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GR Focus Review

Phanerozoic tin and tungsten mineralization—Tectonic controls on the distribution of enriched protoliths and heat sources for crustal melting

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ABSTRACT

Phanerozoic primary tin and tungsten deposits and lithium–cesium–tantalum (LCT) type pegmatites define discontinuous belts that reach several thousand kilometers length. Mineralization along these belts is irregularly distributed, diachronous, and occurs in different tectonic settings on both sides of major sutures. Although these deposits formed during late magmatic differentiation processes, magmatism may be related to different geodynamic settings, in particular subduction, continental collision, and anorogenic extension. Here we test the hypothesis that the formation of these belts is explained by a generic process, involving three independent steps as prerequisite for the development of deposits: (i) intense chemical weathering of sedimentary rocks on a stable continent resulting in the enrichment of Sn and W in the protoliths, (ii) sedimentary—followed by tectonic—accumulation of the enriched debris at continent margins, and (iii) heating of the voluminous sedimentary protoliths generating Sn and/or W enriched melts. The Sn and/or W belts reflect the spatial distribution of enriched protoliths, whereas the discontinuous distribution of Sn and W mineralization within the belts reflects both, the locally extreme sedimentary and tectonic accumulation and the distribution of heat sources.

(i) Intense chemical weathering results in the preferential loss of most feldspar-bound elements (e.g., Na, Ca, Sr, and Pb) and the residual enrichment of elements incorporated in or adsorbed on clay minerals (e.g., Li, K, Rb, Cs, Sn, and W), i.e., produces some of the hallmark geochemical signatures of tin granites that also are obtained by extreme magmatic fractionation of granitic melts. Intense chemical weathering occurs in tectonically stable areas with limited topography and may be particularly pronounced in the interior of large continental masses, such as late Proterozoic Rodinia, late Proterozoic to Cambrian Gondwana, and late Paleozoic to early Mesozoic Pangea.
(ii) Sedimentary accumulation occurs when these blankets of chemically intensely weathered sediments are redistributed from the continent interior to the margins of the continent. This fluviatile redistribution is typically related to the fragmentation of megacontinents or supercontinents. Tectonic accumulation may occur when passive-margin sedimentary packages later are reworked in an active margin setting.
(iii) The nature of the heat source controls type of mineralization and its relation to plate boundaries. Internal heating in orogenically thickened crust generates minimum-temperature melts that mobilize elements hosted in feldspar and muscovite and may generate granites and pegmatites with LCT-type signature. The formation of Sn and W mineralization requires higher temperatures to consume biotite. Such temperatures require heat advection from the mantle by (a) mantle-derived melts in subduction setting, (b) emplacement of ultrahigh-temperature metamorphic rocks that had been subducted to mantle depth during continental collision, or (c) mantle-derived melts in extensional settings. The age of mineralization within belt reflects the event of heat input.

The distribution of Sn and W mineralization within belts is the superposition of processes at the passive margin and processes at the active margin. Source enrichment and distribution is related to megacontinents (chemical weathering) and their fragmentation (sedimentary accumulation at the margin of fragments from a megacontinent). Therefore, Sn and W belts generally border to fragments of former megacontinents. Metal mobilization from the source rocks is controlled by the distribution of the heat sources and, thus, by processes at an active margin. The generic model explains both the arrangement of Sn and W mineralization in belts and their distribution with the belts. It allows for recurrent formation of mineralization within a single belt in

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contrasting tectonic settings and to both sides of major sutures. With source enrichment and source accumulation being necessary requirements of mineralization, the generic model also explains unmineralized gaps within Sn and W belts and why there are unmineralized magmatic belts of comparable setting and with granitic rocks of comparable magmatic development. Areas without voluminous packages of enriched protoliths or without ample heat sources to mobilize the ore elements from the protoliths have a low potential for hosting Sn and W mineralization.

Contents

1. Introduction

Most primary Sn and W mineralization is spatially associated with felsic magmatic rocks that generally are interpreted to be the source of these metals (e.g., Ferguson and Bateman, 1912; Taylor, 1979a; Kwak, 1987; Heinrich, 1990; Lehmann, 1990; Štemprok, 1995). Common to these magmatic rocks is that they are highly fractionated and show distinct chemical signatures, such as a pronounced enrichment in Sn, W, Be, Cs, F, B, Li, Rb, Ta, and U, and a marked depletion in Fe, Ti, Mg, Ca, Sr, Eu, Ba, and Zr (e.g., Stussi, 1989; Lehmann, 1990; Förster et al., 1999; Bouchot et al., 2005; Breiter et al., 2005). Tin and W mineralization related to felsic magmatic rocks form a variety of deposit types, including greisen, quartz veins, skarn, and less commonly porphyry-type occurrences and pegmatites (e.g., Kwak, 1987; Plimer, 1987; Štemprok, 1987; Hall, 1990; Štemprok, 1995; Halter et al., 1996; Sinclair et al., 2011; J.W. Mao et al., 2013). The various types depend on the magmatic evolution of the granitic magmas, depth of emplacement, wall rocks, local structural controls of the conduits for melts and fluids, and the evolution of fluids during late-stage magma evolution or hydrothermal interaction between fluids and wall rocks (Heinrich, 1990; Linnen, 1998a; Audétat et al., 2000; Jackson et al., 2000; Sanderson et al., 2008). Apart from Sn and W, these mineralization also may contain economically important amounts of Ta, Nb, Li, B, Ge, Ga, In, and Sc (Schwarz-Schampera and Herzig, 2002; Breiter et al., 2006; Kempe and Wolf, 2006; Sinclair et al., 2006; Ishihara et al., 2011). Geochemically related to Sn and W granites are lithium–cesium–tantalum (LCT) type pegmatites, which generally do not show significant Sn and W mineralization (for an exception see Linnen, 1998a), but contain variable and in part economically significant amounts of Ta, Nb, Li, Rb, Cs, Be, and Ga (e.g., Černý, 1991; Černý and Ercit, 2005; Kontak, 2006; Linnen et al., 2012).

Primary mineralization of Sn and W (and related elements) define together with LCT-type pegmatites distinct belts that may be several thousand kilometers long, as for instance in SE Asia or along the Acadian–Variscan–Appalachian orogenic belt (e.g., Schuiling, 1967). The tin belt extending from South Africa to Nigeria to both sides of the Atlantic Ocean, for instance, includes deposits of Precambrian, Jurassic, and Tertiary (Eocene) age and, therefore, Schuiling (1967) concluded that the diachronous formation of tin deposits within the belt requires the Sn source to be located in the continental crust or possibly in the upper mantle adhering to the continental crust. This conclusion actually also holds in the context of plate tectonics, as both the oceanic and the continental lithosphere are part of the mantle convection cell (see p. 56 ff. in Davies, 2011), i.e., the lithospheric mantle remains stationary relative to the overlaying continental crust. Schuiling (1967), furthermore, concluded “for economic concentrations to occur, a combination of a geochemical *culmination* and an *event* is necessary”. A geochemical culmination was thought to represent a “continent-sized, lower-crustal belt” characterized by above-normal contents of Sn and related elements, whereas event referred to any process able to mobilize Sn and related elements from this enriched source, as for instance an orogeny leading to granitic magmatism. Schuiling (1967) particularly stressed “each of these factors alone is not sufficient to produce workable deposits”. Eventually, research continued along two lines: (i) the spatial and genetic link between Sn mineralization and plate tectonics and (ii) the characterization of the source rocks and whether or not these rocks already were enriched in Sn and related elements.