types of inclusions were distinguished (two-phase Lw-n(m-c) inclusions, with a vapour phase at room temperature of around 50% by volume, with a $T_{mCl}$ of about 2 to 4°C, and proportions of volatiles in favour of nitrogen and minor methane and $CO_2$ (less than 20%); and two-phase Lw-c(m-n) inclusions, with a vapour phase at room temperature of around 50% by volume, with a $T_{mCl}$ of about 10 to 12°C, and proportions of volatiles in favour of $CO_2$ and minor methane and nitrogen (less than 20%). Measured $T_{m\,ice}$ values range from -4 to -8°C for Lw-c(m-n) and from -6 to -11°C for Lw-n(m-c). Volatile phase densities and composition are pretty contrasting between FI types, covering a wide range of $CO_2$ proportions, with two evolutionary trends, one towards the methane pole from a $CO_2$-dominated pole and another towards a nitrogen-rich pole. More saline, aqueous inclusions 8-10 wt.% eq. NaCl, with Th of 350°C, were also observed, as in samples representing the Sn-lodes. Salinities contrasted between the two types. Homogenisation temperatures for Lw-c(m-n) are around 350°C for a salinity of 4 wt%. eq. NaCl, and for Lw-n(m-c), Th is about 250 °C, and salinities are 8 to 11 wt.% eq. NaCl.

**3.** Quartz and tourmaline from Mata da Rainha Sn-W lodes show usually two-phase (liquid and vapour) FI, Lw-c or Lw, depending on the presence of gas. Three-phase FI, Lc-w (liquid $H_2O$, liquid $CO_2$ and vapour $CO_2$), were also found in quartz, sometimes coexisting with single-phase Lc or Lc-(w) IF, the latter comprising tiny amounts of water with a blackish appearance. The preserved fluids, predominantly aqueous with a less dense volatile phase or subsequently enriched in volatiles, do not have typical magmatic-derived characteristics. Instead, they show features alike of fluids resulting either from migmatite-related processes (expulsion of water during partial melting) or significant chemical interaction with metamorphic rocks. Intersection of the isochores cluster gathered for aqueous FI in tourmaline [mineral phase that denotes the earliest and most synchronous alteration (tourmalinisation and greisenisation) at the magmatic-hydrothermal transition] with the lithostatic thermal gradients (of 40°C/km and 50°C/km) yield a three-stage evolution: (i) the first, with predominantly aqueous fluids (low-density $CO_2$) trapped in the range 320-470°C and 180-280 MPa for the sub-episode of tourmaline growth, that also corresponds to the first stage of quartz formation in some lodes, (ii) the second, recorded by FI in quartz from different lodes, following a moderate drop in pressure; and (iii) the third, also documented for several lodes, denoted by three-phase carbonic inclusions preserved in quartz. The latter FI are profuse in other quartz aggregates, depicting a lower temperature range (240-290°C) but identical pressure values; thus, it is reasonable to assume that lithostatic pressures are kept. This hypothesis is supported by Th values recorded by Lc-w inclusions, which are at least 260 °C when observed (due to decrepitation), defining pressures above 100-120 MPa. Accordingly, an evolution at pressure conditions close to lithostatic from high temperature conditions, probably of the order of 400-450 °C, to values of the order of 250-300 °C could be inferred for the Mata da Rainha system. Compared with the P-T path reported in literature for the Panasqueira world-class deposit, and despite the poorer constraints at Mata da Rainha, the latter ore system is characterised by lower temperatures of around 50-80°C, but pressure values are alike of those estimated for the tungsten- and topaz-stages at the Panasqueira. However, the record of a long-lasting, polyphasic history as the one at Panasqueira is not documented for Mata da Rainha. Significantly, there are no signs of fluid inflows correlative of late evolving stages developed after orogen exhumation and decompression, and these should represent one of the keys to develop a huge deposit as Panasqueira.

**4.** The ore-forming fluids involved in the Pedra-Alta (Sn-Li) system are also aqueous with low salinity and low volatile content. Fluids with a $CO_2$-dominant volatile phase are associated with amblygonite and quartz deposition, and fluids in cassiterite show variations from $CO_2$-dominated to $CH_4$-dominated. Total homogenisation temperature of FI ranges from 280°C to 315°C in amblygonite, 295°C to 395°C in quartz, and 235°C to 330°C in cassiterite. Considering the computed isochores, cassiterite growth starts at *ca*. 400°C and 110 MPa from low salinity $CO_2$-dominated fluids and ends at lower temperature conditions from fluids with a volatile phase enriched in $CH_4$. This record plausibly traces an increasing participation of fluids compositionally buffered by the metasedimentary rocks hosting the quartz lodes throughout the ore-forming events with the formation of amblygonite at high temperature and pressure and with quartz at lower pressure. Such interpretation is consistent with indications provided by stable isotope analyses ($\delta^{18}O$ and $\delta D$) of selected quartz and cassiterite grains extracted from Pedra Alta samples. The $\delta^{18}O$ and $\delta D$ values obtained in quartz were +14.1 ‰ and -63.7 ‰, respectively; in cassiterite, the $\delta^{18}O$ values range from +6.4 ‰ to +6.5 ‰ and $\delta D$ is of -37.1‰. The isotopic composition of hydrothermal fluids estimated with experimental fractionation mineral-water equations and the minimum and maximum values of FI total homogenization temperatures, points to the involvement of mixtures, in variable proportions, of components derived from "magmatic waters" with others isotopically equilibrated with metamorphic rocks.

**5.** In the Vale Pião W-system, aqueous fluids trapped on scheelite show minor salt and volatile components. FI in disseminated scheelite, both in quartz lodes and breccias, shows volatile phases enriched in $CH_4$ and $N_2$; when in veinlets, scheelite preserves FI that includes $CO_2$, being the $N_2$ content higher than $CH_4$. Scheelite from quartz lodes and breccia were trapped under similar P-T conditions (>220ºC, >50 MPa).

**6.** The comparison of P-T evolution outlined by FI studies in W-dominant quartz lode systems (Segura W-prospect, Mata da Rainha, and the early stages (W) at Panasqueira) and Sn-dominant quartz lode systems (Segura Sn-mine; the muscovite-apatite stage at Panasqueira) shows that pressure conditions are the primary difference between both mineralisation types. These were probably close to lithostatic pressure during the W-dominant mineralising stage and mainly hydrostatic during the Sn-dominant mineralising stage. Such a difference could be related to the exhumation of crustal blocks at the end of the Variscan orogeny, triggered either by an important event of isostatic rebound at *ca*. 300 Ma or a generalised orogenic collapse peaking at the Carboniferous-Permian transition; in literature, interpretations diverge on the reasons behind undisputed features preserved in the geological record. Therefore, the W-dominant mineralising stage should take place at depths of *ca*. 10 km (2-3 kbar), most likely around 310 ± 5 Ma. The hydrostatic pressures inferred for the Sn-dominant mineralising stage indicate shallower crustal levels (*ca*. 3-4 km), conceivably achieved few million years after (*ca*. 300 ± 5 Ma).

### Mineral assemblages potentially enriched in valuable by-products

The exposure conditions in many old Sn-W mining sites (*e.g*. Pedra Alta, Mata da Rainha, Segura) and abandoned exploration works (*e.g*. Monsanto, Mata da Rainha, Medelim) greatly limited the performed sampling, hindering the intended detailed characterisation of mineral infillings of several aplite-pegmatite swarms and quartz lodes. Despite these difficulties, new results were obtained for the aplite-pegmatite bodies of Segura, mostly those forming the Cerro Queimado array, complementing the information available for this system, as well as for other mineralised sets in the SAPG strip (such as Cabeço de Argemela, Panasqueira and Vale Pião). Of the results obtained, the following stand out:

**1.** The mineralogy of the Cerro Queimado (Segura) aplite-pegmatite bodies is quite diverse and the two main Li-carriers are Li-(Na,Al)-phosphates and lepidolite. The former mineral phases were studied with detail using an original methodology based on mapping of phosphorus by micro-XRF, at the thin-section scale, followed by semi-quantitative analysis of the phosphates by SEM equipped with WDS, which, after due calibration, provide accurate analyses. Phosphates display complex relationships, as the early phases may be dissolved and replaced by a succession of lately formed phosphates. The earliest phosphate phases (Li-Al), often associated with topaz, occur preferentially as large euhedral crystals, sometimes centimetre-sized prisms oriented perpendicular to the aplite layers and growing towards the core of the pegmatite veins. These early phases are replaced by a pervasive Na-Al-Li phosphate, shown to be a mixture of the montebrasite and lacroixite at the microscale; Ca-Sr phosphates crystallise later, at the expense or onto the two early Li-(Al, Na) phosphates. These rocks also comprise Fe-Mn (Al) phosphates, grown as isolated grains during a relatively early stage and showing a succession of overgrowths with significant changes in their Fe/Mn ratio.

**2.** In the same aplite-pegmatite bodies, Nb-Ta oxides occur as individual grains dispersed in the silicate matrix. These oxides do not form only exsolution grains in or from cassiterite, as reported in previous studies. Euhedral elongated grains of Nb-phases are a few 10 µm to 100 µm and more in length and display BSE imaging spectacular zoning, mostly oscillatory. Acicular Nb-phases contain significant amounts of W (4 to 5 % $WO_3$) and Mn (10-13%) and are characterised by oscillations in Ta, from 10 to 20%. Overgrowths of Ta-Nb-phases with significant Nb-Ta variation formed on the initial core enriched in Nb.

**3.** Cassiterite grains are euhedral and crystallised onto the thin prisms of Nb-Ta phases. These grains may display limited zoning/replacement or very complex textures with significant substitution, particularly in samples enriched in lepidolite. Cassiterite may contain up to 8% $Ta_2O_5$ and 1% $WO_3$, besides tiny inclusions of Ta-(Nb) phases (tantalite with 60% $Ta_2O_5$). It is unclear whether these inclusions could be considered exsolutions; they appear primarily as inclusions of the latest growing zones of the complex geometry of the Ta phase overgrowths.

**4.** Fine-grained tourmaline-bearing aplites to the south of Segura also show elongated and zoned acicular Nb-Ta phases along with abundant (Na-Al, and Fe-Mn) phosphates, as small grains dispersed within the rock, in addition to apatite.

## WP4

### Mineral Fingerprints and Footprints

(*T4.1 - Proxies and vectors to rare metal enriched (aplite-)pegmatites; T3.2 - Proxies and vectors to (magma-tic-)hydrothermal ore systems; T3.3 - Reassessments of alluvial heavy minerals from old exploration surveys*)

### Mineral compositional features in ore systems vectoring

The composition of several minerals in different settings were successfully tested as finger- and footprints to different mineralisation types. A summary of the most relevant data gathered for muscovite, tourmaline, cassiterite and zircon show that:

**1.** Trace elements in muscovite could be used as footprints of granite fertility and of metal enrichment processes concurrent of magmatic differentiation and later magmatic-hydrothermal transformations. Muscovite flakes in granite rocks are frequently zoned, such as those forming the *ms*-rich granite facies in the Segura-Piedras Albas (Cabeza de Araya) pluton or the strongly differentiated granite facies and pegmatites in the Penamacor-Monsanto pluton at Medelim and Monsanto, respectively. The rims of these flakes are characterised by high contents in Li, Rb, Cs, and Sn, recording the role of fluids (or magmas) enriched in incompatible elements at the end of the crystallisation path of such granite facies. At Segura, the contrasted trends of geochemical differentiation outlined by muscovite, corroborate the existence of two distinct magmatic episodes, one documenting the evolution of the inner-outer granite facies of Piedras Albas (Cabeza de Araya), the other supporting the development of the outermost *ms*-rich granite facies and the Li-bearing aplite-pegmatite bodies. The strong co-variation between K/Rb and Cs indicates that Rayleigh fractional crystallisation should be the main differentiation mechanism; the extreme Rb- and Cs-enrichment displayed by muscovite in adjoining pegmatites requires at least > 95% fractionation of the initial *ms*-granite composition.

**2.** Micas from Segura and Argemela Li(-Sn)-rich systems are compositionally similar. A specific feature of the Segura system is the development of lepidolite pseudo-greisen which forms at the expense of the albite-Li-phosphate pegmatites; fluids could be either linked to a second stage, or to the ultimate evolution of the initial fluids released by the *ms*-rich granite facies. The composition of micas from quartz lode selvages at Panasqueira and Mata da Rainha are also comparable, confirming the analogies between these two W(-Sn)-rich mineralising systems.

**3.** Tourmaline grains disseminated in granite rocks are typically schorlitic with low #Mg (Mg/(Mg+$Fe_T$)) and #Ca (Ca/(Ca+Na+K)), whereas metasediment tourmalines are dravitic with higher #Mg and #Ca. The #Mg *vs* #Ca cross-plots show (i) magmatic differentiation trends for composite granites, with a progressive decrease in #Mg and #Ca, (ii) compositional variability within metasediments and (iii) mixing lines for each hydrothermal system between tourmaline compositions buffered by metasediments and by magmatic-hydrothermal fluid sources. The mixing line range discloses the hydrothermal system magnitude (time, space, and mineralising fluid volume), as shown by the wider trend for the Panasqueira deposit compared to smaller deposits such as Góis or Segura. However, complete interpretation of mixing lines, or deviations from it, require detailed petrography and careful microprobe spatial and compositional control to address aspects such as multiple tourmaline generations, compositional zoning, or even diffusion mechanisms. In general, hydrothermal tourmaline documents a progressive increase in #Mg and #Ca, reflecting a simultaneous rise of the magmatic-hydrothermal fluid component. Except for Panasqueira, tourmalinites at the Penamacor-Monsanto batholith exo-contact record the lowest #Mg values denoting their proximity to the intrusion. For systems like Góis, where no granites are known in the vicinity, the trend starts at higher #Mg values, and a more distal position relative to a causative granitic intrusion is believed.

**4.** Tourmaline is particularly abundant in Mata da Rainha, developing quartz-tourmaline veins often associated with massive schist tourmalinisation and greisen-like metasomatism of granites along the granite-schist contact. Twenty-eight thick-slice sections were prepared to study these tourmaline occurrences and to determine the fluids that flowed through different structures in the surveyed area. Three tourmaline types were recognised, forming: (i) dark masses composed of densely agglomerated microcrystals of tourmaline in the altered schist; (ii) coarse-grained crystals, often euhedral into rods and prisms, in quartz veins; and (iii) disseminated grains in pegmatites and greisen. Micro-XRF mapping provided the first chemical image of growth zones in tourmaline, particularly the contrasted distribution of Fe, Ti (Mg, Mn and sometimes Ca); in general, Ti, Fe and Ca are concentrated in the outer dark bands, whereas Mg tends to concentrate in the cores of zoned tourmalines. The LA-ICP-MS profile (craters 60 µm in diameter) confirms that Ti is enriched towards the edge of tourmalines. Concentrations rise from 2000 ppm Ti and 90 ppm Li at the core of the grain to as high as 5000 ppm Ti and 120 ppm Li towards the rim. Manganese and Zn generally remain constant along the profile, except for a slight drop in the concentration of both elements at the outer rim. Gallium is steady at 100 ppm. Vanadium fluctuates along the profile with no apparent relationship to Fe-Ti enriched or depleted zones. Tourmalines from Mata da Rainha and Panasqueira are compositionally comparable (particularly in what concerns Sn, Li, Cu, Zn, Sr and V), indicating that processes involved in both ore-forming systems are of the same type.

**5.** The mean $\delta^{11}B$ values displayed by tourmaline in hydrothermal quartz veins and greisen facies of Mata da Rainha are very close (varying between 2‰ and 3‰) and do not show significant variations along the edge-core profiles; on the contrary, the range of $\delta^{11}B$ values in tourmalines in strongly altered schists is far more extensive. Tourmalines from quartz veins in contact with pegmatite-aplite bodies at Mata da Rainha are isotopically identical to those from the Penamacor-Monsanto granite system, and there is a good correspondence between the boron isotopic compositions of tourmaline forming the altered schists at Mata da Rainha, Argemela and Panasqueira. Compared to tourmalines from Argemela and Segura systems, the Mata da Rainha samples tend towards lighter $\delta^{11}B$ values (-11, -12.5 ‰) but, in general, the obtained isotopic data fall within the range characteristic of both continental crust and S-type granites, not allowing a clear discrimination between a granitic or a sedimentary source. Nonetheless, the similarity in textural arrangements and the crystal chemical and isotopic characteristics showed by tourmaline in different settings suggest that similar processes might generate significant or massive tourmalinisation in (heterogeneously modified) granite bodies, or near their margins, before the formation of quartz lodes. So, tourmalinisation might be used as a guide to the proximity of potentially mineralised rock domains.

**6.** Cathodoluminescent (CL) imaging, micro-X-ray fluorescence (m-XRF) element mapping, combined with quantitative chemical analyses by electron probe microanalyzer (EPMA) and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), were used to characterise cassiterite from several Sn-W deposits within de SAPG strip. CL imaging and m-XRF mapping revealed primary and secondary growth textures, namely oscillatory zoning, sector zoning, and dissolution-reprecipitation features. Minor (>1000 ppm) to trace (<1000 ppm) element enrichment in Ti, Nb, Ta, Fe, Mn, W, Zr, Hf, Al, Ga, Sc are common, but their variation among deposits and within each deposit, even at the grain scale, reveals multi-phase and complex mineralising systems. Cassiterite hosted in magmatic rocks (*e.g.*, Argemela rare metal granite and Segura aplite-pegmatites) have typically high contents of Nb (up to 30,000 ppm), Ta (up to 50,000 ppm), Fe (up to 7,000 ppm), Mn (up to 12,000), Al and Zr (up to 2,800 ppm), and Hf (up to 700 ppm), and low contents of Ti (<500 ppm) and V (<1 ppm). In contrast, cassiterite from hydrothermal quartz lodes (*e.g.*, Sandinha, Vale Pião, Panasqueira, Mata da Rainha, Capinha, and Segura) are generally enriched in Ti (>3,000 ppm and up to 10,000 ppm) and V (30-500 ppm). In hydrothermal W>Sn systems, such as Panasqueira, Sandinha and Vale Pião, W contents can reach up to 4,000 ppm, being even higher in Cerro Queimado (Segura) Li-aplite pegmatites (up to 1.5% W). Variations within this dichotomy reflect local chemical signals acquired by mineralising fluids during their evolution, such has in Panasqueira, where cassiterite associated with the sulphide stage deviates from its hydrothermal fingerprint to become exclusively enriched in Fe. In Pedra Alta and Medelin, intermediate fingerprints between hydrothermal and magmatic cassiterite were recognised. Also, in Mata da Rainha and in Argemela quartz lodes, individual grains record an initial composition compatible with hydrothermal fluids equilibrated with metasedimentary host rocks, subsequently affected and recrystalised by fluids with a clear magmatic component. Besides these element fingerprints, element ratios, such as Fe/Mn, Nb/Ta, Zr/Hf, Al/Ga, Ti/Al, Hf/Ga, Ti/Zr, and the Ti-(Fe+Mn)-(Nb +Ta) proportions are sensitive to magmatic-hydrothermal ore-forming processes and can be used to discriminate among deposit types, mineralising styles, compositional fluid endmembers, and characteristic mixing trends. Our study also included alluvial cassiterite from the Segura region, demonstrating its use as an excellent exploration tool for Sn-W ore deposit systems (see below).

**7.** Trace element distribution in zircon is useful as an exploration vector towards granite-related ore-forming systems. This was tested by analysing with SHRIMP the REE contents in zircon grains extracted from different granitoid facies and dyke swarms, namely those representing the (Cambrian-)Lower Ordovician (Batão, Oledo/Idanha-a-Nova, Zebreira and Fundão) and the Carboniferous (Capinha, Salvaterra do Extremo, Orca, Monsanto, Segura, Panasqueira) suites. The REE contents and their CN-normalised patterns for oscillatory or sector zoned zircons in granitoid rocks lacking effects of late metasomatic or hydrothermal processes are similar, despite of their age. The patterns match those typically revealed by magmatic zircons, displaying an evident LREE-HREE fractionation together with slight positive Ce-anomalies and pronounced negative Eu-anomalies. In the same rocks, other texturally analogous zircons present REE CN-normalised patterns typified by larger positive Ce-anomalies, possibly denoting consecutive zircon crystallisation stages under conditions of higher oxygen partial pressure. Identical explanation justifies the contrasting Ce and Eu anomalies obtained for many zircon grains in porphyry dykes and laccoliths (Furão and Marcelina), although requiring higher LREE saturation, as indicated by the LREE enrichment trend.

**8.** Zircons from aplite/pegmatite bodies rarely preserve oscillatory zoning, conceivably due to a significant interaction with fluid-saturated melts, although blurry oscillatory zoning is common. Even so, their REE CN-normalised patterns are indistinguishable from those above described for zircons in contiguous granite facies. Larger differences exist when zircons came from aplite-pegmatite or granite samples subjected to strong compositional changes, which are usually related to an increase of mineralisation footprints. In such cases, zircon grains have complex internal textures in which the secondary domains cut through the primary growth zones, showing, in addition, trends towards LREE enrichment along with the fading or elimination of positive Ce anomalies. Despite the care put into the analytical work, part of this LREE enrichment might be due to incidental sampling of submicrometric inclusions of, *e.g.*, monazite or apatite. However, the textural and compositional changes recognised for these zircons are irrefutable, being comparable with other well documented case-studies.

**9.** Additional evidence for late compositional changes experienced by zircons from differentiated rocks or granitic facies affected by mineralising fluids are provided by high U and $^{204}$Pb contents, ranging from 500 to 10000 ppm, and often above 1 wt%, respectively. It is well known that the replacement of Zr by tetravalent cations (Th, U and Hf) is favoured in most evolved granites. Heterogeneous REE incorporation could be related to fluid-mediated dissolution-precipitation reactions under P-T conditions compatible

Co-funded by the Horizon 2020 programme
of the European Union

with aplite-pegmatite development. Furthermore, micro-domains significantly enriched in U (>3000 ppm) and Th (>100 ppm) might experience increased levels of metamict (radiation damage) transformations able to generate significant structural disturbances, enhancing susceptibility to late compositional changes. Similar compositional records in zircons were also reported for many other Carboniferous granite facies of the Iberian Variscides, and in other segments of the European Variscan orogen, thus suggesting that REE, U, and Th contents in zircon are sensitive to late magmatic and magmatic-hydrothermal processes concurrent of mineralisation.

### Alluvial heavy minerals in granite-related mineral systems exploration; the case of Segura

The Segura mining field, the easternmost segment of the SAPG strip, includes several arrays of Sn-W quartz lodes and Li-Sn aplite-pegmatites, which are genetically related to Carboniferous granites. An extensive collection of alluvial samples was comprehensively examined, and the main results achieved could be summarised as follows:

**1.** Sediment geochemistry indicates granite-related Ti-enrichment, locally disturbed by mineralisation, suggesting magmatic and metamorphic/metasomatic titaniferous phases. Therefore, Segura alluvial samples and the geochemistry of their $TiO_2$ polymorphs (rutile, anatase, and brookite) were investigated, and their potential as exploration tools for Sn and W deposits was evaluated. The heavy-mineral assemblages proved to be good proxies for bedrock geology, and $TiO_2$ polymorph abundances were found to be suitable indicators of magmatic and/or metasomatic hydrothermal processes. The trace element geochemistry of Segura's alluvial rutile, anatase, and brookite is highly variable, implying multiple sources and a diversity of ore-forming processes. The main compositional differences between $TiO_2$ polymorphs are related to intrinsic factors, and to the P-T-X parameters of their forming environments. Anomalous enrichment, up to 9% Nb, 6% Sn and W, 3% Fe, 2% Ta, and 1% V in rutile, and up to 1.8% Fe, 1.7% Ta, 1.2% Nb, 1.1% W 0.5% Sn and V in anatase, were registered. Brookite usually has low trace element content (<0.5%), except for Fe (≈1%). HFSE-rich and granitophile-rich rutile is most likely magmatic, forming in extremely differentiated melts, with Sn and W contents enabling the discrimination between Sn-dominant and W-dominant systems. Trace element geochemical distribution maps show pronounced negative Sn (rutile + anatase) and W (rutile) anomalies linked to hydrothermal cassiterite precipitation, as opposed to their hydrothermal alteration halos and to W-dominant cassiterite-free mineralized areas, where primary hydrothermal rutile shows enrichment alike of magmatic rutile. This contribution recognises that trace element geochemistry of alluvial $TiO_2$ polymorphs can be a robust, cost- and time-effective, exploration tool for Sn(W) and W(Sn) ore deposit systems.

**2.** The alluvial cassiterite (± tourmaline/quartz), wolframite (± quartz), scheelite and tourmaline (+ phyllosilicates ± quartz), were studied under binocular microscope and their regional scale mapping spatial distribution analysed, in an area up to 26 $km^2$, of the Segura region. The pattern defined by the abundance/distribution of cassiterite and wolframite alluvial grains correspond to concentric haloes around the endo- and/or exo-contacts of the Segura granite, representing the footprint, on the alluvial deposits, of different arrays of Sn-rich magmatic-hydrothermal lodes. The most significant lodes are hosted in the BG siliciclastic metasediments (Malpica do Tejo *Fm.*) and controlled by WNW-ESE to NW-SE structures, which preserve evidence of multiple reactivation events. These lodes, scattered across the western side of the Segura mining region and documenting different mineralising events, justify the increase of cassiterite and wolframite grains in alluvial sediments, and, most likely, the observed trend to higher variation of physical properties displayed by cassiterite grains. The metallogenic zoning is also reflected by the increase of the alluvial wolframite/cassiterite ratio sourced by distal Sn-W quartz lodes; the predominance of tin- over tungsten-rich ores is indicated by the prevalence of cassiterite over wolframite in alluvial sediments. Alluvial scheelite shows well-defined exo-granitic concentric haloes nearby the Segura and Estorniños granites, although displaying configurations distinct from those defined by cassiterite and wolframite. This dissociation suggests a different origin for the sources of scheelite, conceivably related to metasomatic processes affecting some of the sections of the metasedimentary pile hosting the granites.

**3.** The anomalies traced by the concentration of alluvial cassiterite and wolframite grains over the main cluster of Sn-W-bearing lodes in the Segura region are similar in magnitude with those reported for other segments of the SAPG strip where comparable ore-forming systems occur. The magnitude of scheelite anomalies can also be framed within reported figures for scheelite-rich ores from other countries.

**4.** The increase of alluvial tourmaline abundance is a vector to the Segura granitic rocks. Meaningful amounts of tourmaline + phyllosilicates (± quartz) composite grains indicate usually the broad regional metasomatic halo related to the granitic intrusions. Significant populations cassiterite + tourmaline/quartz and wolframite + quartz composite grains are proxies to Sn(-W) lodes or, in the first case to their decametric metasomatic alteration halo, representing an ore guide. In the Segura southern region, the distal Estorniños granite exo-contact area is outlined by low tourmaline abundance and variability. However, the scheelite halo, cassiterite abundance /variability, along with cassiterite + tourmaline composite grains, consistently point to an unexplored Sn- mineralising peri-batholitic system.

**5.**The alluvial heavy minerals assemblages reflect the influence of proximal sources in each catchment area. The impact of mixing effects (signing distinct sources) on the mineral abundance should be assessed and sorted locally, using compositional fingerprints.

**6.** The approach used in MOSTMEG can be applied in other regions hosting (un)known Sn-W mineralising systems, in brownfield and greenfield scenarios. The study of alluvial heavy minerals represents also a powerful tool to delimit other targets for critical and strategic raw materials.

## WP5
### Geochemical Fingerprints and Footprints
(*T5.1 - Multi-element geochemical proxies and vectors to granite-related mineralization; T5.2 - Multi-system isotopic proxies and vectors to granite-related mineralization*)

### Geochemical proxies to granite-related mineral systems

The geochemical and isotopic characterisation of the main plutons and aplite-pegmatite swarms exposed across the SAPG strip shows that the Carboniferous(-Permian) granite suites display different degrees of differentiation and metal enrichment. An overview of the results obtained provides the following highlights:

**1.** The strongly differentiated and ferroan leucogranites to which the magmatic-hydrothermal ore-forming processes are related show evident enrichment in P, F, Be, Li, Ta, Sn, Nb (on average, up to 25×, 15×, 70×,

Co-funded by the Horizon 2020 programme
of the European Union

500×, 150×, 800×, and 20× the upper continental crust, respectively) and K/Rb < 150; Nb/Ta < 5; Y/Ho ≠ 28; Sr/Eu > 200; Eu/Eu* < 0.1; Zr/Hf < 15 and U/Th > 10. These features are comparable to those found in many other Sn-W(±Li) provinces worldwide and are robust enough to assess the mineral exploration potential of granite-dominated settings.

**2.** The intensity of lanthanide tetrad effect ($TE_{1,3}$) co-varies with magmatic differentiation and metal enrichment. The Li-phosphate-bearing Argemela Rare Metal Granite and the Li-rich aplite-pegmatite dykes from Segura deviate from this geochemical trend, displaying $TE_{1,3}$ <1.1, but also high $P_2O_5$ contents. This suggests that $TE_{1,3}$ values and $P_2O_5$ (wt%) contents can be used together to separate three different magmatic-hydrothermal systems: (i) dominated by P+F±B (P>B), with strong aqueous high-temperature REE signatures, and related to Li-Sn Peraluminous-High-Phosphorous granites and Li-phosphates-bearing aplite-pegmatite dykes ($TE_{1,3}$ < 1.1); (ii) dominated by F+P±B (F>P) and related to W-Sn-Li High-Phosphorous granites and lepidolite-bearing aplite-pegmatite dykes ($TE_{1,3}$ up to 1.4); and (iii) dominated by F+B±P (F>B) and related to Sn-Ta-Nb Peraluminous-Low-Phosphorous granites ($TE_{1,3}$ up to 2.1). Such data suggests also that the degree of the lanthanide tetradeffect can be a very useful whole-rock geochemical fingerprint of granite differentiation and exploration vector for different types of granite-related ore systems.

**3.** Near the Segura pluton, hyper-differentiated magmas enriched in F, P, and Li migrated through shallowly dipping fractures, which were sub-perpendicular to the schistosity of the host Neoproterozoic to Lower Cambrian metasedimentary series, to form two swarms of low-plunging aplite–pegmatite dykes. The high enrichment factors for the fluxing elements (F, P, and Li) compared with peraluminous granites are of the order of 1.5 to 5 and are a consequence of the extraction of low-viscosity magma from the crystallising melt. With magmatic differentiation, increased P and Li activity yielded the crystallisation of the primary amblygonite–montebrasite series and Fe-Mn phosphates. The high activity of sodium during the formation of the albite–topaz assemblage in pegmatites led to the replacement of the primary phosphates by lacroixite. The influx of external, post-magmatic, and Ca-Sr-rich hydrothermal fluids replaced the initial Li-Na phosphates with phosphates of the goyazite-crandallite series and was followed by apatite formation. Dyke emplacement in metasediments took place nearby the main injection site of the muscovite granite, which plausibly occurred during a late major compression event.

### What do mineralogical variations in contact metamorphic haloes tell us?

Another research line explored in MOSTMEG was the imprint of contact metamorphic aureoles by hydrothermal processes. To our knowledge, the approach followed represents an innovative contribution that might assist the delimitation of concealed granite-related mineralisation. In this regard, particular attention was given to the Argemela and Segura systems, and the achieved results shows that:

**1.** The hydrothermal system developed around the Argemela hyper-differentiated intrusion yield significant transformations in the BG schists. Quartz-tourmaline metasomatosed shales formed at the contact and a muscovite-biotite zone beyond in the semi-distal zone. The main assemblage currently observable in the latter is a muscovite-biotite (chloritized afterwards) association, with hexagonal shaped spots interpreted as phantoms of the pre-existing cordierite blasts. Accordingly, the mineral assemblage records successive transformations involving superimposed metamorphic and hydrothermal histories: (i) a cordierite spotting conceivably related to a concealed granite at depth, (ii) growth of neo-formed biotite and muscovite triggered by the Argemela-related hydrothermal fluids, and complete retrogression of the cordierite spots into a mica+ biotite assemblage, (iii) path to the chlorite field due to the subsequent decrease of temperature conditions. For many kilometres the schists show spots that hardly could be related to the Argemela and Fundão granites, to the E-SE, or to Serra da Estrela granites, to the N. This suggests the presence of other intrusive bodies at depth, more extensive than the currently exposed granites.

**2.** Along a profile to the SE of the Argemela intrusion, bulk rock samples taken were analysed for minor and trace elements, and the principal rock-forming minerals (muscovite, biotite, chlorite, tourmaline) by electron probe and LA-ICP-MS. Within a few hundred metres of the contact, the schists show increased concentrations of Li, F, Sn, Cs and Rb due to recrystallisation of the mica, and of B due to pervasive tourmalinisation. Fluorine and lithium concentrations appear to be fairly good indicators of the proximity of intrusions at distances that exceed the significant metasomatic impact observed in the first 10 metres of the caused significant transformations in the BG schists. Near the granite intrusion, concentrations of B, Li, F, Sn, Cs and Rb (W) are exceptionally high in the metasomatised schists. The effects identified at close distance diminish sharply with distance from the contact. However, there is still a plateau of several hundred metres before concentrations fall back to the level of the healthy surrounding rocks. Fluorine and lithium concentrations in muscovite, which are very high close to the intrusion, are reasonably good indicators of the proximity of intrusions at distances that exceed the significant metasomatic impact observed within 10 metres of the contact with the intrusion.

**3.** In the Segura area, the BG metasediments are also affected by an envelope of contact metamorphism, resulting in the development of spots over a width of 1 km around the pluton. The spots growth depends on lithology and deformation, as some spots develop along Al-enriched microstructures resulting from the transposition of foliation planes. Spots initially composed of inferred cordierite are then affected by retrogression and hydrothermal alteration processes. These transformations are revealed on the scale of the samples and thin sections by micro-XRF chemical images, which show patches that are not often resolved at macroscale, the (transposed) bedding and the deformation patterns that affect it. An albite-chlorite-ilmenite-(rutile)- (biotite) association fill the almond-shaped spots, which are generally inferred to be a former cordierite grain but cannot be confirmed, and the matrix is formed of muscovite and biotite-quartz. These mineral associations were altered by widespread muscovitisation in relation to the penetration zones of the sub-horizontal intrusive dykes developed perpendicular to the foliation. Later, a retrogression path in greenschist facies conditions (chlorite isograde) affected the early grown mineral assemblages.

## WP6
### Predictive Modelling
(***T6.1 - Model's parametrization and production; T6.2 - Model's validation***)

### Advantages of using the mineral-system approach in planning exploration surveys

In the MOSTMEG project, the conceptual framework and distribution of the research tasks followed the Mineral Systems Approach (MSA), which considers the foundation of ore-forming systems in the framework of lithospheric-scale processes from a time privileged viewpoint of metal, ligand, and fluid

Co-funded by the Horizon 2020 programme
of the European Union

sources, followed by metal transport and deposition in different traps. According to evidence compiled in many regions, this approach improves prediction of geological models when used in exploration surveys. One of the keys for this success is the consideration of multiple spatial scales, from hundreds to few kilometres, and multiple mapping criteria, adjusted to the intended mineralisation types, that improve the resolution of exploration models, especially when in presence of co-existent but diachronic mineralising events, which could also be framed in a time-space setting. Considering these broad principles:

**1.** The critical inherited features at the province scale were appraised, seeking for the main constraints for the sources of melts/fluids and metals at the district scale, and the determinant factors for ore formation at the deposit scale in function of the mineralisation type/style; and

**2.** Some aspects related to physical dispersion were assessed by the inspection of heavy minerals in alluvial sediments not exposed to significant transport.

The main goal was to figure out the most favourable transient events in the geodynamic evolution able to stimulate metallogenic processes that, combined with favourable pathways for melts/fluid flow, and the sources of metals, ligands, and fluids, might have led to the ore genesis. Additionally, some features related to preservation were considered because this is also important in the multiplicative relationship that determines the ore endowment of each deposit.

### Key criteria mapping and identification of promising areas for mineral exploration endeavours

Despite the high number of samples analysed within the scope of the MOSTMEG project, complementing published data from different granitic bodies, the obtained data density is not sufficiently robust to support reliable spatial interpolations. This fragility, substantiated by high asymmetries in the spatial distribution of information, prevents the construction of maps for the entire SAPG strip. However, this mapping can be performed for some of the selected targets, demonstrating the plausibility of the methodology supported by the criss-crossing of geological, geochemical and mineralogical criteria. According to the MSA approach, these criteria were grouped into four categories, as follows: critical factors, constituent processes, targeting, and mappable proxies. Avoiding redundancies, namely the repetition of the results presented previously, we leave here the basic ideas that allowed the creation of several bubble maps for the SAPG strip, highlighting the anomalous domains in different metals (which concentrations were normalised to the upper continental crust values) or distinguishing specific geochemical signals with element molar ratios. Concisely:

**1.** CRITICAL FACTORS include as: (i) **main sources**, the formation of “fertile” or “specialised” melts (depending on energy, protoliths nature and metal endowment, fluxing components, *etc*.) and the processes of extreme fractionation of pluton-sized granitic batches; (ii) **active pathways**, the structural constraints posed to the magma transport, directing the flow through the crust and late separation of evolved residual melts or critical fluids; (iii) **main traps**, the crystallisation and cooling rates of granite melts, influencing the chemical transport and differentiation, besides the metal enrichment in residual portions; (iv) **prevalent modifications**, all the consequences imposed by exhumation, which should be better investigated in future.

**2.** CONSTITUENT PROCESSES involved in: (i) the **main sources** comprise the assessment of crustal melting processes in time (in particular, from *ca*. 315 to 290 Ma); (ii) the **active pathways** include the appraisal of cycles of renewed rock permeability increasing, namely those related to crustal-scale shearing/faulting; (iii) the **main traps** embrace the survey of the most efficient processes that lead to the production of highly differentiated (and metal-fertile) batches and/or the split-up of supercritical fluids, besides mixing with external fluid components; (iv) the **prevalent modifications** encompass the study of processes able to strengthen or weaken the primary geochemical anomalies during late evolving stages, mostly during the Alpine Cycle. For all these items, the gathered information is quite satisfactory for the sources and active pathways, as well as on the wide diversity of mechanisms that could confine the efficiency of the major traps. Evidence for supergene mineral assemblages and secondary accumulations is also available, although at limited scales.

**3.** TARGETING should consider: (i) in the **main sources** criteria, the spatial distribution, volume and attributes of highly differentiated peraluminous granite suites, particularly the ferroan leucogranites enriched in a wide range of incompatible elements, besides compositional overprints found in contact metamorphism aureoles; (ii) in the **active pathways** criteria, the structural arrangements supported either by networks of shear zones (connection domains of conjugate systems; evidence of multiple reactivation) or networks of folding-related structural discontinuities; (iii) in the **main traps** criteria, the characteristics displayed by distal and proximal swarms of aplite-pegmatite bodies or compositionally and texturally zoned pegmatites, in addition to those exhibited by the quartz-lode systems (density, internal connection, evidence of multiple infilling stages); (iv) in the **prevalent modifications**, the prevalent topographic highs and ridges, weathering vulnerability of critical mineral phases and the physical dispersion of heavy minerals in superficial settings.

**4.** MAPPABLE PROXIES must contemplate: (i) in the **main sources** criteria, the key features of granite suites (textural, mineral, geochemical, geochronological) and fertility footprints (expressed as mineral abundance and composition, besides geochemical ratios and indexes) ; (ii) in the **active pathways** criteria, the structural patterns (density, connection, mineral infillings, age) and alteration pathways in country rocks (as provided by mineral and geochemical guides); (iii) in the **main traps** criteria, the mineral/ geochemical vectors to mineralisation); (iv) in the **prevalent modifications**, the study of heavy minerals in alluvial sediments (carrying out its classification and compositional analysis) complemented, whenever possible, with soil or stream sediment geochemistry. Combination of different proxies proven useful in delimiting promising exploration targets. As mentioned above, it is impossible to overlap equally in GIS the information layers for the whole SAPG strip, because of the strong asymmetry of sampling so far completed. However, plotting the results gathered in studies based on alluvial heavy minerals, and on whole-rock geochemistry, already confirmed that this work is feasible although confined to areas where sampling density is moderate to high.

**5.** Throughout the SAPG strip, besides the brownfield areas surrounding sites subjected to mining in the past, such as those to the north-northwest of the Lousã-Góis-Vale Pião region, other regions must be investigated. This is the case of the large and poorly explored region extending to the west and southwest of the Panasqueira-Argemela systems. Future mineral exploration endeavours should also consider the distal Estorniños granite exo-contact, to the south of Segura, a promising area for scheelite mineralisation.

Co-funded by the Horizon 2020 programme
of the European Union

## 2.2 Main deliverables and milestones planned and delivered

| Milestones | | Planned delivery date (*) | Effective delivery date (*) | Partners involved | Comments (on-time, delayed, not delivered (explain why), etc.) |
|---|---|---|---|---|---|
| M1.1 | Preliminary Database: compilation of literature data and other preparatory activities. A first steering group meeting will evaluate the field work done and will direct sample selection for subsequent studies. | 10 | 10 | UC/FCUL | Achieved on-time |
| M2.1 | Geochemical onset; sample preparation for elemental and isotopic analyses according to adequate methods. | 7 | 7 | FCUL/USP | Achieved on-time |
| M2.2 | Geochemical and isotopic analyses completed. | 24 | 24 | USP/FCUL | Achieved on-time |
| M3.1 | Beginning of sample preparation, polished sections, mineral separation. | 7 | 7 | FCUP/CNRS | Achieved on-time |
| M3.2 | Petrography & sample selection for subsequent analytical methods completed. | 24 | 24 | FCUP/CNRS | Achieved on-time |
| M3.3 | Mineral and fluids data acquisition completed. | 29 | 29 | CNRS/FCUP | Achieved on-time |
| M3.4 | Mineral and fluids data reduction/treatment completed. | 33 | 33 | CNRS/FCUP | Achieved on-time |
| M4.1 | Onset of alluvial sediment study. | 7 | 7 | LNEG | Achieved on-time |
| M4.2 | Onset mineral fingerprints and footprints evaluation. | 25 | 25 | UÉvora/CNRS | Achieved on-time |
| M4.3 | Mineral and fluids proxies and vectors completed. | 38 | 38 | UÉvora/CNRS | Achieved on-time |
| M5.1 | Onset of geochemical and isotopic data evaluation. | 22 | 22 | FCUL/USP | Achieved on-time |
| M5.2 | Geochemical and isotopic vectors and proxies defined. | 33 | 33 | FCUL/USP | Achieved on-time |
| M5.3 | Discriminant geochemical and isotopic indices tested/validated. | 39 | 39 | FCUL/USP | Achieved on-time |
| M6.1 | Model Parametrization onset. | 34 | 34 | FCUL/USP/CNRS | Achieved on-time |
| M6.2 | Model Parametrization completed. | 39 | 39 | FCUL/USP/CNRS | Achieved on-time |

| | | | | | |
|---|---|---|---|---|---|
| M6.3 | Model's validation completed. | 44 | 44 | FCUL/USP/CNRS | Achieved on-time |
| M6.4 | Testing model with stakeholders. | 45 | 45 | ALL | Achieved on-time |

(*) The planned and effective delivery dates (nº of months) are those in the reviewed Gantt chart, considering the 9-month extension (required and approved) for the MOSTMEG project.

| Deliverables | | Planned delivery date (*) | Effective delivery date (*) | Partners involved | Comments (on-time, delayed, not delivered (explain why), etc.) |
|---|---|---|---|---|---|
| D1.1 | Preliminary database: harmonized database for the available rock, mineral, and fluid chemical data for the Segura-Argemela-Panasqueira-Góis strip. | 10 | 10 | UC/FCUL | Delivered on time<br><br>Available on the project webpage (INT) |
| D1.2 | Stratigraphic/structural map: updated geological map, expressing the most relevant tectonic, structural and stratigraphic features identified during field work. | 10 | 10 | UC/FCUL | Delivered on time<br><br>Available on the project webpage (PU) |
| D1.3 | Sampling dataset. | 12 | 12 | UC/FCUL | Delivered on time<br><br>Available on the project webpage (PU) |
| D2.1 | Geochemical database: updating the preliminary database with multi-element whole-rock geochemical data collected in Task2.1. | 24 | 24 | FCUL/USP | Delivered on time<br><br>Available on the project webpage (PU) |
| D2.2 | Isotopic database: updating the preliminary database with isotopic data collected in Task2.2. | 24 | 24 | FCUL/USP | Delivered on time<br><br>Available on the project webpage (INT) |
| D3.1 | Mineral and fluid chemistry database: updating the preliminary database with mineral and fluid geochemical data collected in Task3.1. | 33 | 33 | CNRS/ FCUP | Delivered on time<br><br>Available on the project webpage (INT) |
| D3.2 | Mineral and fluid chemistry database: updating the preliminary database with mineral and fluid geochemical data collected in Task3.2 | 33 | 33 | CNRS/ FCUP | Delivered on time<br><br>Available on the project webpage (PU) |

| | | | | | |
|---|---|---|---|---|---|
| D3.3 | By-products database: catalogue of valuable by-product elements associated with the different types of mineralization previously identified. | 33 | 33 | CNRS/ FCUP | Delivered on time<br><br>Available on the project webpage (PU) |
| D4.1, 4.2, 4.3 | Mineral fingerprint & footprint database: catalogue of vectors and proxies (e.g., mineral indexes, mineral chemical indexes) for different types of mineralization. | 38 | 38 | UÉvora/CNRS/ LNEG | Delivered on time<br><br>Available on the project webpage (PUB) |
| D5.1 | Geochemical fingerprint & footprint database: catalogue of whole-rock geochemical vectors and proxies for diverse granite-related deposits. | 39 | 39 | FCUL/USP | Delivered on time<br><br>Available on the project webpage (PU) |
| D5.2 | Isotopic fingerprint & footprint database: catalogue of whole-rock isotopic vectors and proxies for diverse granite-related deposits | 39 | 39 | FCUL/USP | Delivered on time<br><br>Available on the project webpage (PU) |
| D6.1 | Model: A GIS toolbox to targeting granite-related mineralization types/styles. | 45 | 45 | FCUL/USP/CN RS | Delivered on time<br><br>Available on the project webpage (INT) |
| D7.1 | Progress Report #1. | 12 | 12 | ALL | Delivered on time<br><br>Available on the project webpage (PU) |
| D7.2 | Progress Report #2. | 24 | 24 | ALL | Delivered on time<br><br>Available on the project webpage (PU) |
| D7.3 | Progress Report #3. | 36 | 36 | ALL | Delivered on time<br><br>Available on the project webpage (PU) |
| D7.4 | Seminar #1 - Presentation and discussion with interested stakeholders of the results achieved during the former years of the project. Promotion of the methodological tools in development within potential users, namely in industry. | 39 | 39 | ALL | Delivered on time<br><br>Available on the project webpage (PU) |

| | | | | | |
|---|---|---|---|---|---|
| D7.5 | Atlas of mineral and chemical textures: image atlas of key textural features of minerals and their chemistry from different granite-related deposits, for terminology systematics and to be used as an exploration tool reference. | 39 | 39 | CNRS | Delivered on time<br>Available on the project webpage (PU) |
| D7.6 | Final Report. | 45 | 45 | ALL | Delivered on time<br>Available on the project webpage (PU) |
| D7.7 | Seminar #2 - Launch and demonstration of a GIS toolbox to interested stakeholders. | 45 | 45 | ALL | Delivered on time<br>Available on the project webpage (PU) |
| D7.8 | Scientific Meetings - Participation & presenting at scientific meetings within the scope of the project (5/6 abstracts and/or extended abstracts). | 12-45 | 12-45 | ALL | Delivered on time<br>Available on the project webpage (PU) |
| D7.9 | Papers - 7/8 papers in highly ranked and widely diffused journals. | 24-45 | 24-45 | ALL | Some being prepared<br>Available on the project webpage (PU) |
| D7.10 | Advanced training to the appointed MSc research fellows. | 1-45 | 1-45 | FCUP/LNEG | Delivered on time<br>Available on the project webpage (PU) |

(*) The planned and effective delivery dates (nº of months) are those in the reviewed Gantt chart, considering the 9-month extension (required and approved) for the MOSTMEG project.

The databases on the project's webpage, still needing a final verification and completion, will be totally public after the planned publications are completed.

The number of papers planned for D7.9 was not fully achieved by the end of July 2024, but several manuscripts are being prepared to be submitted in the following months, as listed in section 4.2. Therefore, it is expected that the indicated figures will be attained or even exceeded in a near future.

The intended MSc training (D7.10) was improved, and four other theses were completed in the framework of the MOSTMEG project, as indicated in section 5.2. These MSc theses will be formally presented in September 2024.

Co-funded by the Horizon 2020 programme of the European Union

## 2.3 TRL for each partner

| | Coordinator Partner 1 (Fac.Ciências Univ. Lisboa and IDL) | Partner 2 (Fac. Ciências Univ. Porto) | Partner 3 (Univ. Évora, Geociências - HERCULES) | Partner 4 (Lab. Nacional de Energia e Geologia, I.P.) | Partner 5 (Universidade de Coimbra) | Partner 6 (Inst. Geociências da Univ. São Paulo, Dep. Mineralogia e Geotectónica e Centro de Pesquisas Geocronológicas) | Partner 7 (CNRS - GeoRessources) |
|---|---|---|---|---|---|---|---|
| TRL at Project Start | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| TRL at Project End | 1 | 1 | 1 | 2 | 1 | 1 | 1 |
| Year to market 0 1, 2-5, >5 | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

# 3. INTERNATIONAL COOPERATION

## 3.1 Consortium composition

*If there were any changes in the consortium composition since the start of the project, please indicate which partner(s) and their justifications.* The consortium composition did not change.

## 3.2 Will the cooperation continue after the end of this project?

3.2.1. *If yes and if you applied for another project, please name the funding instrument*:

The possibility of continued cooperation, involving different partners, is high, but no project proposal has been designed to date nor any specific funding was identified for this purpose.

☐ *If yes and on commercial terms, indicate the partners involved*:

Likely future collaborations and common projects will not involve commercial issues.

## 3.3 Project meetings, workshops held during the implementation period

| Meeting objective | Partners involved | Date | Place |
|---|---|---|---|
| Steering Group 1st Meeting | All | October 30, 2020 | Videoconference |
| Steering Group 2nd Meeting | All | April 23, 2021 | Videoconference |
| Annual Meeting and Steering Group 3rd Meeting | All | September 18, 2021 | Hybrid attendance (virtual and in-person); Lisbon |

| | | | |
|---|---|---|---|
| Steering Group 4th Meeting | All | March 4, 2022 | Videoconference; |
| 2nd Annual Meeting and Steering Group 5th Meeting | All | October 03, 2022 | Hybrid attendance (virtual and in-person); Coimbra |
| 3rd Annual Meeting | All | October 2-3, 2023 | Hybrid attendance (virtual and in-person); Lisbon |
| Steering Group 6th Meeting | All | October 3, 2023 | Hybrid attendance (virtual and in-person); Lisbon |
| Seminar I | All | February 8-9, 2024 | Open; in-person attendance; Lisbon |
| Seminar II | All | June 7-8, 2024 | Open; hybrid attendance (virtual and in-person); Évora |
| Steering Group 7th Meeting | All | June 8, 2024 | In-person attendance; Évora |

In addition to the listed meetings (agenda details in https://mostmeg.rd.ciencias.ulisboa.pt/), several others occurred involving different subgroups of partners (and researchers), in person or by videoconference, to comprehensively discuss specific problems and results meanwhile obtained.

The Annual Meeting and Steering Group 3rd Meeting were preceded by a Joint Fieldtrip (13th-17th September 2021). This Joint Fieldtrip, attended by 11 researchers from 4 project partners (coming from Portugal and France), was instrumental to: (i) provide the main highlights on the geological background of the Segura-Argemela area; (ii) observe and discuss data provided by key exposures of mineralised structures (arrays of aplite/pegmatite veins and quartz lode systems) and their host rocks; (iii) increase the sampling densification in specific targets to support forthcoming detailed studies (WP3, WP4 and WP5); and (iv) refine several details of the intended research programme, reinforcing the collaborative efforts between the project partners.

A Joint Fieldtrip (May 30 – June 2, 2022), involving three researchers from FCUL and two from IGc-USP, was organised to: (i) provide the main highlights on the geological background of the Segura-Argemela area; (ii) observe and discuss data provided by key-exposures of mineralised structures (arrays of aplite/pegmatite veins and quartz lode systems) and their host rocks; and (iii) increase the sampling densification in specific targets to support forthcoming detailed studies (WP2 and WP5).

The 2nd Annual Meeting and Steering Group 5th Meeting were preceded by a Joint Fieldtrip (September 29 – October 2, 2022) attended by 14 researchers from 4 project partners (CNRS-GeoRessources, FCUL, UCoimbra and LNEG). This Joint Fieldtrip was instrumental: (i) to realise some particular geological features of the Góis-Segura strip western segment, namely in the sector of Figueiró dos Vinhos – Pedrogão Grande – Castanheira de Pêra; (ii) to discuss the recently obtained field data and complement the sampling programme in the Argemela and Mata da Rainha areas, consolidating the ongoing research related to WP3, WP4 and WP5; and (iv) to refine several details of the intended research plan, reinforcing the collaborative efforts between the project partners.

Considering the work accomplished by September 2023, it was decided to focus the 3rd Annual Meeting on a broad discussion on data/results so far obtained, encouraging integrated interpretations of their consequences and planning activities for the following months, closing the MOSTMEG project. During the 6th Steering Group Meeting, the best dates for the two Seminars foreseen in the MOSTMEG proposal (open to all interested parties) were discussed, as well as their contents, aiming the largest possible participation of companies and other institutions implicated in mineral exploration activities, namely in Portugal.

The main objectives of the two open Seminars were the: (i) dissemination and discussion of the project outputs; (ii) demonstration of methods and tools to improve the recognition of critical fingerprints and footprints to mineralising systems; and (iii) appraisal of implications on the design of future mineral exploration surveys directed at Sn-W and Li ore systems, namely those hosted in the Góis-Panasqueira-Argemela-Segura strip. The first Seminar registered a high attendance, with ca. of 50 participants, 20 of which from mining or mineral exploration companies operating in Portugal, in addition to 3 representatives from the National Geological Survey and 1 from the Portugal Mineral Resources Cluster. The second Seminar, despite having 35 pre-registered participants, ended up being attended by ca. 20 (plus 7 in videoconference), 6 of them representing companies, 2 the National Geological Survey and 2 the Portugal Mineral Resources Cluster.

# 4. DISSEMINATION

## 4.1 References on dissemination tools

☐ Relevant project movie clips on YouTube or another video channel

☒ Project website (https://mostmeg.rd.ciencias.ulisboa.pt/);

☐ Social and professional networks and blogs

☐ Input to standards (white papers/ regulations)

☒ Other, please specify: LNEG website: https://www.lneg.pt/en/project/mostmeg-2/

## 4.2. Details on business fairs during which project results were showcased

| Identification of the business fair | Partner(s) involved | Location | Date |
|---|---|---|---|
| There was no participation in business fairs. | | | |

## 4.3. Details on the publications that result from the funded project

| **Peer review papers** (authors, title, journal, year, issue, pp.) | Open Access (Yes/No) | Partner(s) involved | Website address |
|---|---|---|---|
| Martins, I.; Mateus, A.; Cathelineau, M.; Boiron, M.-C.; Ribeiro da Costa, I.; Gaspar, M.; Dias da Silva, Í. (2022) The lanthanide tetrad effect as an exploration tool for granite-related rare metal ore systems: examples from Iberian Variscides. Minerals 12(9), 1067. | Yes | P1, P7 | https://doi.org/10.3390/min12091067 |

Co-funded by the Horizon 2020 programme
of the European Union

| | | | |
|---|---|---|---|
| Gaspar, M.; Grácio, N.; Salgueiro, R.; Costa, M. Trace element geochemistry of alluvial $TiO_2$ polymorphs as a proxy for Sn and W deposits. Minerals 2022, 12(10), 1248. | Yes | P1, P3, P4 | https://doi.org/10.3390/min12101248 |
| Cathelineau M.; Boiron M.-C.; Lecomte, A.; Martins, I., Dias da Silva, Í.; Mateus, A. (2024) Lithium-, Phosphorus-, and fluorine-rich intrusions and the phosphate sequence at Segura (Portugal): a comparison with other hyper-differentiated magmas. Minerals 14(3), 287. | Yes | P1, P7 | https://doi.org/10.3390/min14030287 |

In addition to the 3 published papers, there are several manuscripts in different stages of preparation, namely the following (preliminary titles):

1. Multistage granitoid magmatism in the Segura-Panasqueira area (Central Iberian Zone, Portugal); consequences to metallogenic processes. *Partners involved: P1, P6, P7*
2. Geochemical and isotopic characteristics of the Beiras Group metasediments (Neoproterozoic-Cambrian, Central Iberian Zone, Portugal): basin constraints, constituent's provenance, and implications for metal endowment: *Partners involved: P1, P6, P7*
3. Metasomatism and F, Li, Cs enrichment in Beiras Group schists around the Argemela hyper-differentiated intrusion (CIZ, Portugal). *Partners involved: P7, P1*
4. Shear deformation and contact metamorphism of the Beiras schists: textural, mineralogical, and geochemical consequences (Central Iberian Zone, Portugal). *Partners involved: P7, P1*
5. Decoding alluvial heavy minerals from Segura (Castelo Branco, Portugal) to target Sn mineralising systems. *Partners involved: P4, P1*
6. P-T-X evolution of the fluids associated with Li-Sn mineralization from Pedra Alta mine (Argemela, Portugal). *Partners involved: P2, P1*
7. Are the REE, U, and Th contents of zircon sensitive to magmatic-hydrothermal processes concurrent of mineralisation? *Partners involved: P1, P6, P7*
8. What is hidden behind cassiterite geochemistry? A multiscale deciphering approach from ore-forming systems to mineral exploration. *Partners involved: P1, P3, P4, P7*
9. Schist tourmalinisation: magmatic vs. metamorphic fluids mobilized around the Orca granite contact (Portugal). *Partners involved: P7, P1*
10. New insights into the Penamacor-Monsanto granite system (Central Iberian Zone, Protugal). *Partners involved: P1, P6, P7*
11. Time frame of tectonic and magmatic interactions in the genesis of late orogenic Sn-W ore deposits: the study case of Mata da Rainha mining district (Góis-Panasqueira-Argemela-Segura strip, Portugal). *Partners involved: P1, P6, P7*
12. Long lasting magmatic flare up in the Ordovician margin of north Gondwana; a view from the Fundão Pluton (Iberian Massif, Portugal). *Partners involved: P1, P6*
13. Metallogenesis of the Vale Pião W–Sn–(Au) deposit (Góis, Portugal): constraints from geochemistry, mineralogy and fluid inclusions. *Partners involved: P1, P2*

| **Publications dedicated to general public** (authors, title, journal, year, issue, pp.) | **Partner(s) involved** |
|---|---|
| There are no publications directed to the general public. | |

## 4.4 Communications in scientific meetings

Please list the communications in scientific events that resulted from the funded project, underlining the name of the funded partners.

| Authors | Title | Meeting name & place | Year | Partner(s) involved | Oral Communication /Poster |
|---|---|---|---|---|---|
| Martins I., Mateus A., Ribeiro da Costa I., Gaspar M., Dias da Silva I. | The lanthanide tetrad effect as an exploration tool for granite-related rare metal ore systems: examples from Iberian Variscides. | SEG 2022 Conference (Denver, Colorado, USA) *Minerals for Our Future*. Theme: *Critical Minerals for Our Energy Future: Geology and Ore Deposit Models*. | 2022 | P1 | Oral (ID4112) |
| Gaspar M., Ribeiro da Costa I., Mateus A., Martins I., Rodrigues P. | Assessment of tourmaline composition as a vectoring tool for Sn-W deposits – the Góis-Panasqueira-Segura Belt (Central Portugal). | SEG 2022 Conference (Denver, Colorado, USA) *Minerals for Our Future*. Theme: *Critical Minerals for Our Energy Future: Geology and Ore Deposit Models*. | 2022 | P1 | Oral (ID4317) |
| Yakovenko A., Guedes A., Boiron M.C., Cathelineau M., Martins I., Mateus A. | Fluid inclusion studies in quartz from the Li-rich pegmatite veins from Segura., 10-11 February 2022. Book of Abstracts, p. 43 | Jornadas ICT (Univ. Porto, Portugal) | 2022 | P2, P7, P1 | Oral |
| Martins I., Mateus A., Ribeiro da Costa I., Gaspar M., Dias da Silva, Í. | Geochemistry and ore-forming processes of multistage granitic magmatism in the Central Iberian Zone: Segura-Panasqueira Belt (Portugal) case study. | 16th SGA Biennial Conference 2022 (Rotorua, New Zealand): *The critical role of minerals in the carbon-neutral future* (Virtual format conference). | 2022 | P1 | Oral |
| Yakovenko, A., Guedes, A. | Mineralogy and fluid inclusion studies in quartz from the Li-rich pegmatite veins from Segura. Book of abstracts, p. 343 | Young Researcher Meeting - IJUP. 4-6 May. | 2022 | P2 | Oral |
| Dias da Silva, Í, Martins, I, Mateus, A. | Does the lithostratigraphic harmonization of the Beiras Group (Panasqueira-Segura area) disclose any pre-Ordovician structure? In Lopes, F. C., Dinis, P. A., Duarte, L. V. e Cunha, P. P. (Coords.). Livro de Resumos. Departamento de Ciências da Terra da Universidade de Coimbra (eds.). Págs. 187-188. ISBN: 978-989-98914-8-7. | XI Congresso Nacional de Geologia: Geociências e Desafios Globais. Coimbra, 16-20 julho de 2023 | 2023 | P1 | Oral |
| Mateus, A., Tassinari, C.C.G., Martins, I., Borba, | Geological meaning of the REE distribution in zircons from granitoid, aplite and pegmatite bodies of the Panasqueira-Segura area. In Lopes, F. | XI Congresso Nacional de Geologia: Geociências e Desafios Globais. Coimbra, 16-20 julho de 2023 | 2023 | P1, P6 | Oral |

| | | | | | |
|---|---|---|---|---|---|
| M.L., Dias da Silva, Í., Sato, K | C., Dinis, P. A., Duarte, L. V. e Cunha, P. P. (Coords.). Livro de Resumos. Departamento de Ciências da Terra da Universidade de Coimbra (eds.). Págs. 407-408. ISBN: 978-989-98914-8-7. | | | | |
| Salgueiro, R., Grácio, N., Gaspar, M., de Oliveira, D. | Alluvial Sn and W minerals mapping for mineral resources exploration and research in Segura mining region (Portugal). In Lopes, F. C., Dinis, P. A., Duarte, L. V. e Cunha, P. P. (Coords.). Livro de Resumos. Departamento de Ciências da Terra da Universidade de Coimbra (eds.). Págs. 415-416. ISBN: 978-989-98914-8-7. | XI Congresso Nacional de Geologia: Geociências e Desafios Globais. Coimbra, 16-20 julho de 2023 | 2023 | P4, P1 | Poster |
| Yakovenko, A., Guedes, A., Noronha, F., Mateus, A. | Evolução composicional dos fluidos associados às mineralizações de Li-Sn da mina Pedra Alta (Argemela). In Lopes, F. C., Dinis, P. A., Duarte, L. V. e Cunha, P. P. (Coords.). Livro de Resumos. Departamento de Ciências da Terra da Universidade de Coimbra (eds.). Págs. 431-432. ISBN: 978-989-98914-8-7. | XI Congresso Nacional de Geologia: Geociências e Desafios Globais. Coimbra, 16-20 julho de 2023 | 2023 | P2, P1 | Poster |
| Yakovenko, A., Guedes, A., Noronha, F., Mateus, A. | PTX evolution of the fluids associated with Li-Sn mineralization from Pedra Alta mine (Argemela, Portugal) | Goldschmidt 2023 Conference, Lyon (France), Session: 7c - *From ore fluids, ore formation, and mineral reactivity, to environmental geochemistry* [session in honour of Hubert L. Barnes], Theme 7: Energy and resources. | 2023 | P2, P1 | Poster |
| Mateus, A. | A inevitabilidade da prospecção mineral e mineração nas etapas futuras do desenvolvimento da Civilização Humana. In Lopes, F. C., Dinis, P. A., Duarte, L. V. e Cunha, P. P. (Coords.). Livro de Resumos. Departamento de Ciências da Terra da Universidade de Coimbra (eds.). Págs. 6. ISBN: 978-989-98914-8-7 | XI Congresso Nacional de Geologia: Geociências e Desafios Globais. Coimbra, 16-20 julho de 2023 | 2023 | P1 | Oral |
| Mateus, A., Cathelineau, M., Tassinari, C., Boiron, M.-C., Hollanda, M.H., Salgueiro, R., Guedes, A., Moita, P., Pereira, A. | Multi-scale and interdisciplinary approaches to the granite-related ore-forming systems in the Segura-Argemela-Panasqueira-Góis belt (Portugal); insights for innovative exploration surveys. | RawMat2023, the 2nd INTERNATIONAL CONFERENCE ON RAW MATERIALS AND CIRCULAR ECONOMY, Athens, Greece, 28 August – 2 September. | 2023 | P1, P2, P3, P4, P5, P6, P7 | Oral |
| Mateus, A. | Lithium and rare metal granites in Portugal. | International Congress METALS FOR ELECTRIC MOBILITY. Nancy, France, 19 and 20 September 2023. | 2023 | P1 | Oral |

# 5. IMPACT

## 5.1 Major developments of the project for each partner

| Development | Partner # | Details |
|---|---|---|
| Product | 1 | Geological and other thematic maps for the Segura-Argemela-Panasqueira-Góis Strip, besides detailed maps for the most promising target areas, such as Segura, Medelim, Mata da Rainha, Fundão-Argemela. |
| | 4 | Mineral mapping of alluvial cassiterite, wolframite, scheelite, tourmaline, $TiO_2$ polymorphs and garnet (grains, average abundance or populations), at suitable regional scales. |
| Method | 1 | Improvement of analytical profiles with EPMA for quantitative analyses of oxide phases. |
| | 3 | Methodological development by combining different analytical techniques for specific mineral phases, relevant in the understanding of metallogenic processes. |
| | 4 | The alluvial heavy minerals approach proves useful in mineral resources exploration and research studies, providing a large collection of data and information related to Sn(-W) mineralising systems and their geological settings. |
| | 6 | Refinement in the use of micro-XRF for systematic mapping of rocks. |
| Model | 1 | Geological model improvements oriented to mineral exploration surveys on granite-related, rare metal-enriched, systems. The improvements include new mineral and geochemical vectors, besides geochronological constraints. |
| Process | N/A | |
| Service | N/A | |
| Equipment | N/A | |
| Prototype | N/A | |
| New organisational method | N/A | |
| New marketing concept or strategy | N/A | |

Other, please specify:

Partner 6 (Nancy, GeoRessources): development of routine analysis of trace elements (strategic elements, rare earth) in a variety of minerals (micas, tourmaline, cassiterite, wolframite, phosphate, oxides).

Co-funded by the Horizon 2020 programme
of the European Union

## 5.2 Master Thesis/PhD Thesis within the framework of the project

| Partner # | Author | Title of the Master Thesis/PhD Thesis | Gender (F/M) |
|---|---|---|---|
| P2 | Yakovenko A. | Estudo de inclusões fluidas dos filões pegmatíticos litiníferos de Segura, MSc Thesis, Faculdade de Ciências, Universidade do Porto, 2021. | F |
| P7 | Lahcen Khouya | Tourmalinisations, marqueurs des systèmes magmatiques-hydrothermaux à W de la région de Mata da Rainha, Portugal. RAPPORT DE STAGE DE MASTER 2. Master 2 SMGE: Systèmes Métallogéniques: Géologie et Exploration. Faculté des Sciences et Technologies, Université de Lorraine, 2023 | M |

MSc theses to be submitted and discussed in September 2024

1. Ana Rita Oliveira de Andrade. Fácies graníticas constituintes da bordadura ocidental do plutão de Fundão: manifestações tardias do magmatismo Câmbrico-Ordovícico ou acreções sin- a tardi-orogénicas de idade Carbónica? Consequências metalogenéticas. Mestrado em Geologia, Faculdade de Ciências, Universidade de Lisboa. P1, F
2. Beatriz Feteira de Carvalho Pereira. Caracterização petrográfica e geoquímica das fácies graníticas contíguas ao sistema filoniano W-Sn de Mata da Rainha (Fundão); implicações metalogenéticas. Mestrado em Geologia, Faculdade de Ciências, Universidade de Lisboa. P1, F
3. Maria Inês Viegas Roque da Silva. Deformação progressiva não coaxial vs. sobreposição de diferentes fases de deformação: levantamento geológico-estrutural de pormenor na área-chave de Perais (bordo meridional da ZCI). Mestrado em Geologia, Faculdade de Ciências, Universidade de Lisboa. P1, F
4. David Guilherme de Macedo Castro. Modelação numérica de padrões estruturais resultantes de deformação progressiva não coaxial, e/ou sobreposição entre diferentes fases de deformação, com base nos afloramentos-chave da área de Perais (bordo meridional da ZCI). Mestrado em Geologia, Faculdade de Ciências, Universidade de Lisboa. P1, M

PhD Thesis to be submitted by the end of September 2024

1. Ivo José Dias Martins. Long-lived, granite-related ore systems: what factors rule the development of distinct mineral assemblages and/or contrasting grades? Doutoramento em Geologia (Metalogenia), Faculdade de Ciências, Universidade de Lisboa. P1, M

## 5.3 Intellectual property rights applied

**Partner #1**

☒ No

☐ Patent. If applicable, precise title and date of priority:

☐ Design / Models. If applicable, precise type, reference and filing date:

☐ Trademarks. If applicable, precise trademark, type and filing date:

**Partner #2**

☒ No

☐ Patent. If applicable, precise title and date of priority:

☐ Design / Models. If applicable, precise type, reference and filing date:

☐ Trademarks. If applicable, precise trademark, type and filing date:

**Partner #3**

☒ No

☐ Patent. If applicable, precise title and date of priority:

☐ Design / Models. If applicable, precise type, reference and filing date:

☐ Trademarks. If applicable, precise trademark, type and filing date:

**Partner #4**

☒ No

☐ Patent. If applicable, precise title and date of priority:

☐ Design / Models. If applicable, precise type, reference and filing date:

☐ Trademarks. If applicable, precise trademark, type and filing date:

**Partner #5**

☒ No

☐ Patent. If applicable, precise title and date of priority:

☐ Design / Models. If applicable, precise type, reference and filing date:

☐ Trademarks. If applicable, precise trademark, type and filing date:

**Partner #6**

☒ No

☐ Patent. If applicable, precise title and date of priority:

☐ Design / Models. If applicable, precise type, reference and filing date:

☐ Trademarks. If applicable, precise trademark, type and filing date:

Co-funded by the Horizon 2020 programme
of the European Union

**Partner #7**

☒ No

☐ Patent. If applicable, precise title and date of priority:

☐ Design / Models. If applicable, precise type, reference and filing date:

☐ Trademarks. If applicable, precise trademark, type and filing date:

## 5.4. Additional details concerning possible licenses granted

If details need to be treated confidentially, please indicate as such.

| Detailed description |
|---|
| N/A |

## 5.5 Region/country impact of the ERA-MIN project per partner

**Partner #1**

The impact of the MOSTMEG project is positively assessed from three distinct, although complementary, perspectives. The first perspective necessarily includes the important contribution to the geological knowledge of the Segura-Argemela-Panasqueira-Góis strip and the main mineralising systems hosted there. The main outputs of this contribution include: (i) the harmonized geological map for the entire strip at 1:100,000 scale; (ii) the multi-element and multi-system isotopic geochemical analysis of metasediments from the Beiras Group, never previously carried out; (iii) detailed characterisation and dating by absolute geochronology (with different procedures and mineral phases) of many granitoid facies and mineralising systems; (iv) the substantiated identification of various geochemical and mineral fingerprints and footprints useful for the design of innovative mineral exploration surveys; (v) insights into metallogenetic and geodynamic models; and (vi) the delimitation of areas potentially hosting hidden mineral resources. The second perspective comprises the methodological development used in the MOSTMEG project, and all the improvements introduced over time due to the regular sharing of analytical results and technical means, boosting the impact of tools that can be transferred to mineral exploration surveys conducted by companies of variable size and proficiency. The third perspective concerns the strengthening of national and international scientific cooperation relationships, involving researchers, some of them at the beginning of their careers, spreading across different institutions. The possibility of these intertwines support future applications for new R&DT projects is quite high.

**Partner #2**

The outputs of MOSTMEG project comprise a huge data compilation and outputs that will be made available and allow exploration and mining companies to plan actions on similar types of deposits in the North region with the consequent economic growth, jobs, and collateral gains. This will increase awareness regarding the north region's geologic resources on local administration, facilitating the planning for attracting stakeholders, investors, fundraising and investments, economic growth, and social actions. The project developed new tools that will be transferred to the academia and the mining industry, thus significantly impacting the design of advanced training programs for exploration geologists.

**Partner #3**

The involvement within ERA-MIN project MOSTMEG allowed the Laboratory HERCULES (University of Évora) led to the creation and refinement of a methodological development (e.g. LA-ICP-MS and CL) for analysing detrital mineral phases, establishing an applicable prospecting tool for the region. Additionally, the project significantly enhanced the collaboration between the FCUL (IDL) and LNEG teams, fostering stronger research partnerships.

**Partner #4**

The impact of the project was positively beyond expectations having regional and transregional implications for the understanding of the Segura-Argemela-Panasqueira-Góis strip, based on heavy minerals from proximal alluviums. Despite their proven successful use in the old national surveys, the new approach applied, the outputs on minerals physical and (the contribution to) chemical characterisation along with mineral(s) populations mapping at a regional scale brought new achievements for the knowledge on the Segura Sn-W mineralising systems and their geological setting. The approach enabled insights into the footprints of magmatic and/or hydrothermal mineralisation and metasomatic events on regional alluvial deposits, which help to better understand and constrain where, in terms of space and environment, the Sn-W mineral deposits are, and can plausibly occur. Consequently, the outputs also enhance discovery of other potential Critical Raw Materials in the region related to Variscan granites. The collaboration with national and international researchers and institutions promoted the exchange of knowledge and applying the best practices in the project development that was fundamental to all and to the training of younger researchers.

**Partner #5**

The impacts of the MOSTMEG project include: (i) contributions to the geological and geochemical knowledge of the metasediments from the Beiras Group, affected by Ediacaran contact metamorphism due to nearby late- to post-orogenic Cadomian intrusions, in the Castanheira de Pera region; (ii) data on multi-element and REE for metasediments of the Beiras Group, never previously carried out; and (iii) the establishment of national and international scientific relationships between UC and the other partners must also be highlighted.

**Partner #6**

Participation in the MOSTMEG project allowed the continuity of cooperation in long-established research activities between FCUL/IDL (Portugal) and IGC/USP (Brazil), opening paths for new collaborations with other researchers and institutions. Additionally, it was possible to share experiences and promote integrated discussions of results on different geological processes of common interest, using as reference critical exposures of litho-stratigraphic sections, granite facies, structural arrangements and different styles of mineralisation [Sn, W , W(-Sn), Li] in the Góis-Panasqueira-Argemela-Segura strip.

**Partner #7**

The project enabled: (i) continue to exploit the results obtained locally at Panasqueira within the ERAMIN-NewOres framework on a regional scale; (ii) discuss with the Portuguese partners the concepts of metal enrichment from source rocks (metasomatism) to deposits and strengthen the collaboration between Nancy and Portugal; (iii) systematically apply new chemical-mineralogical mapping approaches to representative examples of fluid-rock interactions and complex mineralogical assemblages (phosphates, schist spots); (iv) development of more integrated studies of metal cycles in the crust from field to laboratory studies thanks to the collaborations; (v) assert the Nancy team's expertise in the field of differentiated rare-metal granites on a French and international scale.

# 6. FINANCIAL STATUS

**Cost overview and deviations from budget (€)**

| Partner # | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| TOTAL BUDGET | 260,274.20€ | 49,500.00€ | 47,025.00€ | 53,852.23€ | 17,437.50€ | 64.859.00€ | 278,715.00€ |
| National/regional Financing | 75,589.20€ | | 47,025.00€ | 35,394.30€ | 17,437.50€ | 0.00€ | 162,815.00€ |
| Own financing | 184,685.00€ | | 0.00€ | 18,458.23€ | 0.00€ | 64.859,00€ | 115,900.00€ |
| TOTAL Spent at Final Term | 254,256.70€ | 49,373.75€ | 46,770.26€ | 56,465.37€ | 13,346.09€ | 21,619.67€ | 275,054.47€ |
| National/regional Financing | 69,571.70€ | 49,373.75€ | 46,770.26€ | 33,266.98€ | 13,346.09€ | 0.00€ | 159,154.47€ |
| Own financing | 184,685.00€ | | 0.00€ | 23,198.39€ | 0.00€ | 21,619.67€ | 115,900.00€ |
| DEVIATION (against the forecasted expenses at that time) | 6,017.50€ | 5,800.00€ | 254.74€ | -2,612.84€ | 4,091.41€ | 0.00€ | 3,660.53€ |
| National/regional financing | 6,017.50€ | | 254.74€ | 2,127.32€ | 4,091.41€ | 0.00€ | 3,660.53€ |
| Own financing | 0.00€ | 49,500.00€ | 0.00€ | -4,740.17€ | 0.00€ | 0.00€ | 0.00€ |

Please explain main deviations (if applicable):

Regarding Partner 2 (FCUP), the financial status considered the receipt of the advance of the funds received in July/2021 in the amount of €7,425.00 and the Advance on account of the expense presented in the 1st PP in the amount of €2,936.10, Advance Settlement on account of the expense presented in the 1st PP in the amount of €1,651.55, Advance on account of the expense presented in the 2nd PP in the amount of €6.257.85, Advance on account of the expense presented in the 3rd PP in the amount of €6,655.10, Advance Settlement on account of the expense presented in the 2nd PP in the amount of €3,520.05, Advance payment due to the expense presented in the 4th PP in the amount of €7,889.34, Advance Settlement due to the expense presented in the 3rd PP in the amount of €3,646.30 and in order to continue the financial execution of the MOSTMEG project, FCUP granted two loans (€7,000.00 in 2021 and €7,654.98 in 2022).

In what concerns Partner 4 (LNEG), and for the item "Own Financing", it was considered that the PI allocation to the project would remain in an identical proportion during the 9-month extension of the project, therefore giving rise to the negative value registered in this item. The main deviations recorded by LNEG that induced smaller budget amount spent are due to: 1) the restrictions indicated in section A.4 of the 3rd progress report that affected the amount spent in the scholarship holder missions; and 2) the sustainable budget management based on the development of the WP4 Task 4.3 activities (established in priority study areas and dependent on the available time, as mentioned in the 1st progress report).

**Project Consortium Coordinator signature:** **Date:**

Antonio Mateus

Assinado de forma digital por Antonio Mateus
DN: cn=Antonio Mateus, o=DG-FCUL, ou, email=amateus@fc.ul.pt, c=PT
Dados: 2024.07.28 18:25:03 +01'00'

Co-funded by the Horizon 2020 programme of the European Union