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Minimum Concentrations of Critical Minerals for Exploration—How Good Is Good Enough?

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ABSTRACT

Disruption in critical minerals supply chains has resulted in the evaluation of various types of mineral deposits for critical minerals potential. Much of the study on critical minerals focuses on occurrence and characterization, but little research has addressed what concentrations of critical minerals in a mineral deposit are required to make an exploration target into an operating mine. Understanding the cut-off grades of ore deposits being actively mined is one criterion to determine if concentrations in an exploration target are high enough. Cut-off grade is defined as the minimum amount of mineral contained in a ton of ore that is sent to the processing plant. Among many factors, cut-off grade depends upon the size and type of the deposit and mining operation, the processing technique, and market prices. This research does not aim to define cut-offs for determining if a mineral deposit is economic. Rather, it defines estimates of concentrations of critical minerals that could be considered good enough for further exploration. For example, ~2% total rare earth oxide (TREO) is the cut-off grade for Mt. Pass carbonatite, but 500 ppm TREO could be an exploration target for coals.

INTRODUCTION

According to United States Geological Survey (USGS), a critical mineral is one that is essential to the economic well-being of a nation and whose supply may be disrupted due to geological, geopolitical, or environmental factors (Nassar et al., 2020). For example, rare earth elements (REEs) are critical to the production of electrical vehicles (EV) motors as well as wind turbines, yet the global share of China rose to over 95% in 2010 (IEA, 2021), since when its production quota has fallen to nearly 70% in 2023 (Statista, 2023). This and similar situations with many of the critical minerals raise deep global concerns about supply chain vulnerabilities (Bauer et al., 2011).

Critical minerals find uses in the production of renewable energy, electronics, agricultural products, and common household items (McLemore, 2020). As consumption and demand for critical minerals keep rising, efficient exploration strategies for assessing the viability of mineral deposits are necessary to ensure sustainable supply. One key approach is the application of cut-off grade as a fundamental concept in mineral exploration projects. Cut-off grade refers to the minimum concentration of minerals required to justify further exploration efforts based on factors such as, type and size mineral deposit, mining and processing technologies, associated by-products/co-products and the market price of these minerals.

Typically, economic cut-off grades are used to determine whether a mineral deposit can be mined profitably. However, this paper focuses on preliminary cut-off grades needed to establish whether critical minerals within a deposit are high enough to justify further exploration and detailed evaluations. By comparing mineral deposit grades, size, production and extraction technology, and other economic factors with established and active mines, exploration teams can estimate cut-off grades that justify further exploration.

CRUSTAL ABUNDANCE

Crustal abundance refers to the average concentration of an element within the Earth's crust. Concentrations of common elements may be expressed in percent, while trace elements are usually expressed in parts per million (ppm) or even parts per billion (ppb). In mineral exploration, crustal abundance values serve as way to compare how enriched or depleted a particular element is within the Earth's crust.

By comparing crustal abundance to an element's concentration within a deposit, exploration geologists can begin to set thresholds to identify anomalous targets. Such anomalies also suggest geological processes that concentrated these elements, forming potential mineral deposits (Moon et al., 2006). Table 1 and Figure 1 show the concentration of trace elements (ppm, except where noted) within the upper continental crust, compiled from Rudnick and Gao (2003), Hu and Ga o (2008), and Park et al. (2012).

CUT-OFF GRADE IN MINERAL EXPLORATION

Understanding the cut-off grades of mineral deposits being actively mined is one criterion to determine if concentrations in an exploration target is high enough. Unlike economic cut-off grade which determines whether a mineral deposit is profitable to mine, preliminary cut-off grade attempts to assess the potential viability of a mineral deposit in its exploration stage. This is necessary for exploration teams to determine whether to allocate more resources for further exploration work based on how the project compares with metrics from similar existing projects in active production.

DETERMINANTS OF CUT-OFF GRADE

The size (tonnage) of a mineral deposit plays a key role in defining cut-off grade. Large deposits will generally give more flexibility to mine lower grades due to economies of scale, which could make lower grade deposits with large tonnages economically viable. Conversely, small deposits require higher cut-off grades in ensuring profitability due to cost in mining and processing smaller volumes of ore.

Variations in mining and processing methods also affect cut-off grades of different mineral deposit types. Brine lithium deposits, such as Salar del Hombre Muerto in Argentina and Salar de Atacama in Chile, both contain lithium in saline groundwater, which generally rely on solar evaporation to concentrate lithium over time. Lithium-bearing pegmatites contain lithium as spodumene or other lithium minerals where traditional mining and processing techniques are required to exploit the deposit. Due to the lower cost associated with brine deposits, they generally have lower cut-off grades, ~200 mg/L (Zheng, MP, et al., 2023), while pegmatite lithium deposits require higher cut-off grades between 0.4% and 1.0% Li_2O (Patriot, 2023; SEC, 2023) due to high cost of mining and processing of the ore.

Additionally, the cut-off grade of a mineral deposit is affected primarily by the economic value of its associated by-products and co-products. For instance, niobium, uranium, or zirconium can be recovered as byproducts in some REE deposits. These byproducts tend to increase the profitability of the deposit and can reduce the cut-off grade of the primary REE. The Bayan Obo deposit is the world's largest REE resource and also contains iron and niobium as co-products. Revenues from the iron ore production ultimately subsidize the REE production cost, thereby reducing the economic burden on REE extraction (Castor & Hedrick, 2006)

METHODOLOGY

In determining the cut-off grade of critical minerals for further exploration work, a review of minerals deposits of active operating mines of either the same or similar types were conducted. These deposits were classified into three categories (low, medium, and high targets) based on their economic cut-off grades. The classification serve as benchmark for establishing thresholds for exploration cut-off grades. Exploration grade thresholds are set at least 90% of the lowest cut-off grade observed in operating mines of similar or comparable deposits. By benchmarking to known operating grades, this ensures exploration efforts align with realistic economic and operational standards thereby minimizing the risk of pursuing sub-economic grades (Rendu, 2014).

COMPARISON WITH EXISTING MINERAL DEPOSITS

In determining the exploration cut-off grade for critical minerals, it is essential to compare prospective deposits with known operating mines of either the same or similar deposits. This process of benchmarking will help set realistic expectations for determining cut-off grades reasonable enough to justify further exploration.

For instance, the Mountain Pass mine, which is among the most significant REE deposits in the world, is a carbonatite-hosted REE deposit with TREO cut-off grade between 2–3% (SEC, 2021) and an average grade of ~8% (NS Energy, 2020). The Bayan Obo deposit in China is the largest REE deposit in the world, accounting for about 70% of global REE production (Statista, 2023). It is also a carbonatite-hosted deposit with an average grade of ~5% TREO (Castor & Hedrick, 2006). While its TREO cut-off grade is not explicitly stated, it is expected to be lower than that of the Mountain Pass deposit. Comparatively, similar deposits with TREO cut-off grade around 1% may be considered significant, particularly when sustained by favorable recovery rates and large-scale operations.

Lithium deposits occur either as brine or pegmatite deposits whose concentration of lithium is usually reported as Li_2O% for pegmatite deposits or milligrams per liter (mg/L) in brine deposits. Salar de Atacama mine in Chile is one of the largest and highest-grade brine lithium deposit in the world with ~800 mg/L cut-off grade (SEC, 2023). According to a 2023 SEC pre-feasibility study for the Silver Peak lithium operation in Nevada, a cut-off grade of ~50 mg/L has been adopted for several lithium brine projects in North America. Setting an exploration cut-off grade of ~50 mg/L for a brine deposit could still be considered prospective, particularly with improved extraction technology.

The Greenbushes Mine in Australia, which is the largest and highest grade pegmatite lithium deposit has between 0.5–0.7% Li_2O (SEC, 2023). Similar projects with cut-off grades around 0.4% Li_2O might still be considered attractive for further exploration, depending on deposit size, mining and processing methods as well as other economic factors.

PRELIMINARY CONCLUSION

Incorporating established cut-off grade (as benchmarks) into mineral exploration strategies can enhance the effectiveness of target prioritization and increase the chances of successful mines. This approach can be achieved by categorizing deposits of active mines into low, medium, and high targets based on their cut-off grades, which provide a structured framework for exploration.

By regularly updating benchmarking data to reflect evolving market conditions, operational costs, and technological advancements, exploration grades can be set at 90% of the lowest cut-off grade of operating mines to ensure that potential deposits compares with operational thresholds.

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REFERENCES

[1] Bauer, D., Diamond, D., Li, J., Sandalow, D., Telleen, P., & Wanner, B. (2011). Critical materials strategy. U.S. Department of Energy.

[2] Castor, S. B., & Hedrick, J. B. (2006). Rare earth elements. *Industrial Minerals and Rocks: Commodities, Markets, and Uses*, 769–792.

[3] Hu, Z., & Gao, S. (2008). "Upper Crustal Abundances of Trace Elements: A Revision and Update." Chemical Geology, 253(3–4), 205–221.

[4] International Energy Agency. (2021). *The Role of Critical Minerals in Clean Energy Transitions*. Retrieved from https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

[5] McLemore, V.T. (2020), "Critical minerals in New Mexico; work needed to realize resources," Mining Engineering, v. 72, no. 2, pp. 31–31, https://me.smenet.org/abstract.cfm?preview=1&articleID=9501&page=31.

[6] Moon, C.J., Whateley, M.K.G., & Evans, A.M. (2006). *Introduction to Mineral Exploration*. Wiley-Blackwell.

[7] Nassar, N. T., Brainard, J., Gulley, A., Manley, R., Matos, G., Lederer, G., & Fortier, S. (2020). Evaluating the mineral commodity supply risk of the US manufacturing sector. Science Advances, 6(8), eaay8647.

[8] NS Energy. (2020). Mountain Pass Rare Earth Mine.

[9] Park, J., et al. (2012). "Chemical Composition of the Continental Crust as Revealed by Studies in East Asia." Geochemical Journal, 46(4), 297–312.

[10] Rendu, J. M. (2014). An Introduction to Cut-off Grade Estimation (2nd ed.). Society for Mining, Metallurgy, and Exploration.

[11] Rudnick, R. L., & Gao, S. (2003). "Composition of the Continental Crust." In The Crust (Vol. 3, pp. 1–64). Elsevier-Pergamon.

[12] SEC, 2021, Annual report pursuant to section 13 or 15(d) of the securities exchange act of 1934.

[13] SEC Technical Report Summary, Pre-Feasibility Study - Greenbushes Mine, Western Australia 2023.

[14] SEC Technical Report Summary, Pre-Feasibility Study - Salar de Atacama Región II, Chile, 2023.

[15] SEC Technical Report Summary, Pre-Feasibility Study – Silver Peak Lithium Operation- Nevada, USA dated February 14, 2023.

[16] Statista. (2023). Share of global rare earths production in China from 2016 to 2023. Retrieved from https://www.statista.com/statistics/1294393/share-of-global-rare-earths-production-in-china/.

[17] Zheng, MP., et al., (2023) Classification and mineralization of global lithium deposits and lithium extraction technologies for exogenetic lithium deposits. China Geology 6 (2023) 547–566.

[18] https://patriotbatterymetals.com/patriot-files-ni-43-101-technical-report-on-the-cv5-mineral-resource-estimate-corvette-property-quebec-canada/.

APPENDIX I

Table 1. Concentration of trace elements (ppm, except where noted) within the upper continental crust – compiled from Rudnick and Gao (2003), Hu and Gao (2008), and Park et al. (2012)

Element (ppm, unless noted)	Shaw et al. (1967, 1976)	Eade and Fahrig (1973)	Condie (1993)	Gao et al. (1998)	Sims et al. (1990)	Plank and Langmuir (1998)	Peucker-Eherenbrink and Jahn (2001)	Taylor and McLennan (1985, 1995)	Wedepohl (1995)	Rudnick and Gao (2003)	Hu and Gao (2008)	Park et al. (2012)	Recommended values (ppm)
Li	22			20				20		21	41		41
Be	1.3			1.95				3	3.1	2.1	1.9		1.9
B	9.2			28				15	17	17	47		47
N									83	83			83
F	500			561					611	557			557
S	600			309					953	621			621
Cl	100			142					640	370			370
Sc	7	12	13.4	15				13.6		14			14
V	53	59	86	98				107		97	106		106
Cr	35	76	112	80				85		92	73		73
Co	12		18	17				17		17.3	15		15
Ni	19	19	60	38				44		47	34		34
Cu	14	26		32				25		28	27		27
Zn	52	60		70				71		67	75		75
Ga	14			18				17		17.5	18.6		18.6
Ge				1.34				1.6	1.4	1.4	1.3		1.3
As				4.4	5.1			1.5	2	4.8	5.7		5.7
Se				0.15				0.05	0.083	0.09			0.09
Br									1.6	1.6			1.6
Rb	110	85	83	82				112	110	84	94		94
Sr	316	380	289	266				350		320			320
Y	21	21	24	17.4				22		21			21
Zr	237	190	160	188				190		193			193
Nb	26		9.8	12		13.7		12		12	11.6		11.6
Mo				0.78	1.2			1.5	1.4	1.1	0.6		0.6
Ru (ppb)							0.34			0.34		0.03	0.000003
Rh (ppb)												0.018	0.0000018
Pd (ppb)				1.46			0.52	0.5		0.52		0.526	0.0000526
Ag (ppb)				55				50	55	53			0.0053
Cd	0.075			0.079				0.098	0.102	0.09	0.06		0.06
In								0.05	0.061	0.056	0.066		0.066
Sn				1.73				5.5	2.5	2.1	2.2		2.2
Sb				0.3	0.45			0.2	0.31	0.4	0.075		0.075
Te											0.027		0.027
I									1.4	1.4			1.4
Cs				3.55		7.3		4.6	5.8	4.9			4.9
Ba	1070	730	633	678				550	668	624			624
La	32.3	71	28.4	34.8				30		31			31
Ce	65.6		57.5	66.4				64		63			63
Pr								7.1	6.3	7.1			7.1
Nd	25.9		25.6	30.4				26		27			27
Sm	4.61		4.59	5.09				4.5	4.7	4.7			4.7
Eu	0.937		1.05	1.21				0.88	0.95	1			1
Gd			4.21					3.8	2.8	4			4
Tb	0.481		0.66	0.82				0.64		0.7			0.7
Dy	2.9							3.5		3.9			3.9
Ho	0.62							0.8		0.83			0.83
Er								2.3		2.3			2.3
Tm								0.33		0.3	0.37		0.37
Yb	1.47		1.91	2.26				2.2		2	2.34		2.34
Lu	0.233		0.32	0.35				0.32		0.31	0.36		0.36
Hf	5.8		4.3	5.12				5.8		5.3			5.3
Ta	5.7		0.79	0.74		0.96		1	1.5	0.9	0.92		0.92
W				0.91	3.3			2	1.4	1.9	1.4		1.4
Re (ppb)							0.198	0.4		0.198			0.0000198
Os (ppb)							0.031	0.05		0.031			0.0000031
Ir (ppb)	0.02						0.022			0.022		0.022	0.0000022
Pt (ppb)							0.51			0.5		0.599	0.0000599
Au (ppb)	1.81			1.24						1.5			0.00015
Hg	0.096			0.0123					0.056	0.05			0.05
Tl	0.524			1.55				0.75	0.75	0.9	0.55		0.55
Pb	17	18	17	18				17	17	17			17
Bi	0.035			0.23				0.13	0.123	0.16	0.23		0.23
Th	10.3	10.8	8.6	8.95				10.7		10.5			10.5
U	2.45	1.5	2.2	1.55				2.8		2.7	2.6		2.6

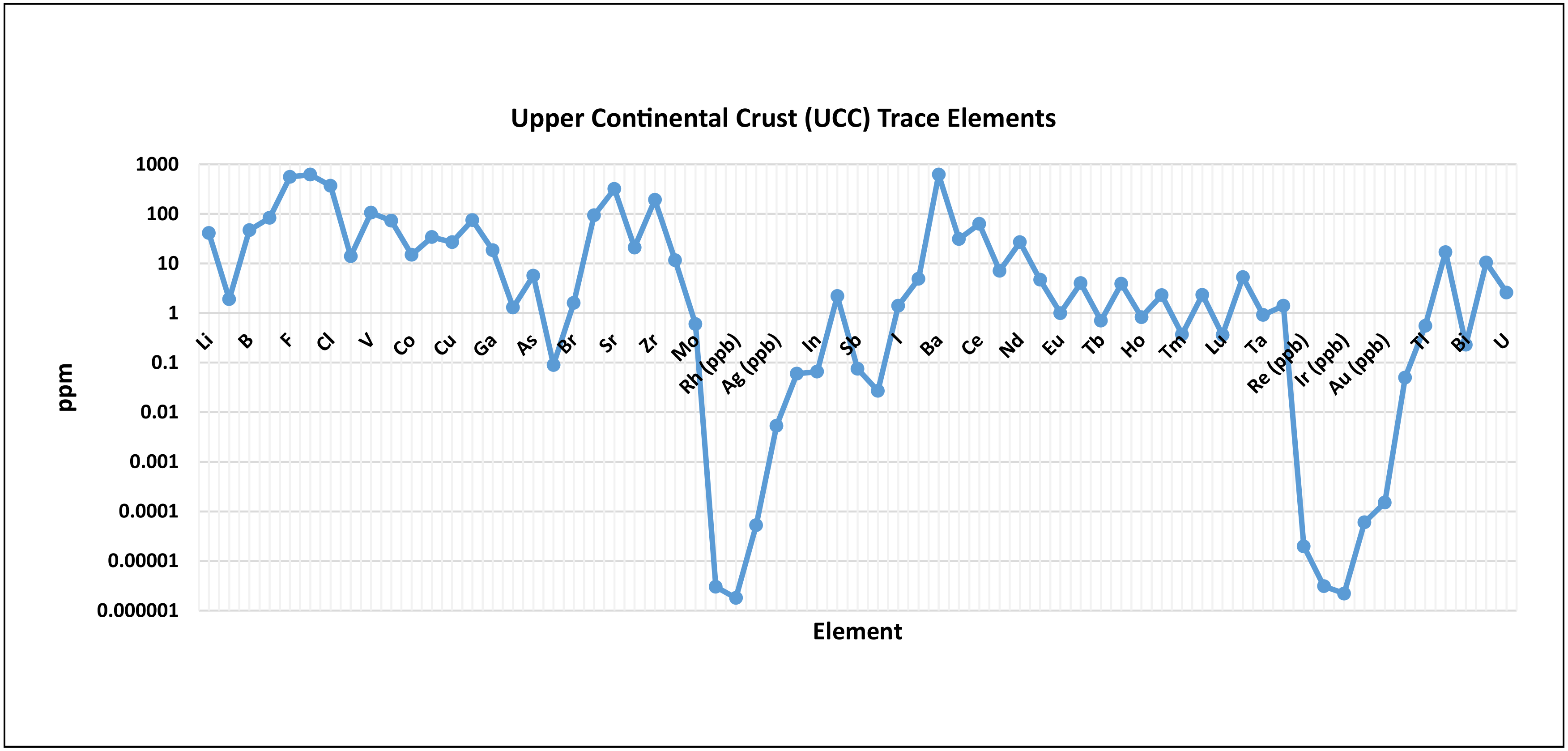

Figure 1. Graphical plot showing concentration of trace elements (ppm, except where noted) within the upper continental crust – compiled from Rudnick and Gao (2003), Hu and Gao (2008), and Park et al. (2012)