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Editorial

From “strategic” tungsten to “green” neodymium: A century of critical metals at a glance

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ABSTRACT

The relative criticality of mineral commodities is evaluated using a wide range of parameters and in different contexts (e.g., from the standpoint of their importance to national security, or to a specific industrial application), which explains the multiplicity of classification schemes and variations in terminology applied to these commodities in the literature, media and government reports. The core group of critical metals, listed alphabetically, includes: antimony, beryllium, chromium, cobalt, gallium, germanium, indium, lithium, niobium, platinoids, rare-earth elements (REE, including yttrium), tantalum and tungsten. The present retrospect briefly describes the emergence of critical metals as a distinct resource type and the evolution of society's perception of these commodities over the past 100 years.

> *Those who hold the purse strings of mineral resources, hold power, those who lose them lose power.*
>
> [Alan M. Bateman (1961, p. 331)]

The present Special Issue was conceived at the 1st International Workshop on Critical Metals in Beijing in September of 2012 (Fig. 1), which attracted delegates from 10 countries, and provided a great forum for sharing some current ideas on the sources of these metals and processes leading to their concentration in such unique deposits as Bayan Obo (northern China). This type of publication seemed very timely, given the recent upsurge of interest in the exploration community and among the general public in rare earths and other obscure denizens of the Periodic Table, whose names most of us tend to forget as soon as we pass that inorganic chemistry exam in college. So, what exactly are these elements and why all the attention?

The concept of critical and strategic mineral resources is not new and traces its history at least one hundred years back to World War I, when many of the involved nations began to experience severe shortages of materials required to sustain their war effort (e.g., the infamous Shell Crisis of 1915) just a few months into the conflict. It was also then that the “criticality” of certain trace elements was recognized by politicians, economists and industrialists, when Germany secured control of the bulk of global tungsten production, leaving the Entente Powers to scramble for alternative sources of this important metal (Limbaugh, 2010). Tungsten was a staple ingredient of high-speed steel tools required for fast and efficient production of weapons and ammunition, which gave whoever had a sustainable supply of it an edge over their opponents — precisely the reason why the Shell Crisis did not affect Germany. This efficiency owes much to the War Materials Department (Kriegsrohstoffabteilung) established in Berlin already in August of 1914. In the first two years of the War, the market demand for W quadrupled, whereas the price of WO_3 concentrate rose tenfold, precipitating numerous mining rushes across the western USA and other countries (Andrews, 1955; Limbaugh, 2010). This was a lesson duly learned and already in 1922, the Army and Navy Munitions Board was established in the US War Department to acquire and stockpile materials that were critical to the military–industrial complex, followed by the State Committee for Reserves in the USSR (1931), and similar organizations in other countries. The expediency of these measures became obvious when a new war broke out in 1939. It is not surprising, therefore, that early definitions of critical materials had military connotations, such as that given by the Army and Navy Munitions Board:

> “*Strategic and Critical Materials* are those materials required for essential uses in a war emergency, the procurement of which in adequate quantities, quality, and time is sufficiently uncertain for any reason to require prior provision for the supply thereof”
>
> [(DeMille, 1947, p. 3).]

To reflect the increasing role of advanced materials, like W alloys, in mainstream manufacturing, as well as in countless new applications that were now inseparable from the notion of technological progress and economic prosperity (telecommunication, electronics, nuclear

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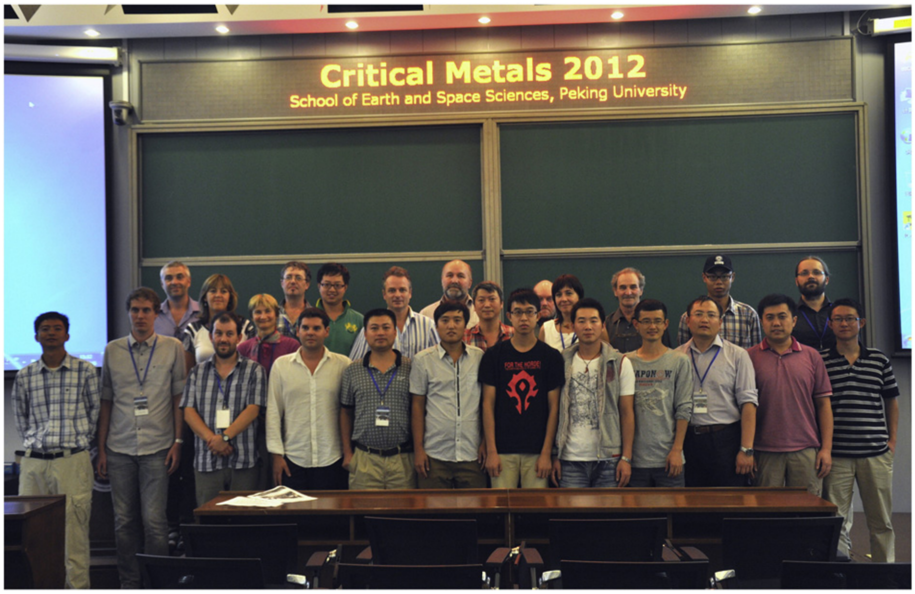

Fig. 1. Participants of the 1st Critical Metals Workshop in Beijing, China (September 2012).

energy, etc.), the above definition was later expanded beyond the defense sector and to include crises other than war (e.g., natural disasters or civil unrest). For example, the US Congress (1983) characterized these materials as those "needed to supply the military, industrial, and civilian needs of the Unites States during a national defense emergency and whose supplies are dependent on imports" (p. ix), drawing a distinction between "strategic" resources, whose supply was under potential threat, and those "critical" to the US economy (Jones, 1988). In many other countries, no such distinction is made, and any resource vital to the national economy and/or security is considered "strategic" or "strategically important" (e.g., Shestakov, 2000; UK House of Commons, 2011). The term "critical" re-emerged in the international business and political lingo with concentration of >50% of the global production of some rare elements in relatively few countries by the 1990s (e.g., W, rare earths and Sb in China, Nb in Brazil, Be in the US, and Pt in South Africa), which coincided with commercialization of many new technologies dependent on these elements (hybrid and electric vehicles, energy-efficient lighting, solar panels, touch screens, etc.), rapid economic growth of China and several other developing countries, and with increasing pressure on both miners and manufacturers to extract and utilize these metals in a socially and environmentally responsible way (e.g., Chakhmouradian and Wall, 2012). In the past few decades, a variety of new terms have been coined to underscore a specific critical aspect of the commodity: high-tech metals, green metals, etc. Clearly, there is no universally accepted register of such commodities. The criticality of the same element is viewed and assessed differently by each country and even by different government-appointed bodies in the same country (cf. entries 1 and 2 in Table 1). In the long term, these lists are also affected by largely unpredictable changes in the geopolitical situation and market dynamics (cf. entries 3 and 4 in Table 1). It is important to note in this context that not all stockpiled materials are necessarily critical; for instance, Zn was stockpiled in Japan in the 1970s to mitigate overproduction in a weak market (Hewitt and Wall, 2000).

In recent years, a quantitative approach has been increasingly applied to the assessment of criticality, based on such parameters as the scarcity of a commodity, diversity and stability of its available supply, substitutability of the element in various types of end products and its amenability to profitable recycling, as well as various geopolitical, environmental factors and anticipated impact of any supply disruptions on the economy (BGS, 2012; Committee on Critical Mineral Impacts on the US Economy, 2008; European Commission, 2010; Graedel et al., 2012; Skirrow et al., 2013; Speirs et al., 2013; US DoE, 2011). Although there is much variation in quantifiable parameters and individual rankings (see Fig. 2 for some examples), about a dozen symbols appear on several lists (Table 1), with rare earth elements (REE) most consistently identified as critical. The light lanthanide Nd, for instance, is an essential ingredient of permanent magnets used in a wide range of things, from the Patriot missile to the Toyota Prius hybrid and other clean-tech applications. Again, it is not just the importance of REE-based materials for industry or defense, that catapulted this and related metals into the headlines a few years back, but a whole series of changes in the political and economic structure of the world since the 1980s (Chakhmouradian and Wall, 2012; Hatch, 2012), which allowed China to capitalize on its remarkable Bayan Obo and ion-adsorption clay deposits (Kynicky et al., 2012; Smith et al., this issue). Further examples can be found in a recently published compendium covering rare earths, Sb, Be, Co, Ga, Ge, In, Li, Mg, Pt-group metals, Re, Nb, Ta and W (Gunn, 2014).

The core group of critical and strategic elements highlighted in Table 1 and Fig. 2 is not a geochemically coherent group; they range from lithophile alkalis and alkali earths (Li, Be) to siderophile d-metals (Co and the platinoids), chalcophiles (Ga, Ge, In, Sb), high-field-strength lithophiles (Nb, Ta, W), and elements which are difficult to pigeonhole (e.g., Y and lanthanides). For this reason, it would be impracticable to attempt here even a brief overview of their mineral deposits, or processes that control their distribution in the crust. Some of the commodities listed in Table 1 were covered at considerable length in previously published Special Issues of Ore Geology Reviews, including Ni (González-Álvarez et al., 2013), Mn (Polgári and Gutzmer, 2012), W (Mao et al., 2011), Cr and Pt-group metals (Economou-Eliopoulos et al., 2008), Ga, Ge, In and Sc (Schwarz-Schampera, 2006). The economic geology of Sb, Li and Co, at least in the realities of today's market, was addressed by Wu (1993), Kesler et al. (2012) and Mudd et al. (2013), respectively. The emphasis of the present Special Issue is on the metallogeny of critical metals that have not yet received a global- or continent-wide coverage in this journal, namely REE, Nb and Ta. In addition to papers stemming from oral presentations at the Beijing Workshop, we invited contributions from several leading research groups who were unable to attend this meeting. As a whole, the Issue covers the majority of deposit types currently being explored for REE, Nb and Ta ores, even though the Chinese ion adsorption clays may seem somewhat underrepresented relative to their commercial importance (Chi and Tian, 2008) and the possibility of extraction of valuable heavy REE from similar deposits elsewhere using low environment-

Table 1
Non-fuel critical and strategic resources: an overview; underlined are the core group of elements appearing on multiple lists.

Organization	Classification category: resources	Reference
US Department of Defense	*Strategic and critical non-proprietary materials* (*listed in order of decreasing shortfall value*[a]): Sn, **Sb**, Al_2O_3 (fused crude), SiC, **Y**, **W**, **Ta**, Bi, **Ge**, Mn metal (electrolytic), **Dy**, fluorite (acid grade), **Be** metal, **Er**, **Cr** metal, **Ga**, **Tb**, **Tm**, Sc	US DoD (2013)
US Department of Energy	*Critical materials, short- and medium-term*: **Dy**, **Eu**, **Nd**, **Tb**, **Y** *Near-critical materials, short- or medium-term*: **Ce**, **In**, **La**, Te, **Li**	US DoE (2011)
European Commission	*Critical raw materials* (*listed alphabetically*): **Sb**, **Be**, **Co**, fluorite, **Ga**, **Ge**, graphite, **In**, Mg, **Nb**, **PGM**[b], **REE**[c], **Ta**, **W**	European Commission (2010)
European Commission	*Critical raw materials* (*listed alphabetically*): **Sb**, **Be**, borates, **Cr**, **Co**, fluorite, **Ga**, **Ge**, graphite, **In**, magnesite, Mg, **Nb**, **PGM**[b], phosphate, **REE**[c], Si, **W**	European Commission (2014)
Government of the Russian Federation	*Strategic mineral resources*[d]: U, Mn, **Cr**, Ti, bauxite, Cu, Ni, Pb, Mo, **W**, Sn, Zr, **Ta**, **Nb**, **Co**, Sc, **Be**, **Sb**, **Li**, **Ge**, Re, **HREE**[e], Au, Ag, **PGM**, diamonds, ultra-pure quartz	Resolution 50-p of 16.01.1996
UK Government	*Strategically important metals* (*listed alphabetically*): **Sb**, **Be**, **Cr**, **Co**, **Ga**, **Ge**, Au, Hf, **In**, **Li**, Mg, Ni,**Nb**, **PGM**, Re, **REE**, **Ta**, Ti, **W**, V	UK House of Commons (2011)
Geoscience Australia	*Critical commodities* (*listed in order of decreasing criticality*)[f]: **REE**, **Ga**, **In**, **W**, **PGM**, **Co**, **Nb**, Mg, Mo, **Sb**, **Li**, V, Ni, **Ta**, Te, **Cr**, Mn	Skirrow et al. (2013)

[a] Listed are the materials whose shortfall value relative to the National Defense Stockpile exceeded US$1 million.
[b] Platinum-group metals (platinoids), including Ru, Rh, Pd, Os, Ir and Pt.
[c] Rare-earth elements, including the lanthanides (La–Lu) and Y; in some sources, Sc is also included in this category. Note that some organizations rank each individual REE separately (e.g., US DoD, 2013; US DoE, 2011), rather than collectively as the "rare earth basket".
[d] Defined as mineral resources whose export is controlled, restricted or not permitted to prevent harm to the security or economy of the country (Shestakov, 2000).
[e] Heavy REE (including Y).
[f] Commodities ranking below 12 (see Fig. 2 for further details) are not listed.

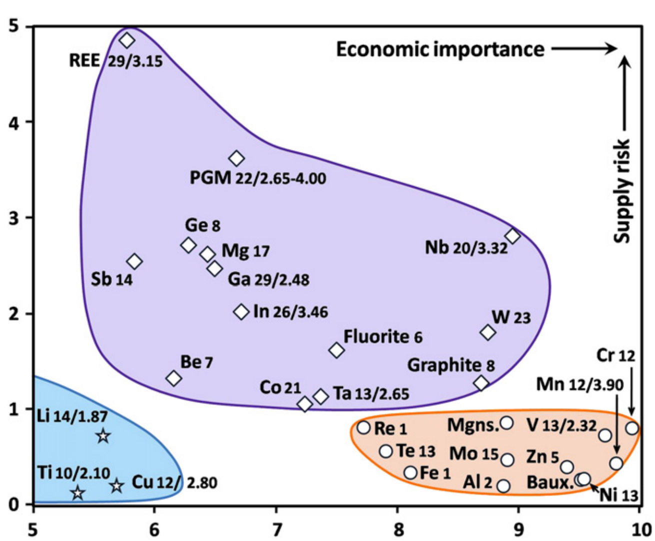

Fig. 2. Discrimination diagram, commonly referred to as a criticality matrix, showing the relative economic importance of mineral commodities most susceptible to supply disruptions in today's resource market according to a recent report by the European Commission (2010). In this instance, only the economically important commodities with a high supply risk (>5 and 1, respectively) were classified as critical (purple field). Low supply-risk industrially important materials (beige field) can potentially become critical if any of the risk-defining variables (e.g., political stability in the source region) change. Commodities in the blue field (only a portion of it shown in this figure) are not considered critical in the cited report, but some of these commodities (in particular, Li) have been identified as near-critical or strategic by other organizations (cf. Table 1). The chemical symbols are followed by the criticality score, assigned to these different types of resources by Skirrow et al. (2013) based on their synthesis of several assessment reports, and by the weighted score of the relative importance of end-use applications for some of the metals for the US economy (separated by a forward slash), evaluated on a scale of 0 to 4 (Committee on Critical Mineral Impacts on the US Economy, 2008).

impact methods. The shortage of papers on "ionic clays" reflects the comparative lack of adequate understanding of these materials, which may drive the next phase of research and technological development in this area in the near future.

The present Issue opens with a series of contributions on rare earths, including a review of the genesis of the previously mentioned world-class Bayan Obo deposit by Smith et al., followed by detailed studies of REE mineralization in carbonatitic and related rocks from the Kola Peninsula, Russia (Zaitsev et al.), Bear Lodge deposit in Wyoming, USA (Moore et al.), and Wicheeda Lake complex in British Columbia, Canada (Dalsin et al.). The long-debated carbonatite–Bayan–Obo connection is placed under scrutiny again by Zhu et al. based on new isotopic evidence. The new age constraints on carbonatite-hosted REE deposits in southwestern China are discussed by Liu et al., and the REE geochemistry and mineralogy of granites supporting ion-adsorption clays of southern China by Wang et al. The well-known association of REE with Nb is explored in further detail by Graupner et al. and Kempe et al. on the example of complex igneous–hydrothermal systems at Vergenoeg (South Africa) and Khalzan Buregte (Mongolia), respectively. The next five papers put the spotlight on Nb, Ta and other "less critical" high-field-strength elements (HFSE). Mitchell's review of primary and secondary Nb deposits in carbonatites is followed by a detailed account of Nb, Ta and Zr distribution in the Aley carbonatite deposit in British Columbia by Chakhmouradian et al. Melcher et al. present a systematic study of Ta–Nb–Sn mineralization in African pegmatites and rare-metal granites, Badanina et al. describe compositional variations in columbite-group minerals from pegmatites at Kolmozero (Kola Peninsula), and Aseri et al. examine the effects of F on the solubilities of Ta, Nb, Zr and Hf minerals in experimental haplogranitic melts. The Issue concludes with two contributions on geologically remarkable, but little studied systems, namely In-rich epithermal polymetallic veins (Lopez et al.), and carbonatite-hosted Mo deposits (Song et al.).

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References

Andrews, M.G., 1955. Tungsten: The Story of an Indispensable Metal. The Tungsten Inst., Washington (DC), (27 pp.).

Bateman, A.M., 1961. Minerals: supply and demand. Bull. At. Sci. 17, 331–335.

BGS, 2012. Risk List 2012. British Geological Survey, UK, (available at http://www.bgs.ac.uk/downloads/start.cfm?id=2643).

Chakhmouradian, A.R., Wall, F., 2012. Rare earth elements: minerals, mines, magnets (and more). Elements 8, 333–340.

Chi, R., Tian, J., 2008. Weathered Crust Elution-deposited Rare Earth Ores. Nova Sci. Publ., New York, (308 pp.).

Committee on Critical Mineral Impacts on the US Economy, 2008. Minerals, Critical Minerals, and the U.S. Economy,.

US Congress, 1983. Strategic and Critical Nonfuel Materials: Problems and Policy Alternatives. US Congr. Budget Office, Washington (DC), (85 pp.).

DeMille, J.B., 1947. Strategic Minerals: A Summary of Uses, World Output, Stockpiles, Procurement. McGraw-Hill Book Co, New York, (626 pp.).

Economou-Eliopoulos, M., Garuti, G., Mungall, J., 2008. Ore-forming processes associated with mafic and ultramafic rocks. Ore Geol. Rev. 33, 1–2.

European Commission, 2010. Critical raw materials for the EU. Report of the Ad-hoc Working Group on Defining Critical Raw Materials (85 pp.).

European Commission, 2014. Report on critical raw materials for the EU. Report of the Ad-hoc Working Group on Defining Critical Raw Materials (41 pp.).

González-Álvarez, I., Rirajno, F., Kerrich, R., 2013. Hydrothermal nickel deposits: secular variations and diversity. Ore Geol. Rev. 52, 1–3.

Graedel, T.E., Barr, R., Chandler, C., Chase, T., Choi, J., Christoffersen, L., Friedlander, E., Henly, C., Jun, C., Nassar, N.T., Schechner, D., Warren, S., Yang, M.-y., Zhu, C., 2012. Methodology of metal criticality determination. Environ. Sci. Technol. 46, 1063–1070.

Gunn, G. (Ed.), 2014. Critical Metals Handbook. Wiley-Blackwell, UK (454 pp.).

Hatch, G.P., 2012. Dynamics in the global market for rare earths. Elements 8, 341–346.

Hewitt, K., Wall, T., 2000. The Zinc Industry. Woodhead Publ. Ltd, Cambridge (UK), (218 pp.).

Jones, G.K., 1988. United States dependence on imports of four strategic and critical minerals: implications and policy alternatives. Boston Coll. Environ. Aff. Law Rev. 15, 217–294.

Kesler, S.E., Gruber, P.W., Medina, P.A., Keoleian, G.A., Everson, M.P., Wallington, T.J., 2012. Global lithium resources: relative importance of pegmatite, brine and other deposits. Ore Geol. Rev. 48, 55–69.

Kynicky, J., Smith, M.P., Xu, C., 2012. Diversity of rare earth deposits: the key example of China. Elements 8, 361–367.

Limbaugh, R.H., 2010. Tungsten in Peace and War, 1918–1946. Univ. Nevada Press, Reno, Nevada, (312 pp.).

Mao, J., Pirajno, F., Cook, N., 2011. Mesozoic metallogeny in East China and corresponding geodynamic settings — an introduction to the special issue. Ore Geol. Rev. 43, 1–7.

Mudd, G.M., Weng, Z., Jowitt, S.M., Turnbull, I.D., Graedel, T.E., 2013. Quantifying the recoverable resources of by-product metals: the case of cobalt. Ore Geol. Rev. 55, 87–98.

Polgári, M., Gutzmer, J., 2012. Manganese metallogenesis: introduction to the special issue. Ore Geol. Rev. 47, 1–4.

(Guest Editor)Schwarz-Schampera, U., 2006. Special issue on electronic metals. Ore Geol. Rev. 28 (146 pp.).

Shestakov, A.V., 2000. Economy and Law. (Encyclopedic Glossary) Dashkov & Co, Moscow, p. 568 (in Russ.).

Skirrow, R.G., Huston, D.L., Mernagh, T.P., Thome, J.P., Dulfer, H., Senior, A.B., 2013. Critical Commodities for a High-tech World: Australia's Potential to Supply Global Demand. Austral. Govern. Geosci. Australia, (118 pp.).

Speirs, J., Houari, Y., Gross, R., 2013. Materials Availability: Comparison of Material Criticality Studies — Methodologies and Results. UK Energy Research Centre, (30 pp.).

UK House of Commons, 2011. Strategically important metals. Fifth Report of Session 2010–12. House of Commons, London (146 pp.).

US DoD, 2013. Strategic and Critical Materials 2013 Report on Stockpile Requirements. Office of the Under Secretary of Defense, US Department of Defense (189 pp.).

US DoE, 2011. Critical Materials Strategy. US Department of Energy, (189 pp.).

Wu, J., 1993. Antimony vein deposits of China. Ore Geol. Rev. 8, 213–232.