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Review

Magma-Source Controls on Initial Sn–W Enrichment in Granites: A Review

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ABSTRACT

Tin and tungsten are strategic critical metals, and understanding the mechanisms responsible for their extraordinary enrichment is a frontier research topic in economic geology. The formation of granite-hosted Sn–W deposits involves three successive stages: source enrichment, magmatic transport, and metal precipitation. Partial melting of metasedimentary rocks in the middle–lower crust represents the starting point for the initial enrichment of ore-forming metals, yet the role of this stage in mineralization has long been insufficiently recognized. This review focuses on the controls exerted by magma-source processes on the initial enrichment of Sn and W during granite petrogenesis. It systematically summarizes research progress concerning source-rock composition, the degree of pre-enrichment of ore-forming elements, anatectic conditions, including temperature and oxygen fugacity, the types of minerals involved in melting reactions, and the stability of accessory minerals. Key scientific controversies remain, including the respective contributions of metapelites versus metagreywackes to mineralization, the mechanisms controlling Sn–W coupling and decoupling, and the fractionation behavior of elements and isotopes during disequilibrium melting. Future research should integrate *in situ* microanalysis, phase-equilibrium modeling, and isotopic tracing, using recently exhumed orogens such as the Himalaya as natural laboratories, to elucidate the mechanisms of Sn–W mobilization and initial enrichment during partial melting and thereby advance theories of granite-related Sn–W metallogeny.

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Research Highlights

- Systematically reviews controls on initial Sn–W enrichment during partial melting.
- Identifies key controversies in source composition, pre-enrichment, and melting conditions.
- Proposes the integration of *in situ* analysis and modeling to study disequilibrium melting.

1. Introduction

Tin has historically been a major mineral resource in China; however, owing to resource depletion, its import dependence is increasing. Both tin and tungsten are strategic critical metals in China and are key targets of the National New Round of Strategic Action for Prospecting Breakthroughs. Granite-related Sn–W mineralization is an important product of continental crustal cycling and evolution [1]. Fundamentally, the formation of tin–tungsten deposits and their associated granites is closely linked to the chemical composition of the magma source and to partial melting processes [2, 3]. Investigating fundamental scientific questions related to Sn–W mineralization, particularly the influence of partial melting in the deep source region on the initial enrichment of Sn and W, an aspect that has received relatively little attention, will help refine and enhance our understanding of Sn–W metallogenic mechanisms and granite petrogenesis, and will guide assessments of Sn–W mineralization potential.

As rare metal elements, tin and tungsten must be enriched by approximately 1000 times relative to their crustal abundances to form economically viable ore bodies, highlighting the urgent need to elucidate their mechanisms of extraordinary enrichment [4, 5]. Tin–tungsten deposits are typically genetically associated with highly fractionated, reduced felsic rocks formed by remelting of metasedimentary rocks [6]. Sn–W enrichment and mineralization mainly involve three successive stages from deep to shallow: (1) partial melting of middle–lower crustal metasedimentary rocks (the “source” stage), (2) high degrees of fractional crystallization of granite in the middle–upper crust (the “transport” stage), and (3) fluid exsolution and metal precipitation in the upper crust (the “deposition” stage) (Figure 1) [7–9].

Previous research has extensively investigated the latter two stages of Sn–W mineralization, namely magmatic differentiation and hydrothermal fluid processes in the middle–upper crust, yielding numerous innovative results [10–14]. However, a systematic understanding of the activation and migration of Sn and W, as well as their initial enrichment mechanisms during the transition from partial melting of metasedimentary rocks in the magma source region, the middle–lower crust, to the formation of ore-forming granites, remains lacking [15]. This gap is primarily due to the scarcity of key granulite-facies samples from the deep source region in the middle–lower crust, as well as limitations in the precision and resolution of *in situ* microanalytical techniques.

Constrained by earlier analytical limitations, early research primarily focused on variations in major elements during metamorphism. With the breakthrough development of modern *in situ* microanalysis techniques, it is now possible to determine trace-element concentrations at micrometer- to nanometer-scale spatial resolutions and with ppm- to ppb-level detection limits, enabling quantitative characterization of rare-element migration mechanisms during complex anatectic processes [16–19]. Elemental distribution in rocks is often highly heterogeneous, with certain minerals hosting the majority of trace and/or ore-forming elements and serving as key carrier and/or concentration phases [3, 20]. Sn and W are commonly hosted in fine-grained accessory minerals. With improvements in spatial resolution and analytical precision in elemental analyses, the modes of occurrence of these elements in such fine-grained minerals can be investigated, thereby contributing to a deeper understanding of the behavior of Sn and W during metamorphism. Microstructural observations, together with high-precision *in situ* elemental and isotopic analyses of key minerals, are particularly effective for finely characterizing and reconstructing partial melting processes.

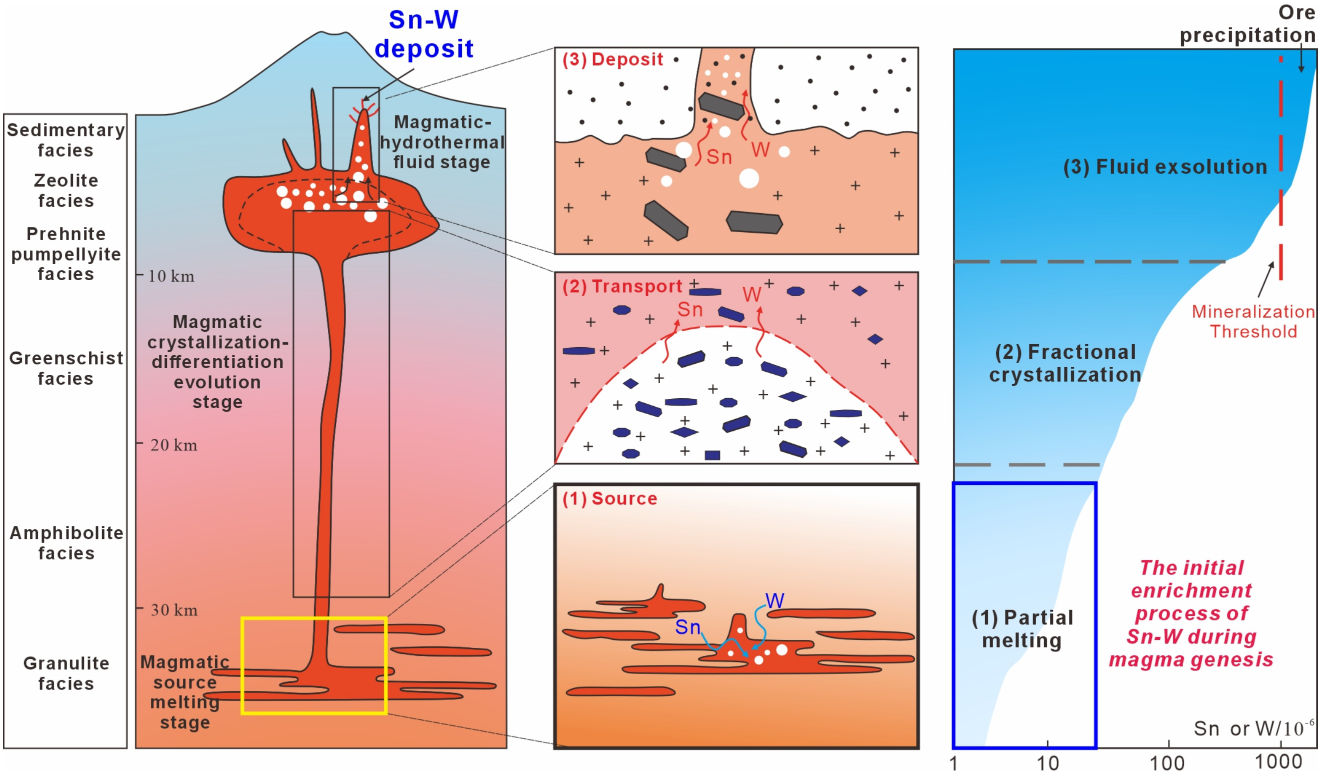

Figure 1. Sn and W enrichment and mineralization mainly involve three successive stages from deep to shallow (modified from [21]).

The geochemical characteristics of ore-forming granites are inherited from the composition of the source rock and the characteristics of the anatectic melt. However, traditional research has mainly focused on the transport of Sn and W in magmas and their exsolution into hydrothermal fluids to form deposits, with less attention paid to the question of how Sn and W are transferred from deep-seated metasedimentary source rocks into anatectic melts and initially enriched therein, ultimately forming granites with ore-forming potential [22]. This review focuses on research progress regarding the influence of magma-source processes on the initial enrichment of Sn and W during granite petrogenesis. It discusses key source processes and controlling factors, including rock composition (metapelite versus metagreywacke), the degree of elemental pre-enrichment, anatectic conditions (fluid-fluxed versus dehydration melting, low- versus high-temperature conditions, oxidized versus reduced conditions, and equilibrium versus disequilibrium melting), minerals involved in melting reactions (muscovite melting at lower temperatures versus biotite melting at higher temperatures), and accessory-mineral stability (e.g., dissolution or recrystallization of apatite, monazite, rutile, titanite, ilmenite, and related phases). Furthermore, this review suggests that future research should focus on the mechanisms of W–Sn and associated-element mobilization, migration, and enrichment during partial melting of metapelites to form granites, as well as on differences in magma-source characteristics between mineralized and barren granites. By emphasizing source-stage control of Sn–W enrichment, this study highlights partial melting of metasedimentary lower-crustal rocks as a critical but previously underappreciated link between crustal anatexis and ore-forming granite fertility, provides a source-oriented framework for understanding Sn–W metallogeny and offers new perspectives for evaluating rare-metal mineralization potential in granite systems.

2. Research Progress and Key Scientific Issues

2.1. Source-Rock Control on Sn–W Granite Fertility

In the last century, research on the origin of tin–tungsten ore-forming granites was dominated by two opposing hypotheses: mantle-derived hotspot processes and crust-derived enrichment mechanisms [23]. It is now widely accepted that, regardless of potential mantle contributions, partial melting of metasedimentary rocks, including metapelites and metagreywackes, in ancient crust is a key process in the formation of tin–tungsten granites [24–27]. During the melting of metasedimentary rocks, the involvement of abundant mica minerals in melting reactions yields melts enriched in rare metals, whereas the participation of organic matter results in reduced magmas with low oxygen fugacity [28–30]. Therefore, metapelites are generally considered the primary source rock type for the formation of reduced S-type tin–tungsten granites [9] (Figure 2). However, experimental studies indicate that the melt productivity of metapelites is limited, suggesting that metagreywackes may represent a favorable source composition for ore-productive granites [31]. Furthermore, the geochemical characteristics of the ore-related pluton at the giant Zhuxi tungsten deposit in China also support its derivation from partial melting of metagreywackes [32]. Thus, whether tin–tungsten ore-forming granites originate from partial melting of metapelites or metagreywackes warrants further in-depth investigation and analysis.

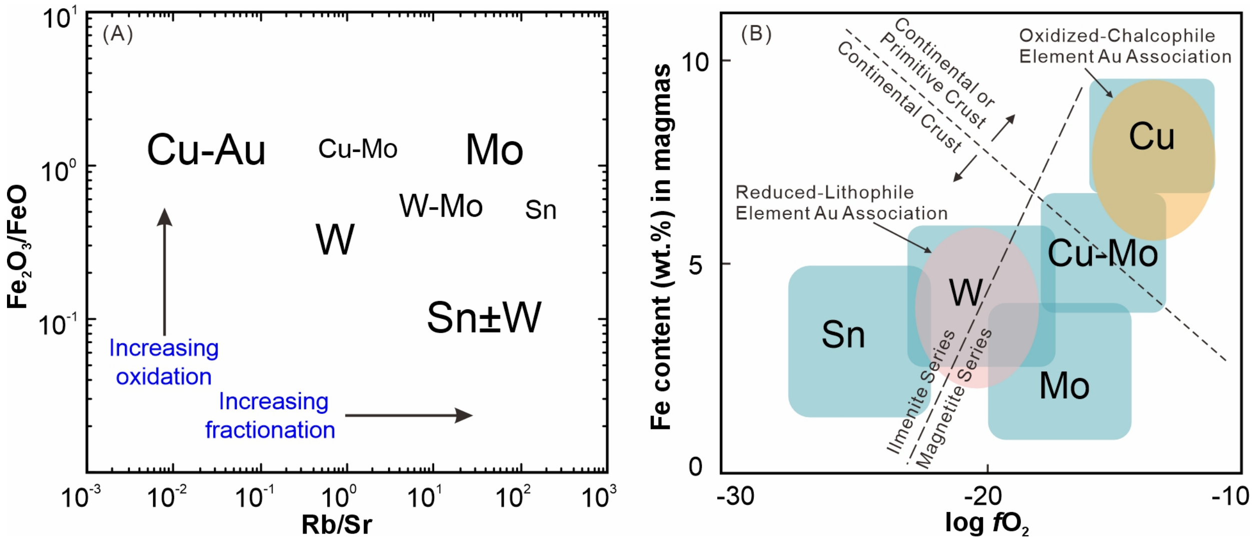

Figure 2. Relationship between granitic magma oxygen fugacity, degree of differentiation, and metal assemblage ((**A**) modified from [33]; (**B**) modified from [34]).

2.2. Role of Source Pre-Enrichment in Sn–W Metallogenic Potential

Tin–tungsten deposits are primarily associated with granites derived from partial melting of the middle–lower crust (Figure 3). Tin–tungsten metallogenic belts are often strictly controlled by tectonic units, indicating that the distribution of source rocks exerts deep-seated control on the spatial localization of Sn–W deposits [24, 35, 36]. Some geologists argue that Sn- and W-pre-enriched crustal zones delimit the distribution of subsequent ore-forming granites, thereby influencing the spatial distribution patterns of tin–tungsten deposits [3, 37, 38]. However, melting experiments by Michaud et al. suggest that although protolith pre-enrichment influences the concentrations of rare elements in the melt, it is not the sole controlling factor; the type of melting reaction, the proportions of reactants, and the partition coefficients of rare elements between the residue and the melt are more important [39]. Furthermore, Lehmann argued that high Sn and W contents in ore-forming granites can be achieved solely through high degrees of magmatic differentiation, without requiring pre-enrichment of the source [22]. However, existing theories struggle to explain the non-linear relationship between the degree of granite differentiation and Sn–W mineralization: on the one hand, highly differentiated granite plutons are not always associated with significant Sn–W mineralization, as exemplified by the Yashan granite in Yichun, Jiangxi [40]; on the other hand, some moderately to weakly differentiated granites host industrial-grade Sn–W deposits [41]. Therefore, the contribution of Sn–W pre-enrichment in source metasedimentary rocks to the ore-forming potential of granites requires quantitative evaluation. Studies of melt inclusions in granites, which can constrain the initial state of the magma, may help address this issue.

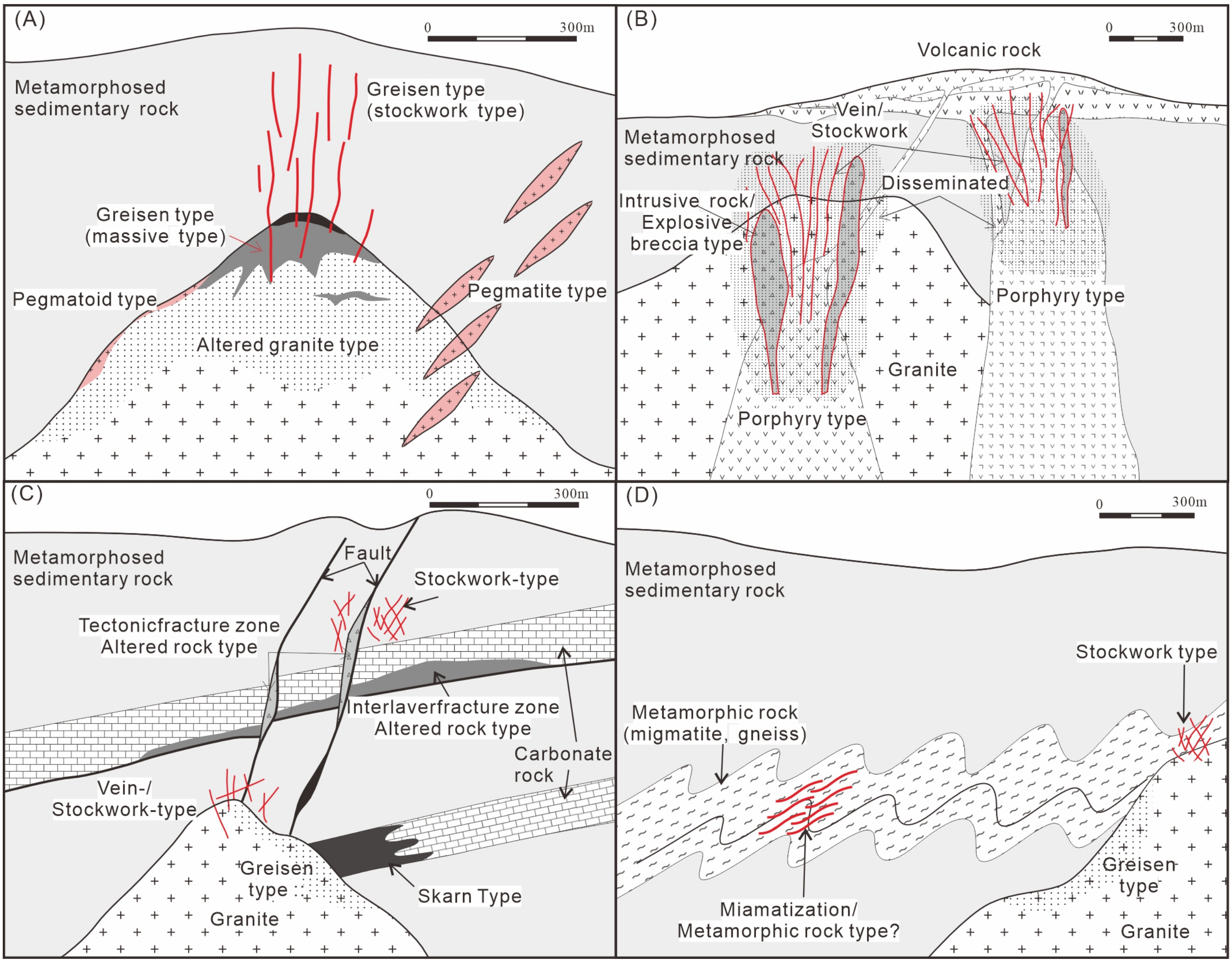

Figure 3. Genetic models for major tin–tungsten deposit types (modified from [42]). (**A**) Altered granite, greisen, pegmatite, and hydrothermal vein-type tin mineralization. (**B**) Porphyry and hydrothermal vein-type tin mineralization. (**C**) Skarn, structural alteration zone, and greisen-type tin mineralization. (**D**) Migmatization or metamorphic hydrothermal-type tin mineralization.

2.3. Anatectic Controls on Sn–W Coupling and Decoupling

Understanding the mechanisms of Sn–W coexistence and separation has long been challenging, but is crucial for understanding the differential enrichment of different elements. Based on comparisons of the geochemical characteristics of ore-forming granites and on modeling calculations, previous studies have proposed that differences in melting temperature in the magma source and variations in the minerals involved in melting reactions control the decoupling of Sn and W mineralization [20]. However, this interpretation struggles to explain the formation of deposits significantly enriched in both Sn and W, such as the Shizhuyuan W–Sn deposit (0.75 Mt WO_3; 0.49 Mt Sn) [43].

Traditionally, because tin is a multivalent element (+2 and +4), its partitioning and mobility during melting are considered to be controlled by oxygen fugacity. (1) In oxidized melts, Sn^{4+} (ionic radius = 0.69 Å) readily substitutes for Ti^{4+} (0.605 Å) and Fe^{3+} (0.645 Å) through isomorphous substitution, preferentially entering the crystal lattices of mafic minerals such as biotite, titanite, amphibole, and magnetite [44–46]. Under these conditions, the mineral/melt partition coefficients for Sn in mafic minerals are significantly greater than 1, leading to Sn retention in the solid residue and the formation of Sn-poor melts [22, 47]. Therefore, partial melting of oxidized source rocks is unfavorable for Sn enrichment in the melt. (2) Under reduced conditions, divalent tin (Sn^{2+}) predominates; its ionic radius increases to 1.18 Å in six-fold coordination, and it exhibits strong incompatibility, with partition coefficients much less than 1, between mafic minerals and the melt. Sn therefore tends to partition into the melt, favoring the formation of Sn-rich granites [47, 48]. However, some scholars suggest that the importance of oxygen fugacity in Sn transport has been overestimated [49]. In contrast, W is predominantly present in melts as ${WO_4}^{2-}$ complexes, and its partitioning behavior is significantly less sensitive to changes in oxygen fugacity than that of Sn [50].

Previous research has extensively investigated the influence of oxygen fugacity on Sn and W mineralization during magmatic and hydrothermal processes [51]. However, relatively little attention has been paid to the control of oxygen fugacity on Sn and W mobilization during partial melting. In this context, existing interpretations are largely limited to preliminary inferences that organic matter or carbonaceous material in metasedimentary rocks may lead to lower oxygen fugacity in anatectic melts. Although Sn and W share similar geochemical properties and often co-occur, they can also be significantly decoupled in specific metallogenic belts or deposits [52, 53]. The specific components and conditions that control melt oxygen fugacity during melting remain unclear, further complicating the role of oxygen fugacity in controlling Sn–W coexistence and separation.

2.4. Temperature- and Mineral-Reaction Controls on Staged Sn–W Mobilization

The role of regional metamorphism in Sn and W mobilization has attracted increasing attention [2, 54, 55]. The melting sequence of metasedimentary rocks in the middle–lower crust (8–12 kbar) exhibits distinct stages. With increasing temperature, successive stages occur: fluid-fluxed melting (650–700 °C), muscovite dehydration melting (700–750 °C), and biotite dehydration melting (750–900 °C), each generating granitic melts (Figure 4). Micas, as layered aluminosilicate minerals, possess unique crystal structures capable of accommodating various trace elements and are important carriers of rare elements such as Sn and W, as well as volatiles (H_2O, F, Cl, B, and P), in metasedimentary rocks [56]. Recent studies suggest that in metasedimentary rocks, W is primarily hosted in muscovite, whereas Sn is mainly hosted in biotite; melts generated by low-temperature muscovite melting are enriched in W, whereas melts become enriched in Sn following biotite melting. This process may control Sn–W decoupling [3, 37]. This implies that, with increasing melting temperature, tungsten mineralization should generally occur slightly earlier than tin mineralization within a single regional mineralizing event. However, case studies of the timing and magmatic temperatures of Sn–W mineralization in the Iberian orogen do not support this view. Most W-rich deposits in Iberia (290–300 Ma) are slightly younger than Sn-rich deposits (310–320 Ma); furthermore, the estimated temperatures of W-mineralizing granites are not lower than those of Sn-mineralizing granites [53]. Therefore, the hypothesis of stepwise activation of Sn and W during mineralization requires further investigation and validation.

2.5. Accessory-Mineral Behavior and Isotope Fractionation During Disequilibrium Melting

Previous research has extensively investigated the formation reactions of major rock-forming minerals, such as quartz, feldspar, mica, and amphibole, during melting. However, ore-forming elements are not controlled solely by rock-forming minerals; the selective breakdown or retention of accessory minerals during non-modal melting may play a decisive role in the mobilization of certain key elements [19, 57]. For instance, during the melting of metasedimentary rocks, in addition to micas, which can significantly concentrate Sn and W, accessory minerals such as titanite, ilmenite, magnetite, and rutile can also host high concentrations of Sn and/or W and may even form metamorphic cassiterite and scheelite [2, 25, 54, 58, 59]. The growth or breakdown of these accessory minerals can strongly influence the amounts of Sn and W entering the anatectic melt. Tin–tungsten granites are generally volatile-rich, but the sources of these volatiles remain poorly constrained. In metasedimentary rocks, H_2O, P, Cl, and F are primarily hosted in apatite, monazite, mica, and amphibole; B is enriched in tourmaline and mica; and S and C are controlled by sulfides and organic matter, respectively. Therefore, the stability of accessory minerals, particularly apatite, critically influences the concentrations of P, Cl, and F entering the anatectic melt [60]. These elements play important roles in the subsequent partitioning behavior of Sn and W in magmatic–hydrothermal systems.

Given that melting typically involves non-modal disequilibrium processes, quantifying how these accessory-mineral behaviors control melt composition is a significant challenge. A fundamental assumption when using stable isotopes to trace the source region during partial melting is that no significant isotopic fractionation occurs between the magma source and the anatectic melt. However, recent studies indicate that during partial melting, radiogenic daughter isotopes and some metal stable isotopes may undergo fractionation, leading to decoupling between the isotopic compositions of the melt and the source [61]. For example, in metasedimentary rocks, Rb and Sr are concentrated in mica and feldspar, respectively. During partial melting, depending on melting conditions, the proportions of mica and feldspar entering the melt, as well as their sequence of breakdown, may differ, inevitably causing significant fractionation of Sr isotopic compositions between the source and the melt. Similarly, the behavior of apatite and monazite can control the Sm–Nd isotopic composition of the melt, whereas zircon controls its Lu–Hf isotopic composition [61, 62]. Boron in metasedimentary rocks is enriched in tourmaline and mica; however, mica is enriched in ^{10}B, whereas tourmaline is enriched in ^{11}B. During metamorphism, tourmaline is significantly more stable than mica, and the preferential breakdown of mica can lead to melts enriched in ^{10}B relative to the source rock; thus, stable isotopes can also undergo fractionation [63]. Accordingly, integrated microanalysis of trace elements and Sr–Nd–Hf–B isotopes in minerals such as mica, feldspar, apatite, monazite, zircon, and tourmaline can reveal whether disequilibrium partial melting occurred in metasedimentary rocks. Quantifying the degree of disequilibrium can help assess the impact of mineral behavior on the differential enrichment of rare elements in the melt.

Significant progress has been made in research on accessory minerals in magmatic and hydrothermal ore-forming systems [64]. However, studies of how the breakdown, retention, and recrystallization of accessory minerals regulate the entry of Sn, W, and ore-related elements into anatectic melts during disequilibrium melting remain relatively scarce, leading to an inadequate understanding of the role of accessory minerals in controlling the initial enrichment of elements during granite petrogenesis.

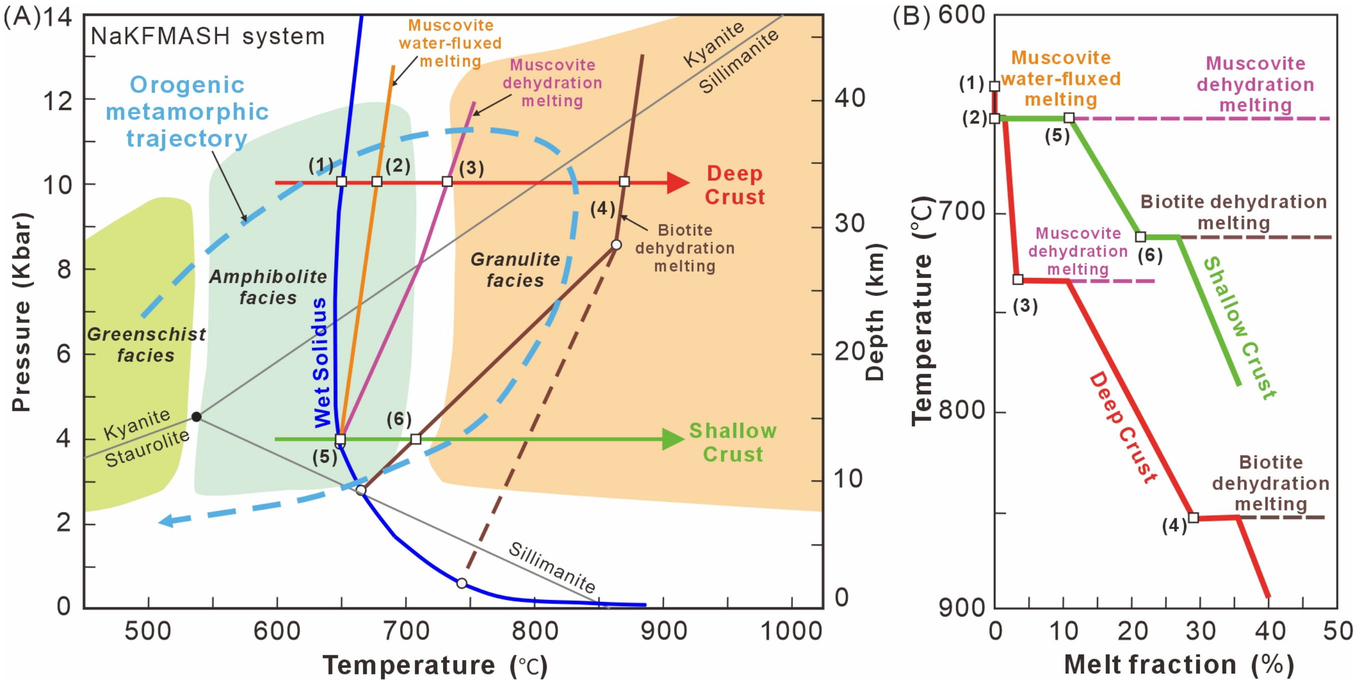

Figure 4. (**A**) Schematic diagram of major melting reactions in the $Na_2O–K_2O–FeO–MgO–Al_2O_3–SiO_2–H_2O$ (NaKFMASH) metapelite system as a function of pressure and temperature. (**B**) Schematic diagram of the relationship between different melting reactions and the melt fraction generated during isobaric heating of the upper and lower crust (modified from [21, 65]). The blue *P*–*T* path in (**A**) represents a typical burial and heating path in an orogenic belt, illustrating the pressure–temperature evolution experienced by rocks during collisional orogenesis and the formation of ore-bearing granites.

3. Future Research Outlook

In summary, although geologists recognize that, in addition to high degrees of magmatic differentiation and post-magmatic hydrothermal processes, anatectic melting in the middle–lower crustal source region also plays a critical role in mineralization, the key controlling factors for the initial enrichment of Sn and W during partial melting remain unclear, and detailed analyses and quantitative descriptions of specific examples are particularly lacking [5, 66]. This is largely due to the difficulty of accessing rocks from the magma source region, namely the middle–lower crust, associated with ore-forming granites. Therefore, it is necessary to select representative areas where metasedimentary source rocks (the “source” stage), ore-forming granites (the “transport” stage), and Sn–W deposits (the “deposition” stage) are all exposed for more in-depth empirical research. The Himalayan orogen, characterized by its young age, rapid exhumation, well-exposed middle–lower crustal rocks without significant overprinting by later tectonic events, and relatively well-preserved mineralization processes and rock types, presents an exceptional opportunity to address this issue, particularly following the discovery of Miocene Sn–W rare metal deposits in the region [67–69].

Previous research on W–Sn deposits has largely focused on magmatic differentiation and fluid mineralization [70], with less attention paid to the partial melting of metapelites, resulting in limited clarity regarding the controls exerted by magma-source processes on W–Sn mineralization. Future research should target key minerals such as muscovite, biotite, and other important accessory phases, including apatite, rutile, titanite, and ilmenite, in metamorphic source rocks as primary research objects. By integrating metamorphic phase-equilibrium modeling, whole-rock mass-balance calculations, and isotopic-fractionation modeling [71], future studies should investigate the mechanisms by which partial melting of metasedimentary rocks controls the mobilization of Sn and W into anatectic melts and their initial enrichment [72]. Key aspects should include source-region composition, the degree of Sn–W pre-enrichment, anatectic temperature and oxygen fugacity, minerals involved in melting reactions, and accessory-mineral stability.

Such research is expected to reveal the controls exerted by deep magma-source melting on the initial enrichment of Sn and W, thereby refining theories of Sn–W metallogeny and granite petrogenesis. By integrating metamorphism, magmatic evolution, and ore-forming processes, and by building on metamorphic P–T–t–composition path modeling, in situ microanalyses of major and trace elements can be used to determine the modes of occurrence and characteristics of carrier minerals for W, Sn, and related elements during metapelite metamorphism. Combined with mass-balance calculations, this approach can quantitatively constrain the activation, migration, and enrichment mechanisms of ore-related elements during metamorphism. It can also bridge the gap represented by the partial melting process between metapelites and ore-forming granites, constrain the magma sources and petrogenesis of ore-forming granites, and clarify the genetic differences between mineralized and barren granites, thereby laying a foundation for assessing W–Sn rare-metal mineralization potential.

4. Conclusions

The extraordinary enrichment of tin and tungsten results from the combined effects of partial melting in the deep source region, high degrees of magmatic differentiation, and hydrothermal processes. Among these, the partial melting of middle–lower crustal metasedimentary rocks serves as the starting point for the initial enrichment of ore-forming metals and fundamentally controls the formation of ore-related granites. Several major controversies remain regarding source-rock composition, the effects of elemental pre-enrichment, the control of anatectic conditions on Sn–W coexistence and separation, and disequilibrium melting processes. Future research should target well-exposed “source–transport–deposition” systems in representative orogenic belts, combining high-precision in situ analyses with integrated multi-method modeling to precisely characterize the activation, migration, and initial enrichment mechanisms of Sn and W during partial melting. This will advance theories of granite-related Sn–W metallogeny and provide a scientific basis for rare-metal exploration.

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Informed Consent Statement

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Data Availability Statement

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Conflicts of Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of AI and AI-Assisted Technologies

AI tools were used to polish the language, after which the author carefully reviewed the manuscript and takes full responsibility for its content.

References

1. Zheng, Y.F. A revisit to continental collision between India and Asia. *Earth Sci. Rev.* **2025**, *264*, 105087. https://doi.org/10.1016/j.earscirev.2025.105087
2. Weber, S.; Legler, C.; Kallmeier, E.; et al. Metamorphic origin of stratiform cassiterite mineralization in the Schwarzenberg – Aue district – Clues to the metamorphic history and pre-orogenic Sn enrichment of the Erzgebirge (Germany). *Lithos* **2023**, *454–455*, 107273. https://doi.org/10.1016/j.lithos.2023.107273
3. Zhao, P.; Yuan, S.; Williams-Jones, A.E.; et al. Temporal separation of W and Sn mineralization by temperature-controlled incongruent melting of a single protolith: Evidence from the wangxianling area, nanling region, South China. *Econ. Geol.* **2022**, *117*, 667–682. https://doi.org/10.5382/econgeo.4902
4. Song, S.; Mao, J.; Yuan, S.; et al. Decoupling of Sn and W mineralization in a highly fractionated reduced granitic magma province: A case study from the Youjiang basin and Jiangnan tungsten belt. *Miner. Depos.* **2022**, *57*, 1251–1267. https://doi.org/10.1007/s00126-022-01094-3
5. Liu, Y.; Schmidt, C.; Li, J.; et al. The role of protolith composition in the formation of tin-enriched granitic melts: A modeling study using the example of the southwest China tin province. *Ore Geol. Rev.* **2024**, *169*, 106094. https://doi.org/10.1016/j.oregeorev.2024.106094
6. Mao, J.W.; Ouyang, H.G.; Song, S.W.; et al. Geology and metallogeny of tungsten and Tin deposits in China, in *Mineral Deposits of China*; Chang, Z.; Goldfarb, R.J., Eds.; Society of Economic Geologists Special Publication 22; Society of Economic Geologists: Littleton, CO, USA, 2019; pp. 411–482. https://doi.org/10.5382/SP.22.10
7. Romer, R.L.; Pichavant, M. Rare metal granites and pegmatites. In *Encyclopedia of Geology*, 2nd ed.; Alderton, D., Elias, S.A., Eds.; Academic Press: Oxford, UK, 2021; pp. 840–846. https://doi.org/10.1016/B978-0-08-102908-4.00003-5
8. Romer, R.L.; Förster, H.J.; Glodny, J. Role of fractional crystallization, fluid-melt separation, and alteration on the Li and B isotopic composition of a highly evolved composite granite pluton: The case of the Eibenstock granite, Erzgebirge, Germany. *Lithos* **2022**, *422–423*, 106722. https://doi.org/10.1016/j.lithos.2022.106722
9. Yu, J.; Cai, Y.; Sun, T.; et al. Distribution and enrichment of rare metal elements in the basement rocks of South China: Controls on rare-metal mineralization. *Ore Geol. Rev.* **2023**, *163*, 105797. https://doi.org/10.1016/j.oregeorev.2023.105797
10. Michaud, J.A.S.; Schmidt, C.; Naumova, M.A. Revisiting redox-driven pathways of tin cycle from source to economic deposit. *Sci. Rep.* **2025**, *15*, 34476. https://doi.org/10.1038/s41598-025-21389-5
11. Mei, Y.; Liu, W.; Guan, Q.; et al. Tungsten speciation in hydrothermal fluids. *Geochim. Cosmochim. Acta* **2025**, *406*, 262–284. https://doi.org/10.1016/j.gca.2024.06.030
12. Rasmussen, K.L.; Falck, H.; Elongo, V.; et al. The source of tungsten-associated magmas in the northern Canadian Cordillera and implications for the basement. *Geology* **2023**, *51*, 657–662. https://doi.org/10.1130/G51042.1
13. Losantos, E.; Borrajo, I.; Losada, I.; et al. Sn and W mineralisation in the Iberian Peninsula. *Ore Geol. Rev.* **2025**, 106542. https://doi.org/10.1016/j.oregeorev.2025.106542
14. Stepanov, A.S. A review of the geochemical changes occurring during metamorphic devolatilization of metasedimentary rocks. *Chem. Geol.* **2021**, *568*, 120080. https://doi.org/10.1016/j.chemgeo.2021.120080
15. Wolf, M.; Romer, R.L.; Franz, L.; et al. Tin in granitic melts: The role of melting temperature and protolith composition. *Lithos* **2018**, *310–311*, 20–30. https://doi.org/10.1016/j.lithos.2018.04.004
16. Spear, F.S.; Pyle, J.M. Apatite, monazite, and xenotime in metamorphic rocks. *Rev. Mineral. Geochem.* **2002**, *48*, 293–335. https://doi.org/10.2138/rmg.2002.48.7
17. Yakymchuk, C.; Acosta-Vigil, A. Geochemistry of phosphorus and the behavior of apatite during crustal anatexis: Insights from melt inclusions and nanogranitoids. *Am. Mineral.* **2019**, *104*, 1765–1780. https://doi.org/10.2138/am-2019-7054
18. Schwindinger, M.; Weinberg, R.F.; White, R.W. The fate of accessory minerals and key trace elements during anatexis and magma extraction. *J. Petrol.* **2020**, *61*, egaa031. https://doi.org/10.1093/petrology/egaa031
19. Volante, S.; Blereau, E.; Guitreau, M.; et al. Current applications using key mineral phases in igneous and metamorphic geology: Perspectives for the future. In *Minor Minerals, Major Implications: Using Key Mineral Phases to Unravel the Formation and Evolution of Earth's Crust*; van Schijndel, V., Cutts, K., Pereira, I., et al., Eds.; Geological Society, London, Special Publications, Vol. 537; Geological Society of London: London, UK, 2024; pp. 57–121. https://doi.org/10.1144/SP537-2022-254
20. Yuan, S.; Williams-Jones, A.E.; Romer, R.L.; et al. Protolith-related thermal controls on the decoupling of Sn and W in Sn-W Metallogenic Provinces: Insights from the Nanling Region, China. *Econ. Geol.* **2019**, *114*, 1005–1012. https://doi.org/10.5382/econgeo.4669
21. Gardiner, N.J.; Palin, R.M.; Koopmans, L.; et al. On tin and lithium granite systems: A crustal evolution perspective. *Earth Sci. Rev.* **2024**, *258*, 104947. https://doi.org/10.1016/j.earscirev.2024.104947
22. Lehmann, B. Formation of tin ore deposits: A reassessment. *Lithos* **2021**, *402–403*, 105756. https://doi.org/10.1016/j.lithos.2020.105756
23. Schuiling, R.D. Tin belts on the continents around the Atlantic Ocean. *Econ. Geol.* **1967**, *62*, 540–550. https://doi.org/10.2113/gsecongeo.62.4.540
24. Romer, R.L.; Kroner, U., Provenance control on the distribution of endogenic Sn-W, Au, and U mineralization within the Gondwana-Laurussia plate boundary zone. In *New Developments in the Appalachian–Caledonian–Variscan Orogen*; Kuiper, Y.D., et al., Eds.; Geological Society of America: Boulder, CO, USA, 2022; Volume 554. https://doi.org/10.1130/2021.2554(02)
25. Romer, R.L.; Kroner, U.; Schmidt, C.; et al. Mobilization of tin during continental subduction-accretion processes. *Geology* **2022**, *50*, 1361–1365. https://doi.org/10.1130/G50466.1
26. Elongo, V.; Falck, H.; Rasmussen, K.L.; et al. Ancient roots of tungsten in western North America. *Geology* **2022**, *55*, 791–795. https://doi.org/10.1130/G49801.1
27. Tang, G.-J.; Wyman, D.A.; Wang, Q.; et al. Large-scale rare-metal pegmatite deposit formation driven by supercontinent assembly. *Geology* **2023**, *51*, 880–884. https://doi.org/10.1130/G51454.1
28. Ishihara, S. The redox state of granitoids relative to tectonic setting and earth history: The magnetite–ilmenite series 30 years later. *Earth Environ. Sci. Trans. R. Soc. Edinb.* **2004**, *95*, 23–33. https://doi.org/10.1130/0-8137-2389-2.23
29. Sato, K.; Kovalenko, S.V.; Romanovsky, N.P.; et al. Crustal control on the redox state of granitoid magmas: Tectonic implications from the granitoid and metallogenic provinces in the circum-Japan Sea Region. *Earth Environ. Sci. Trans. R. Soc. Edinb.* **2004**, *95*, 319–337. https://doi.org/10.1130/0-8137-2389-2.319
30. Sato, K. Sedimentary crust and metallogeny of granitoid affinity: Implications from the geotectonic histories of the Circum-Japan sea region, Central Andes and Southeastern Australia. *Resour. Geol.* **2012**, *62*, 329–351. https://doi.org/10.1111/j.1751-3928.2012.00200.x
31. Patiño Douce, A.E.; Johnston, A.D. Phase equilibria and melt productivity in the pelitic system: Implications for the origin of peraluminous granitoids and aluminous granulites. *Contrib. Mineral. Petrol.*

1991, *107*, 202–218. https://doi.org/10.1007/BF00310707

32. Song, S., Mao, J., Zhang, Z., et al. Lamprophyre magmatism triggering the formation of the Zhuxi granites related to the world-largest scheelite skarn deposit in South China. *Lithos* **2023,** *444–445*, 107106. https://doi.org/10.1016/j.lithos.2023.107106
33. Blevin, P.L. Metallogeny of granitic rocks. In *The Ishihara Symposium: Granites and Associated Metallogenesis*; Geoscience Australia: Canberra, Australia, 2003; pp. 1–4.
34. Thompson, J.; Sillitoe, R.; Baker, T.; et al. Intrusion-related gold deposits associated with tungsten-tin provinces. *Miner. Depos.* **1999**, *34*, 323–334. https://doi.org/10.1007/s001260050207
35. Romer, R.L.; Kroner, U. Sediment and weathering control on the distribution of Paleozoic magmatic tin–tungsten mineralization. *Miner. Depos.* **2015**, *50*, 327–338. https://doi.org/10.1007/s00126-014-0540-5
36. Romer, R.L.; Kroner, U. Phanerozoic tin and tungsten mineralization—Tectonic controls on the distribution of enriched protoliths and heat sources for crustal melting. *Gondwana Res.* **2016**, *31*, 60–95. https://doi.org/10.1016/j.gr.2015.11.002
37. Zhao, P.; Chu, X.; Williams-Jones, A.E.; et al. The role of phyllosilicate partial melting in segregating tungsten and tin deposits in W-Sn metallogenic provinces. *Geology* **2022**, *50*, 121–125. https://doi.org/10.1130/G49248.1
38. Yang, J.H.; Wu, J.H.; Zhou, M.F.; et al. Mantle contributions to global tungsten recycling and mineralization. *Commun. Earth Environ.* **2025**, *6*, 510. https://doi.org/10.1038/s43247-025-02471-2
39. Michaud, J.A.S.; Pichavant, M.; Villaros, A. Rare elements enrichment in crustal peraluminous magmas: Insights from partial melting experiments. *Contrib. Mineral. Petrol.* **2021**, *176*, 96. https://doi.org/10.1007/s00410-021-01855-9
40. Yin, R.; Huang, X.L.; Wang, R.C.; et al. Rare-metal enrichment and Nb–Ta fractionation during magmatic–hydrothermal processes in rare-metal granites: Evidence from zoned micas from the Yashan pluton, South China. *J. Petrol.* **2022**, *63*, egac093. https://doi.org/10.1093/petrology/egac093
41. Liu, M.; Zhao, P.; Hong, W.; et al. Assessing the W-Sn ore formation potential of large granite batholiths: Insights from zircon U-Pb and muscovite Ar-Ar geochronology of the Tianmuchong W-Sn deposit in the Nanling region, South China. *Ore Geol. Rev.* **2024**, 106311. https://doi.org/10.1016/j.oregeorev.2024.106311
42. Lehmann, B., *Metallogeny of Tin.* Springer-Verlag: Berlin, Heidelberg, 1990; pp. 1–211.
43. Lu, H.Z.; Liu, Y.; Wang, C.; et al. Mineralization and fluid inclusion study of the shizhuyuan W-Sn-Bi-Mo-F skarn deposit, Hunan Province, China. *Econ. Geol.* **2003**, *98*, 955–974. https://doi.org/10.2113/gsecongeo.98.5.955
44. Blevin, P.L.; Chappell, B.W. The role of magma sources, oxidation states and fractionation in determining the granite metallogeny of eastern Australia. *Earth Environ. Sci. Trans. R. Soc. Edinb.* **1992**, *83*, 305–316. https://doi.org/10.1130/SPE272-p305
45. Cheng, Y.; Spandler, C.; Kemp, A.; et al. Controls on cassiterite (SnO_2) crystallization: Evidence from cathodoluminescence, trace-element chemistry, and geochronology at the Gejiu Tin District. *Am. Mineral.* **2019**, *104*, 118–129. https://doi.org/10.2138/am-2019-6466
46. Huang, W.Q.; Pan, J.Y.; Ni, P.; et al. Recognition of Neogene tin mineralization in the Southeast Asian tin belt. *GSA Bull.* **2024**, *136*, 5300–5312. https://doi.org/10.1130/B37541.1
47. Wei, C.; Xiong, X.; Wang, J.; et al. Partitioning of tin between mafic minerals, Fe-Ti oxides and silicate melts: Implications for tin enrichment in magmatic processes. *Geochim. Cosmochim. Acta* **2024**, *372*, 81–100. https://doi.org/10.1016/j.gca.2024.03.011
48. Linnen, R.L.; Pichavant, M.; Holtz, F. The combined effects of fO_2 and melt composition on SnO_2 solubility and tin diffusivity in haplogranitic melts. *Geochim. Cosmochim. Acta* **1996**, *60*, 4965–4976. https://doi.org/10.1016/S0016-7037(96)00295-5
49. Schmidt, C.; Gottschalk, M.; Zhang, R.; et al. Oxygen fugacity during tin ore deposition from primary fluid inclusions in cassiterite. *Ore Geol. Rev.* **2021**, *139*, 104451. https://doi.org/10.1016/j.oregeorev.2021.104451
50. Wu, J.; Li, H.; Mathur, R.; et al. Compositional variation and Sn isotope fractionation of cassiterite during magmatic-hydrothermal processes. *Earth Planet. Sci. Lett.* **2023**, *613*, 118186. https://doi.org/10.1016/j.epsl.2023.118186
51. Ma, X.; Wang, H.; Lehmann, B.; et al. Control of magmatic halogen composition and redox state on the zonation of metal mineralization across active continental margins: Perspectives from the world-class South China metallogenic province. *Chem. Geol.* **2024**, *669*, 122363. https://doi.org/10.1016/j.chemgeo.2024.122363
52. Simons, B.; Andersen, J.C.Ø.; Shail, R.K.; et al. Fractionation of Li, Be, Ga, Nb, Ta, In, Sn, Sb, W and Bi in the peraluminous early permian Variscan granites of the Cornubian Batholith: Precursor processes to magmatic-hydrothermal mineralisation. *Lithos* **2017**, *278–281*, 491–512. https://doi.org/10.1016/j.lithos.2017.02.007
53. Borrajo, I.; Tornos, F.; Stein, H.; et al. Geochronology and decoupling controls of Sn-(Ta-Li) and W-(Sn) mineralization in the Iberian Variscan Massif, Spain and Portugal. *Ore Geol. Rev.* **2024**, *173*, 106253. https://doi.org/10.1016/j.oregeorev.2024.106253
54. Cave, B.J.; Large, R.R.; White, C.E.; et al. Does tungsten availability control the presence of tungsten in turbidite-hosted orogenic gold mineralization? Evidence from the Meguma and Bendigo-ballarat Terranes. *Can. Mineral.* **2017**, *55*, 973–999. https://doi.org/10.3749/canmin.1600088
55. Lefebvre, M.G.; Romer, R.L.; Glodny, J.; et al. Skarn formation and tin enrichment during regional metamorphism: The Hämmerlein polymetallic skarn deposit. *Lithos* **2019**, *348–349*, 105171. https://doi.org/10.1016/j.lithos.2019.105171
56. Kunz, B.E.; Warren, C.J.; Jenner, F.E.; et al. Critical metal enrichment in crustal melts: The role of metamorphic mica. *Geology* **2022**, *50*, 1219–1223. https://doi.org/10.1130/G50284.1
57. Yakymchuk, C.; Clark, C.; White, R.W. Phase relations, reaction sequences and petrochronology. *Rev. Mineral. Geochem.* **2017**, *83*, 13–53. https://doi.org/10.2138/rmg.2017.83.2
58. Cave, B.J.; Pitcairn, I.K.; Craw, D.; et al. A metamorphic mineral source for tungsten in the turbidite-hosted orogenic gold deposits of the Otago Schist, New Zealand. *Miner. Depos.* **2017**, *52*, 515–537. https://doi.org/10.1007/s00126-016-0677-5
59. Carocci, E.; Marignac, C.; Cathelineau, M.; et al. Incipient wolframite deposition at Panasqueira (Portugal): W Rutile and Tourmaline Compositions as Proxies for the early fluid composition. *Econ. Geol.* **2021**, *116*, 123–146. https://doi.org/10.5382/econgeo.4783
60. Finch, E.G.; Tomkins, A.G. Fluorine and chlorine behaviour during progressive dehydration melting: Consequences for granite geochemistry and metallogeny. *J. Metamorph. Geol.* **2017**, *35*, 739–757. https://doi.org/10.1111/jmg.12253
61. Zeng, L.; Saleeby, J.B.; Asimow, P. Nd isotope disequilibrium during crustal anatexis: A record from the Goat Ranch migmatite complex, southern Sierra Nevada batholith, California. *Geology* **2005**, *33*, 53–56. https://doi.org/10.1130/G20831.1
62. Yang, L.; Wang, J.M.; Liu, X.C.; et al. Sr-Nd-Hf Isotopic disequilibrium during the partial melting of metasediments: Insight from Himalayan Leucosome. *Front. Earth Sci.* **2022**, 10:891960. https://doi.org/10.3389/feart.2022.891960
63. Wolf, M.; Romer, R.L.; Glodny, J. Isotope disequilibrium during partial melting of metasedimentary rocks. *Geochim. Cosmochim. Acta* **2019**, *257*, 163–183. https://doi.org/10.1016/j.gca.2019.05.008
64. Mangler, M.F.; Gardiner, N.J.; Skeat, D.; et al. Apatite as a pathfinder to tin mineralisation: prospects and caveats. *Miner. Depos.* **2025**, *60*, 1397–1408. https://doi.org/10.1007/s00126-025-01350-2
65. Spear, F.S.; Kohn, M.J.; Cheney, J.T. P-T paths from anatectic pelites. *Contrib. Mineral. Petrol.* **1999**, *134*, 17–32. https://doi.org/10.1007/s004100050466

66. Liu, Y.; Romer, R.L.; Schmidt, C.; et al. Experimental melting of tin-enriched sedimentary protoliths: Implications for the formation of tin-specialized granites. *Lithos* **2025**, 522–523, 108384. https://doi.org/10.1016/j.lithos.2025.108384

67. Cao, H.W.; Pei, Q.M.; Yu, X.; et al. Discovery of the large-scale Eocene Xiwu Pb–Zn–Ag deposit in the Tethyan Himalaya: Geochronology, geochemistry, and C–H–O–S–Pb–Sr–Nd isotopes. *Gondwana Res.* **2023**, *124*, 165–187. https://doi.org/10.1016/j.gr.2023.07.001

68. Cao, H.W.; Pei, Q.M.; Yu, X.; et al. The long-lived partial melting of the Greater Himalayas in southern Tibet, constraints from the Miocene Gyirong anatectic pegmatite and its prospecting potential for rare element minerals. *China Geol.* **2023**, *6*, 303–321. https://doi.org/10.31035/cg2022061

69. Cao, H.W.; Pei, Q.M.; Santosh, M.; et al. Himalayan leucogranites: A review of geochemical and isotopic characteristics, timing of formation, genesis, and rare metal mineralization. *Earth Sci. Rev.* **2022**, *234*, 104229. https://doi.org/10.1016/j.earscirev.2022.104229

70. Wang, Q.; Zhu, R.; Li, W.C.; et al. The role of alkaline silicate-rich fluids in Sn mineralization based on cassiterite solubility experiments. *Geochim. Cosmochim. Acta* **2024**, *373*, 169–176. https://doi.org/10.1016/j.gca.2024.04.001

71. Koopmans, L.; Martins, T.; Linnen, R.; et al. The formation of lithium-rich pegmatites through multi-stage melting. *Geology* **2024**, *52*, 7–11. https://doi.org/10.1130/G51633.1

72. Sun, X., Xu, H.C., Yang, Z.M.; et al. Crustal recycling and metamorphic dehydration govern the fertility of granite-associated tin systems. *Commun. Earth Environ.* **2026**, *7*, 381. https://doi.org/10.1038/s43247-026-03538-4