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GR Focus Review

Metalliferous coal deposits in East Asia (Primorye of Russia and South China): A review of geodynamic controls and styles of mineralization

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ABSTRACT

Metalliferous coal deposits, mainly hosting Zr(Hf)–Nb(Ta)–REE and U(Mo,Se)–REE ores, in East Asia (Primorye of Russia and South China) primarily result from the evolution of plumes ascending from deep mantle and/or asthenospheric flows, both of which incorporate some reworking of the continental crust. This mantle–crust interaction not only led to coal-basin formation but also played a significant role in extensive volcanism and ore-generating hydrothermal activity. Three mineralization styles are identified in these deposits: tuffaceous, hydrothermal-fluid, and mixed tuffaceous–hydrothermal types. The tuffaceous Zr(Hf)–Nb(Ta)–REE deposits have source magmas with an alkali basalt composition, although felsic, mafic, and intermediate types of tuffaceous horizons have been identified in the study area. The mineralization occurred not only in the coal but also in the host rocks, and not only during peat accumulation but also during the later stages of coal development (including coalification and late epigenetic processes). Rare metals in the metalliferous coal deposits are generally either associated with clay and organic matter or occur as secondary minerals derived from decomposition of the primary magmatic rare-metal bearing minerals (e.g. Nb-bearing rutile) under the influence of organic acids and hydrothermal fluids.

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1. Introduction

The term “metalliferous coal” has been widely used to describe coals with practical or potential economic significance for valuable metal production (Hower et al., 2000; Meitov, 2001; Seredin and Finkelman, 2008; Dai et al., 2012; Mastalerz and Drobniak, 2012; Sia and Abdullah, 2012), as well as for the traditional use as an energy source. The term is typically applied to coals with unusually high concentrations of potentially valuable trace elements, typically at least 10-times higher than the respective averages for the same elements in world coals generally (Seredin and Finkelman, 2008). Recent studies have shown that the metals are enriched not only in the coal themselves but also in their host rocks (roof and floor strata) and in non-coal bands or partings within the coal seams (Seredin and Finkelman, 2008; Dai et al., 2010; Zhao et al., 2013; Dai et al., 2014a).

The concentrations of rare metals in the ashes of some metalliferous-coals are equal to or higher than those found in conventional types of rare metal ores (Seredin and Finkelman, 2008; Seredin and Dai, 2012) and much higher than those in common coal ashes and coal-associated sedimentary rocks (Ketris and Yudovich, 2009). For example, weathered-crust elution-deposited ores with ion-exchangeable rare earth elements generally have total rare earth element contents of 0.03–0.25% (Bao and Zhao, 2008; Chi and Tian, 2008), but the concentrations of rare earth elements in common coal ashes average around 0.035% (Ketris and Yudovich, 2009) and 0.1–1.5% in the ashes of metalliferous coals (Seredin and Dai, 2012). Uranium concentrations are around 0.0016% in the ashes of common coals (Ketris and Yudovich, 2009), but 0.1–0.2% in conventional sand-hosted roll-type deposits and up to 0.4% in the ashes from metalliferous-coal deposits (Dai et al., 2015a,b). Concentrations of Zr and Nb are 210 and 20 μg/g respectively in average coal ashes (Ketris and Yudovich, 2009), but reach over 2000 and 200 μg/g respectively in ashes from coal-hosted Zr(Hf)–Nb(Ta)–REE ore deposits (this paper).

Metalliferous coals have been used as sources for metal extraction for over 100 years, since the coals of Wyoming and Utah were used for Au and Ag recovery in the late 19th and early 20th centuries (Jenney, 1903; Stone, 1912). Metalliferous coal deposits containing high concentrations of Ge, Ga, rare earth elements and Y (REY, or REE if Y is not included), Li, Sc, Zr, Hf, Nb, and Ta have recently attracted significant attention as a new source for these rare metals, which are becoming increasingly important in various high-technology applications (Seredin, 2012a; Seredin et al., 2013; Arbuzov et al., 2014). For example, germanium is currently being extracted as a raw material from three Ge-bearing coal deposits: Lincang (Yunnan province of China), Wulantuga (Inner Mongolia of China), and Spetzugli (Primorye, Russian Far East). Together, the latter deposits account for more than 50% of the total annual industrial Ge production in the world (Seredin et al., 2013; Dai et al., 2014b). The Ge in the three coal-hosted Ge ore deposits was derived from the granite basement by hydrothermal solutions during syngenetic and diagenetic stages, and is organically bound (Zhuang et al., 2006; Seredin and Finkelman, 2008; Qi et al., 2011; Dai et al., 2014b,c). A pilot plant for extraction of Ga and Al from coal combustion products (fly ashes) was installed at the Jungar deposit, Inner Mongolia, China (Dai et al., 2012; Seredin, 2012b) at the beginning of 2011. The annual processing capacity of this plant is 800,000-t Al_2O_3 and approximately 150-t Ga (Dai et al., 2012; Seredin, 2012b). Intensive research on resource evaluation and on the origin of the REY, Li, Sc, Zr, Hf, Nb, Ta, and U enrichment in these metalliferous coal deposits (both coals and host rocks), as well as methods for their extraction from coal ashes, have been and are currently being conducted in the USA (Finkelman and Brown, 1991; Hower et al., 1999; Mardon and Hower, 2004; Mastalerz and Drobniak, 2012), Europe (Eskenazy, 1987a,b; Blissett et al., 2014; Yossifova, 2014), Australia (Jaireth et al., 2014), India (Prachiti et al., 2011; Saikia et al., 2015), and, in particular, China (Dai et al., 2010; Wang et al., 2011; Dai et al., 2012; Seredin and Dai, 2012; Zhuang et al., 2012; Sun et al., 2013; Zhao et al., 2013; Dai et al., 2014a,b,c) and Russia (Seredin, 1991, 1996; Arbuzov et al., 2000; Kryukova et al., 2001; Arbuzov et al., 2003; Seredin, 2004; Seredin et al., 2006; Seredin and Tomson, 2008; Arbuzov et al., 2011; Seredin et al., 2013; Arbuzov et al., 2014).

On the other hand, coal-hosted rare-metal ore deposits generally contain high concentrations of toxic trace elements, which could have adverse effects on human health and environments. For example, fly ashes derived from the three giant coal-hosted Ge deposits, Lincang (Yunnan, China), Wulantuga (Inner Mongolia, China), and Spetzugli (Primorye, Russia), are highly enriched in toxic trace elements, including up to (on an organic-free basis) 2.12% As, 1.56% F, 1.22% Sb, 0.55% Pb, 0.04% Be, 0.017% Tl, and 0.016% Hg (Dai et al., 2014b). These high elemental concentrations in the fly ashes are due to their high levels in the raw coals (Zhuang et al., 2006; Qi et al., 2011; Dai et al., 2014c). The coal-hosted U–Se–Mo–Re–V ore deposits preserved within marine carbonate successions in South China are highly enriched in organic sulfur (e.g., 8.77%–10.30% in Yanshan coals, Yunnan, South China; Dai et al., 2008), F (up to 3362 μg/g in Heshan coals, Guangxi, South China; Dai et al., 2013b), Hg (654 ng/g in the Fusui coals, Guangxi, South China; Dai et al., 2013a), as well as Cr, Ni, and Cd (Shao et al., 2003; Zeng et al., 2005; Dai et al., 2015b; Liu et al., 2015). The Late Permian coal in the Huayingshan Coalfield in southwestern China is considered to be a coal-hosted Zr–Nb–REE ore deposit (Zhuang et al., 2012; Dai et al., 2014a) and is enriched in Se (6.99 μg/g; Dai et al., 2014a). Additionally, high concentrations of V, Cr, Co, and Ni in the Late Permian coals of southwestern China were derived from the Emeishan basalts, which served as a sediment source region during peat accumulation (Zhou et al., 2000; Dai et al., 2012; Wang et al., 2012; Zhuang et al., 2012). The enrichment of toxic trace elements in the coals is usually attributed to a combination of geological processes and tectonic controls during peat accumulation, as well as during subsequent diagenetic and epigenetic activities (Ding et al., 2001; Sia and Abdullah, 2012; Yossifova, 2014; Dai et al., 2015b). Thus, investigations of the relationships between tectonic background (e.g., mantle plume formation) and toxic trace elements in coal and in coal-hosted ore deposits might provide a better understanding of the environmental influences of toxic elements during rare metal recovery from coal ash and during coal combustion.

From genetic and practical points of view, the relation between tectonic setting (e.g., mantle plume formation or subduction/collision-related processes) and the development of coal-bearing strata (including coal-hosted ore deposits) may not only provide geologic information about the formation of coal-bearing sequences and regional tectonic history to assist exploration and exploitation of coal resources, but may also assist in the exploration for rare metal ore deposits. This is because the distribution of both coal beds and coal-hosted ore deposits resulted from the same processes of peat/sediment accumulation and rank advance, and were further influenced by interaction between the organic matter and basinal fluids, sediment diagenesis, and synsedimentary volcanic inputs (Ren, 1996; Ruppert et al., 1996; Ward, 2002).

As an example of these interactions, thin beds of kaolinite-rich sediment (tonsteins) of pyroclastic origin, deposited in the original peat-forming environment, have been found in many coal seams in southwestern China (Zhou et al., 1982, 2000; Dai et al., 2011, 2014a) and Russia (Admakin and Portnov, 1987; Admakin, 1991). The tonsteins in the Late Permian coals of that region probably resulted from waning activity of a mantle plume and may serve to indicate the periphery of the Emeishan Large Igneous Province (Dai et al., 2011, 2014d). Some tonsteins, typically of alkali origin, may contain valuable trace elements that could be potentially utilized, or may serve as indicators in exploration for alkali ore deposits (Zhou et al., 2000; Spears, 2012; Dai et al., 2014a). In many cases, the tonsteins contain primary sanidine and/or zircon of magmatic origin that could be used for radiometric age determination, providing absolute ages for chrono-stratigraphic correlation within the globally accepted geologic timescale (Bohor and