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Vanadium as a critical material: economic geology with emphasis on market and the main deposit types

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ABSTRACT

Vanadium is currently considered a critical material in the European Union, the U.S.A., and other jurisdictions. The vanadium mine production for 2021 is estimated at more than 120 000 tonnes; however, the market base is expected to grow rapidly due to the increase in the use of vanadium for redox flow batteries. Currently, world-wide, many projects are in the advanced stages of exploration and development. In the longer term, should vanadium cease to be a critical material and the law of supply and demand applies, the marginal mines will be decommissioned, and the best deposits will remain economic. Depending on the prevailing regulations in specific jurisdictions, geological settings, and the most up-to-date metallurgical research results, the main vanadium deposit types that could be considered as potential exploration and development targets are the vanadiferous titanomagnetite deposits, sandstone-hosted uranium-vanadium deposits (Salt Wash category), shale-hosted vanadium deposits, and base metal-related vanadate deposits. However, placer deposits, surficial uranium-vanadium type mineralisation, and the Minas Ragra type patrónite deposits should also be considered.

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Vanadium; vanadiferous titanomagnetite; ore deposit; uranium; shale-hosted; vanadate; critical; battery



Introduction

We are living through tumultuous, and exciting times that represent extraordinary promotional opportunities for exploration and mining companies targeting materials required for reduction of greenhouse gas emissions by reducing our reliability on fossil fuels (Simandl et al. 2021). Vanadium is one of those materials. It belongs to the categories of ‘critical materials’ and ‘battery materials’ (U.S. Department of the Interior 2018 and European Commission 2020) and is predicted to benefit from high market growth projections because of its use in vanadium redox flow batteries (VRFBs) (Hund et al. 2020). Consequently, it is receiving a lot of attention from the exploration industry, governments, and the public. Since vanadium is also a ‘specialty material’ (i.e. global production does not exceed 200 000 tonnes per year), it is essential to consider the size of market base and the structure of the supply chain before and during the planning of exploration and development activities (Simandl et al. 2021). Environmental aspects and the circular economy are increasingly being considered (e.g. Kinnunen et al. 2022) and will have an increasing impact on the evaluation and planning of future projects. The high rate of anthropogenic enrichment of vanadium in the environment was brought forward by Watt et al. (2018). Of all the trace elements,

vanadium has the highest and 4th highest anthropogenic enrichment factor in the atmosphere and global rivers, respectively (Viers et al. 2009; Schlesinger et al. 2017). At least partly because of this, and the increasing use of vanadium, most major jurisdictions, including the EU, U.S.A., and China are giving the environmental impacts of vanadium extra attention. For example, in the U.S.A., vanadium is one of the substances remaining on the fifth Contaminant Candidate List (CCL 5) issued by the United States Environmental Protection Agency (EPA) on July 19, 2021 (EPA 2021). The CCL identifies selected contaminants that are currently not subject to any national primary drinking water regulation but are known to occur in public water systems. These contaminants (including vanadium) may require future regulation under the Safe Drinking Water Act.

White and Levy (2021) touched upon the main sources of the vanadium released into the environment (mainly steel coproduction, 75%; crude oil processing related, 10%; and mining <10% of the total).

Today, approximately 88% of vanadium is produced from vanadiferous titanomagnetite ores (Rappleye and Haun 2021) including iron- and steel-slugs, which represent more than 69% of the starting raw material in vanadium production (Lee et al. 2021). Historically, vanadium was also extracted

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from uranium-vanadium sandstone-hosted deposits in the U.S.A. and is currently, or was recently, extracted from related tailings solutions (Energy Fuels Inc. 2019). Combustion residues such as fly ash from coal-fired electricity generation plants (Sahoo et al. 2016; Rappleye and Haun 2021), fly ash from oil combustion (e.g. Navarro et al. 2007), and residues from crude oil refining and processing, represent examples of alternative vanadium sources. More research effort has recently been allocated to recovering vanadium from tailings and recycling (Wang et al. 2019; Petranikova et al. 2020) and to produce very high purity vanadium for specialised (niche) applications by electron beam melt refining of V–Al Alloys (Rappleye and Haun 2021).

The main objectives of this paper are to introduce the reader to the economic geology of vanadium and most importantly, discuss a selection of ore-deposit types as potential contributors to the future vanadium supply chain (as potential exploration and development targets). We achieve this by: (a) presenting background information on vanadium (physical, environmental, technical, political, criticality, market/use, and circular economy aspects; and (b) identifying potential exploration targets (deposit types).

Resources, uses, and market

Vanadium is the 22nd most abundant element in the continental crust and it accounts for approximately 0.014% of it (Rudnick and Gao 2003); however, concentrations of at least an order of magnitude higher, and preferably two orders of magnitude higher are required for the economic recovery of vanadium from ore deposits. Global vanadium resources and reserves are estimated at over 63 million tonnes and 22 or 24 million tonnes, respectively (*sensu* USGS; not according to NI-43-101, or JORC guidelines; Polyak 2021, 2022). The global annual mine productions for 2020 and 2021 are estimated at more than 105 000 tonnes and 110 000 tonnes of vanadium content, respectively (Polyak 2022). According to Polyak (2022), most of the known reserves, *sensu* USGS, occur in China (9.5 million tonnes), Australia (6 million tonnes), Russia (5 million tonnes), and South Africa (3.5 million tonnes). Many countries do not collect relevant data. For example, Canada, which is not recognised for its vanadium endowment, has more than 20 prospects and exploration/development projects where vanadium is listed either as the main product or co-product.

Currently, vanadium is used mainly as an alloying agent for iron and steel (>80%) with major market segments in the automotive and construction industries, as a titanium alloy additive, as a catalyst in sulphuric acid production, in battery applications (mainly VRFBs), and in other specialised applications (Polyak

2021). Manganese, Mo, Nb, Ti, and W may replace vanadium to some extent as alloying elements in iron and steel, while Pt and Ni can replace vanadium in applications where it is used for its catalytic properties. No good substitute is currently available for vanadium used in the production of aerospace titanium alloys (Polyak 2021). The VRFBs are used mainly in renewable energy storage where the energy density is not of prime importance and long lifespan and relative safety are required. Should shortage of high purity vanadium feedstock for VRFBs occur, other existing and developing technologies would become potential substitutes (Simandl et al. 2021); however, in short term, this is unlikely. Even under current market conditions, VRFBs are competing in renewable energy storage domain with other technologies such as pumped hydroelectric storage, compressed air energy storage, lead-acid, sodium-sulphur, and lithium-ion batteries (da Silva Lima et al. 2021).

Vanadium resources are not geographically constrained; however, the production of vanadium is. In 2020, China (61.6%), Russia (20.9%), South Africa (9.5%), and Brazil (7.7%) accounted for nearly all global vanadium production (Polyak 2021). It is notable that most vanadium is currently obtained as a byproduct from slags created during iron and steel production. This is likely to continue in the foreseeable future based on resource availability, metallurgical, environmental constraints, and the increasing importance of a circular economy.

Historic variations in global mine production and V_2O_5 prices are shown in Figure 1(a,b), respectively. The gradual build-up of vanadium mine production from 1994 to 2003 resulted in an oversupply (Figure 1(a)). The reduction in global vanadium output in 2003 and 2004 reflects closures of the Windimura mine (Australia) and the Vantec mine (South Africa). The resumption of electric power shortages in South Africa (2008) and global economic downturn of 2009 resulted in a decrease in production. This was followed by a gradual increase in production from 2010 to 2014. The 2015 production drop reflects the closure of a major South African iron mine and closures of related vanadium-producing facilities in South Africa and Austria. A few Chinese vanadium producers had to shut down in 2017 following a series of environmental inspections. Updated regulations regarding high-strength steel in China were announced in February 2018; however, it appears that these regulations were not uniformly enforced across China (Polyak 2020), so the increase in demand for vanadium was less abrupt than originally anticipated. Years 2019 and 2020 were marked by an increase in production capacity in Brazil (Maracas Menchen Mine), and the reopening of the Vametco mine in South Africa (Bushveld Minerals Ltd.) and related production facilities.

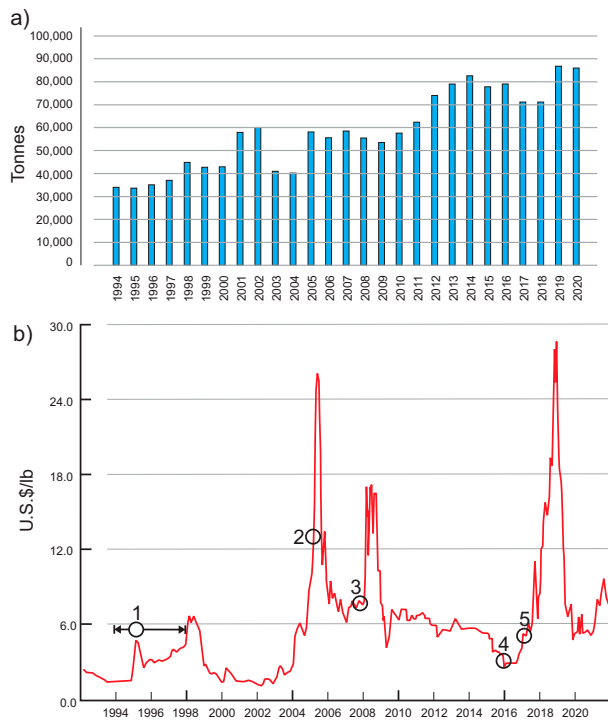


Figure 1. Global vanadium mine production and prices. (a) Vanadium mine production (tonnes of contained vanadium) from 1994 to 2020. Data compiled from the USGS yearly commodity summaries. (b) Variation in prices of V_2O_5 from 1992 to 2021. Event 1 (Ev 1) – liquidation of the V_2O_5 from the U.S.A. strategic stockpiles; Ev 2 – Chinese vanadium steel standards are introduced; Ev 3 – rationing of electricity in South Africa reduces vanadium availability; Ev 4 – EVRAZ Highveld Steel and Vanadium Ltd. (S.A.) placed into receivership; Ev 5 China revises its standards for the tensile strength of rebar products – speculators expect vanadium shortages. Source of data: Vanadium Price.com (2021).

Because vanadium belongs to ‘specialty’ and ‘critical’ material categories (Simandl et al. 2021), the ferrovanadium and V_2O_5 prices are subject not only to variations reflecting the strength of the global economy, but also to wild fluctuations related to electric power shortages and weather conditions in vanadium producing regions, liquidations of stockpiles by major industrialised countries, shutdowns of individual production facilities, changes in government construction policies, levels of enforcement of environmental regulations, and a variety of other supply risks (Figure 1 (b)). The ferrovanadium price fluctuations show the same pattern as V_2O_5 .

Market projections

The Roskill (2021) report for 2021–2030 indicates that in the short term, the vanadium market is set to tighten as China’s plants (those that are recovering vanadium from iron- and steel-slags) are running close to capacity. Numerous vanadium projects are at the planning stage or are currently under

development. However, in the short term, outside of China and Russia, the increase in vanadium production is expected to come primarily from AMG Vanadium LLC’s new facility in Ohio, U.S.A., and from Bushveld Mineral’s Vametco operation, which is gradually increasing its production in South Africa. According to Roskill (2021), the use of vanadium as an alloying agent in steel will continue to dominate the market because of rising vanadium consumption in steel applications by emerging countries. There are also expectations of growing demand from the energy storage sector due to increased use of VRFBs (Hund et al. 2020; Roskill 2021; Simandl et al. 2021), and from the aerospace industry as it recovers from the impacts of the COVID-19 pandemic. These latter two applications are expected to generate an increase in demand for high-purity vanadium oxides (V_2O_5 or V_2O_3). New development projects are unlikely to significantly contribute to vanadium supply before 2024; however, the new International Maritime Organization’s marine fuels regulation (which requires the reduction of sulphur content of ships’ fuel from 3.5% to 0.5%) is likely to create a new source of low-cost supply coming from oil spent catalysts (Roskill 2021). In the longer term, the study commissioned by the World Bank Group suggests that in 2050, the vanadium demand from the energy industry alone will represent between 175% and 250% of the 2019 global vanadium production (figure 4.3 in Hund et al. 2020). The study by International Energy Agency (2021) appears more conservative regarding commercialisation progress of VRFBs than the World Bank’s study by Hund et al. (2020). Such differences in projections are not unexpected, and there is a need to continuously keep in mind ever increasing levels of research, uncertainty associated with commercialisation, competing technologies, and the fact that a single major technological breakthrough could completely invalidate any long-term market projection in this domain (Simandl et al. 2021).

Main vanadium-bearing ore deposits

Four main deposit types from which vanadium was historically extracted, are currently produced from, or may be recovered from in the future are: (1) vanadiferous titanomagnetite (Figure 2(a)), (2) sandstone-hosted uranium-vanadium, (3) shale-hosted vanadium, and (4) vanadate deposits (Kelley et al. 2017; Brough et al. 2019). More detailed information for these four main vanadium-bearing deposit types, together with relevant examples are provided in the next four subsections. Remaining deposit types are described briefly in the section entitled “other deposit types”.

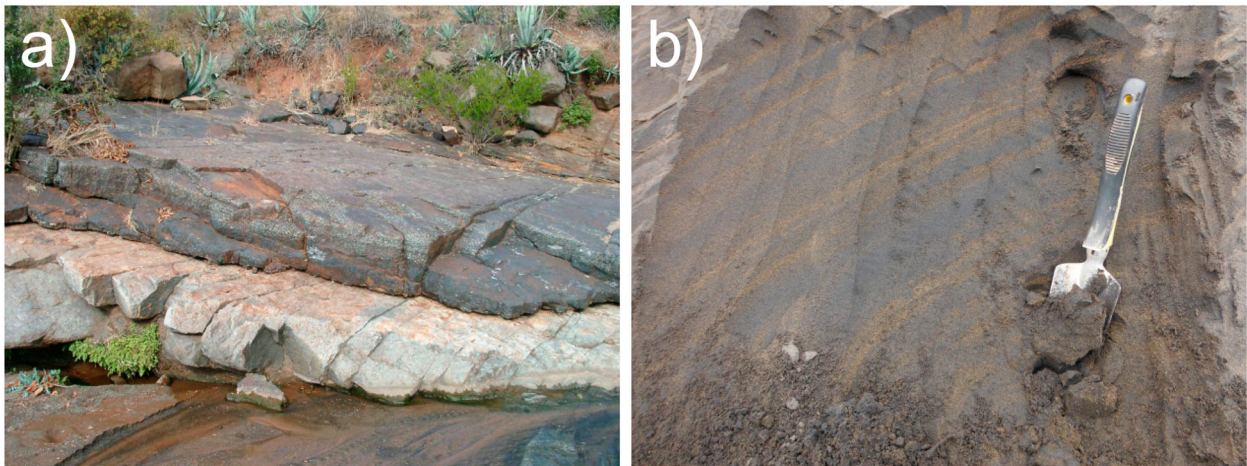


Figure 2. Vanadiferous titanomagnetite mineralisation; (a) Magnetite Layer 1 (dark), approximately 30 cm thick, 2 m above the Main Magnetite Layer, Eastern Bushveld igneous complex, South Africa; photo curtesy of Paul, A.M. Nex; University of the Witwatersrand, South Africa. (b) Mine face exposing vanadiferous titanomagnetite (dark) in dune foreset bedding in the Waiuku Black-sand Member; scoop for scale; photo courtesy of Anthony B. Christie, GNS Science.

Vanadiferous titanomagnetite deposits

Vanadiferous titanomagnetite deposits currently account for the bulk of raw materials for global vanadium production (Zhao 2002; Li et al. 2011; Gao et al. 2018). These orthomagmatic deposits (Figure 2(a)) are commonly hosted by, or associated with, layered mafic-ultramafic-igneous intrusions. Such intrusions are preferentially located in cratonic geotectonic settings (Maier et al. 2013) and there appears to be a broad geological time correlation between the ages of layered intrusions and amalgamation, and the breaking-up of the supercontinents (Smith and Maier 2021). Vanadiferous titanomagnetite sands (Figure 2(b)) are considered separately in the section entitled "other deposit types".

A recent compilation of mafic-ultramafic layered intrusions worldwide (Smith and Maier 2021) indicates that from 565 inventoried intrusions, 74 contain stratiform Fe–Ti–V mineralisation and some also contain stratiform PGE reef-style mineralisation (107), Ni–Cu–(PGE) mineralisation (138), and/or chromitite seams (≥ 35), and several apatite deposits. While most of vanadium-bearing, titaniferous mineralisation in layered intrusions is concordant, discordant bodies are also known (e.g. Kennedy's Vale discordant body in the Bushveld Complex; Scoon et al. 2017).

Selected examples of intrusions containing significant vanadiferous titanomagnetite deposits are the Bushveld layered complex (Figure 2(a), Table 1), South Africa (Willemse 1969; Reynolds 1985; Tegner et al. 2006), Panzhihua and Hongge intrusions, China (Zhou et al. 2005; Bai et al. 2012; Bai et al. 2021), Lac Doré, Québec (Girard and Allard 1998; Arguin et al. 2017; Mathieu 2019), Bell River layered intrusion, Quebec (Taner et al. 2000), Rio Jacaré mafic-ultramafic intrusion (hosting the Maracás

Menchen Mine; Largo project), Brazil (Rodriguez et al. 2017), and the Koillismaa Intrusion (hosting the historical Mustavaara V–Fe–Ti mine), Finland (Karinen 2010; Taipale 2013).

Stratiform Fe–Ti–V oxide mineralisation is commonly located in the upper, more fractionated portions of mafic-ultramafic layered intrusions (e.g. Bushveld complex: Cawthorn and Molyneux 1986; Hughes et al. 2021; Smith and Maier 2021). However, this is not always the case. For example, the Rio Jacaré layered intrusion (Brazil) is reported to contain three Fe–Ti–V orebodies; two of them in the upper portion of the intrusion, and the third one in the lower portion of the intrusion (Sá et al. 2005).

The number, size, thickness, and grade of individual Fe–Ti–V layers vary from one intrusion to another and even within individual intrusions. For example, 16 Fe–Ti–V layers have been identified in the northern limb of the Bushveld complex (Barnes et al. 2004), and up to 26 layers were recognised in the eastern and western limbs of the same intrusion (Cawthorn and Molyneux 1986; Tegner et al. 2006). The oxide layers vary in thickness from few centimetres to >10 metres, some of them consisting almost entirely of vanadiferous titanomagnetite and ilmenite, whereas others contain substantial proportion of silicates (e.g. plagioclase and pyroxene) and anorthosite xenoliths. The Main Magnetite Layer (4th layer from the bottom in the eastern limb) is 1–2 m thick and historically accounted for more than half of the global vanadium yearly production (Crowson 2001). The magnetite layer 21 can reach a thickness of 60 m but is generally in the order of 10 m in thickness (Maier et al. 2013).

In contrast, at the Mustavaara Mine within the Koillismaa Intrusion (Finland), the 80 m thick mineralised zone was subdivided (based on grade) into 'lower layer' (5 m thick; 20–35 wt-%

Table 1. Grade and tonnage of selected vanadiferous titanomagnetite deposits. Other relevant information is provided where available; see the text for discussion.

Deposit	Country	Stage	Resources/reserves*					Magnetite concentrate			References
			Type	Tonnage (Million tonnes)	Grade (% V ₂ O ₅)	Grade (% TiO ₂)	% Fe ₂ O ₃	Magnetite (%)	% V ₂ O ₅	% TiO ₂	
Maracás Menchen Mine	Brazil	Production	Measured & Indicated	63.69	0.8	8.21	N.A.	24	2.46	3.26	Largo Inc. (2021)
Vametco	South Africa	Production	Indicated & Inferred Reserves (probable)**	184.2	0.78	–	–	35	1.98	–	MSA Group (2021)
				46.4	–	–	–	28.4	2.02	–	Bushveld Minerals (2021)
Brits	South Africa	Plan/Dev	Indicated & Inferred	66.8	0.56	–	–	29.87	1.58	–	Whitley et al. (2019)
Mokopane project	South Africa	Plan/Dev	Indicated & Inferred Reserves**	284.8	0.68	5.4	34.8	–	–	–	Croll et al. (2016)
				28.5	1.41	–	–	–	1.75	–	Bushveld Minerals (2021)
Mount Peake	Australia	Plan/Dev	Measured, Indicated & Inferred	160	0.28	5.3	32.9	–	–	–	TNG Limited (2017)
Speewah	Australia	Plan/Dev	Measured, Indicated & Inferred	4712	0.3	3.3	21	–	–	–	King River Resources Limited (2021)
Gabanimtha (Australian Vanadium Property)	Australia	Plan/Dev	Measured, Indicated & Inferred	239	0.73	8.9	47.3	–	–	–	Australian Vanadium Limited (2021)
Gabanimtha (Technology Metals Property)	Australia	Plan/Dev	Measured, Indicated & Inferred	109.5	0.8	10.1	55.6	–	–	–	Technology Metals Australia Limited (2021a)
			Reserves (proven & probable)	29.6	0.88	–	–	–	–	–	
Yarrabubba	Australia	Plan/Dev	Indicated & Inferred	27.7	0.9	9.9	55.3	–	–	–	Technology Metals Australia Limited (2021b)
Lac Dore	Canada	Plan/Dev	Measured & Indicated	215	0.4	7.1	38.8	24.6	1.3	8.7	Longridge and Martinez (2020)
Bell River (Mont Sorcier)	Canada	Plan/Dev	Indicated	113.5	–	–	–	30.9	0.6	1.2	Voyager Metals Inc. (2021)
			Inferred	953.7	–	–	–	32.8	0.6	–	
Mustavaara	Finland	Past producer / Plan/Dev	Measured & Indicated	103.7	–	–	–	15.36	1.6	6.1	Seppä et al. (2021)
Windimurra	Australia	Past producer / Plan/Dev	Measured, Indicated & Inferred	209	0.5	–	–	–	–	–	Atlantic (2021)
			Reserves probable**	87.5	0.49	–	–	–	–	–	
Balla Balla	Australia	Plan/Dev	Measured, Indicated & Inferred	455.9	0.64	13.7	63.9	–	0.8	14.3	Forge Resources Ltd (2011)
			Reserves proven & probable**	229	0.62	13.8	–	–	–	–	
Barrambie	Australia	Plan/Dev	Indicated & Inferred	280.1	0.44	9.18	–	–	–	–	Neometals (2018)

* Resources unless otherwise stated.

** these reserves are or may be included in resource tonnage provided above.

ilmenomagnetite), the ‘middle layer’ (15–50 m thick; 10–15 wt-% ilmenomagnetite), the upper layer (10–40 m thick; 15–25 wt-% ilmenomagnetite) and the upper-most ‘disseminated layer’ (<10 wt-% ilmenomagnetite). The term ‘ilmenomagnetite’ refers here

to vanadiferous titanomagnetite containing fine ilmenite exsolutions (Karinen et al. 2015).

Vanadium is produced either directly from titanomagnetite ores and concentrates, or from the vanadium-enriched slags created by Fe or Ti

extraction from smelting titanomagnetite ores (Gilligan and Nikoloski 2020). Vanadiferous titanomagnetite accumulation typically contain from 0.1 or 0.2% to 1% V_2O_5 (Cawthorn et al. 2005; Kelley et al. 2017), but in some cases their V_2O_5 content is higher. For example, the Highveld Steel and Vanadium Corp's past producing deposit, part of the Bushveld complex, had an average grade of 54.3% Fe, 1.6% V_2O_5 and 14.2% TiO_2 (Taylor et al. 2006). Examples of grade and tonnage of selected vanadium-bearing titanomagnetite deposits with an established production track record or in an advanced stage of development are listed in Table 1.

Considering the V_2O_5 contents of the ore only, and neglecting related parameters, such as the vanadiferous magnetite content of the concentrate that can be successfully produced from the ore and the V_2O_5 content of the vanadiferous magnetite (mineral itself) during the relative ranking of these deposits, can lead to misleading or wrong conclusions.

Furthermore, in some of the deposits, V_2O_5 content of the vanadiferous magnetite grains is nearly constant, whereas in other deposits, non-negligible variations are observed depending on the sample location within the orebody.

When V_2O_5 content of titanomagnetite concentrate exceeds 1 wt-%, direct vanadium extraction could be considered (Gao et al. 2022). When V_2O_5 in the concentrate is below 1 wt-%, in a number of cases, vanadium can be economically extracted from the slag after iron is recovered. The V_2O_5 content of such slag may exceed 10% (Gao et al. 2018); however, commonly it is substantially lower. Thus, vanadium is, or potentially could be, directly recovered from Maracás Menchen Mine, Vametco, Brits, Lac Doré, and Mustavaara deposits, while Bell River deposit is a potential source of iron with the possible recovery of vanadium from related slag (Table 1). Serious efforts are underway, in the name of circular economy, to develop flux-less extraction methods that would lead to the recovery of all three valuable commodities (Fe, Ti, and V) from vanadiferous titanomagnetite ores (e.g. Geldenhuis 2020; Geldenhuis et al. 2020).

The origin of Fe–Ti–V deposits is still debated. A recent review paper on the possible origin of Fe–Ti–V layers (e.g. Figure 2(a)) subdivided proposed layer-forming processes into dynamic (syn-magmatic, hydrodynamic, and late- to post-magmatic) and non-dynamic (related to fluctuations in temperature, pressure, and oxygen fugacity, etc.) (Namur et al. 2015; Smith and Maier 2021). Bai et al. (2021) indicate that some of these deposits, such as the Hongge intrusion (35% Fe–Ti–V oxides) in southwest China, may have a different origin. According to Bai et al. (2021), these Fe–Ti–V oxide deposits formed in feeder conduits (open system) to large igneous provinces,

where the silicates cotectic with Fe–Ti–V oxides occur as phenocrysts in basalts. However, a detailed discussion on this topic is largely outside the scope of this paper.

Because many mafic-ultramafic intrusions hosting classical Fe–Ti–V deposits also contain significant chromite, PGE, Ni, Cu, Co, apatite and other resources (e.g. Von Gruenewaldt 1993; Naldrett et al. 2012; Maier et al. 2013; Prevec 2018; Smith and Maier 2021), such intrusions represent geological environment with an exceptional multi-commodity exploration potential.

Sandstone-hosted uranium-vanadium deposits

Sandstone-hosted uranium deposits represent an important source of uranium and some of them are enriched in Au, Cr, Mo, Re, Sc, Se, Te, and V (International Atomic Energy Agency 2018). Globally, there are more than 1560 known sandstone-hosted uranium deposits, and deposits have been identified on all continents (International Atomic Energy Agency 2018). Sandstone-hosted uranium deposits are subdivided into (i) basal channel (173), (ii) tabular (~880), (iii) roll front (457), (iv) tectonic-lithologic feature associated (32), and (v) related dykes/sills in Proterozoic sandstones (10) (International Atomic Energy Agency 2009, 2018, 2020; Abzalov 2012). Most tabular uranium deposits are Palaeozoic to Cenozoic in age (International Atomic Energy Agency 2020) and can be subdivided into (a) continental fluvial, uranium associated variety with intrinsic reductant, (b) continental fluvial, uranium associated variety with extrinsic bitumen (commonly referred to as 'Grants District' category), and (c) continental fluvial vanadium-uranium variety, commonly referred to in literature as 'Salt Wash' category (International Atomic Energy Agency 2018). The details of the genesis of sandstone-hosted deposits are beyond the scope of this study; however, for the most recent review covering key mineralisation controls, the reader is referred to Cuney et al. (2022).

The deposits of the Salt Wash category have higher vanadium contents than other sandstone-hosted uranium deposits, including Grants subtype deposits (Northrop et al. 1990; International Atomic Energy Agency 2009, 2018, 2020). Consequently, vanadium has been recovered from several deposits belonging to this category as a primary product, or as a co-product of uranium (Hansley and Spirakis 1992; Dahlkamp 2010; Kelley et al. 2017; Barton et al. 2018a).

The Salt Wash category is named after the Salt Wash member of the Morrison Formation within the Paradox Basin, Colorado, U.S.A., which is hosted in selectively reduced (grey) continental fluvial sandstones within a sequence of continental red bed (oxidised) sediments. Distribution of vanadium-uranium

mineralisation is mostly controlled by detrital carbonaceous (reducing) material and paleo-permeability and porosity within the sandstones. Individual, reduced, grey, organic material-rich zones enveloping vanadium-bearing zones are from 500 m to 4 km long, 50–300 m wide and up to 20 m thick. Vanadium-uranium deposits within these reduced zones are smaller and typically range from 100 to 500 m in length, 10–50 m in width, and 1–10 m in thickness (International Atomic Energy Agency 2009). Mineralisation commonly impregnates the sandstone matrix (Figure 3(a,b)) forming irregularly shaped lenticular masses oriented parallel to the bedding and following depositional trend within reduced (grey, lesivated) sediments. Consequently, the reserves of individual deposits rarely exceed 1 million tonnes of ore and are commonly much less (e.g. George R. Simpson and Gloria Emerson mines, Arizona; Chenoweth 2018). According to International Atomic Energy Agency (2018, 2020), individual deposits may contain from 1 to 2000 tonnes U grading 0.05–0.50% U, but the high vanadium content historically made these deposits attractive exploration and development targets. Vanadium-uranium weight ratios for the mineralisation of Salt Wash category range from 1:1 to 20:1 (Dahlkamp 2010) and deposits with the best potential for vanadium recovery generally exceed 1% V₂O₅ and some may have grades exceeding 2.5% V₂O₅ (Kelley et al. 2017). Because of large variations in grade and tonnage and in the vanadium-uranium ratio, and because several high-grade deposits of this type were artisanally-mined and records are not well preserved, Table 2 represents the most convenient way to show that under favourable conditions this deposit type may represent a viable exploration target. This table summarises the vanadium and uranium productions from Salt Wash member of the Morrison Formation within the Paradox Basin by district and indicates that uranium price may be a significant factor determining the desirability of this deposit type as a vanadium exploration/development target.

The ore mineral assemblage in unoxidised mineralised zones consists mainly of uraninite (UO₂), coffinite [U(SiO₄)_{1-x}(OH)_{4x}], vanadian illite-smectite, roscoelite [K(V³⁺, Al)₂(AlSi₃O₁₀)(OH)₂], vanadian chlorite, montroseite [(V³⁺, Fe³⁺)O(OH)] and doloresite [V₃⁴⁺O₄(OH)₄] (Meunier 1994; Shawe 2011). Where mineralised zones came into contact with oxidising meteoric waters, the original uranium mineralogy was at least partially converted to secondary uranium-vanadium bearing minerals (Chenoweth 1981; Shawe 2011) such as carnotite [K₂(UO₂)₂(VO₄)₂·3H₂O], tyuyamunite [Ca(UO₂)₂(VO₄)₂·6(H₂O)] and pascoite [Ca₂Ca(V₁₀O₂₈)·17H₂O]. Vanadium-bearing clays, chlorite, and micas are the main vanadium minerals in both oxidised and unoxidised portions of Salt Wash category deposits.

Most of the well-documented examples of vanadium-uranium deposits where vanadium was/is recovered are in the Paradox Basin (Hansley and Spirakis 1992; Barton et al. 2018a) as summarised in Table 2. The Bigryli tabular sandstone-hosted U–V deposit, Ngalia Basin, Central Australia has also received significant attention (Schmid et al. 2020). The source of uranium in these deposits is widely accepted as originating from the leaching/weathering of igneous rocks; however, the timing of vanadium mineralisation, its source, and the nature of the mineralizing process, are still open for debate (Barton et al. 2018a, 2018b; Schmid et al. 2020).

The methods for extraction of vanadium and uranium from the Salt Wash category deposits are relatively well established and process flow charts from the cold war era are in the public domain (e.g. Merritt 1971; International Atomic Energy Agency 1993; Gao et al. 2022 and references herein). Where geological and hydrological conditions are appropriate, vanadium could also be recovered as a uranium co-product by *in-situ* leaching technologies assuming that it is environmentally acceptable (International Atomic Energy Agency 2001). Since 2018, the Energy Fuels' White Mesa Mill (U.S.A.) was producing vanadium from solutions related to historic tailings (International Atomic Energy Agency 2020). However, it appears that all byproduct vanadium production in Utah ceased in early 2020 and was not restarted in 2021 (Polyak 2022).

Shale-hosted vanadium deposits

Black shales and bitumen contained within them are known to host anomalous concentrations of a variety of trace metals (Lewan and Maynard 1982; Huyck 1989; Hulbert et al. 1992; Coveney 2003; Jowitt and Keays 2011; Johnson et al. 2017; Gadd et al. 2019, 2020). Highly metalliferous black shales (HMBS), also known as hyper-enriched black shales (HEBS), are enriched in organic carbon and trace metals (e.g. Ni, Se, Mo, Ag, Au, Zn, Cu, Pb, V, As, Sb, Se, P, Cr, and U ± PGE) relative to common black shales (Johnson et al. 2017). These authors defined HMBS as shales where $\sum \text{Mo} + \text{Ni} + \text{Zn} + \text{Se} + \text{V} > 1500$ ppm. In comparison, the $\sum \text{Mo} + \text{Ni} + \text{Zn} + \text{Se} + \text{V}$ for world average shale and average black shale are 280 and 434 ppm, respectively. According to this definition, globally, less than 5% of all known black shale stratigraphic units can be referred to as HBMS. The total organic carbon content of HMBS varies from 2 to 55 wt-%, averaging ~10 wt-%, and their high S (1–10 wt-%) and P (500 ppm to 2 wt-%) contents overlap the upper limit of the black shale range (Johnson et al. 2017).

The elevated trace metals may have been introduced into HMBS through a variety of processes

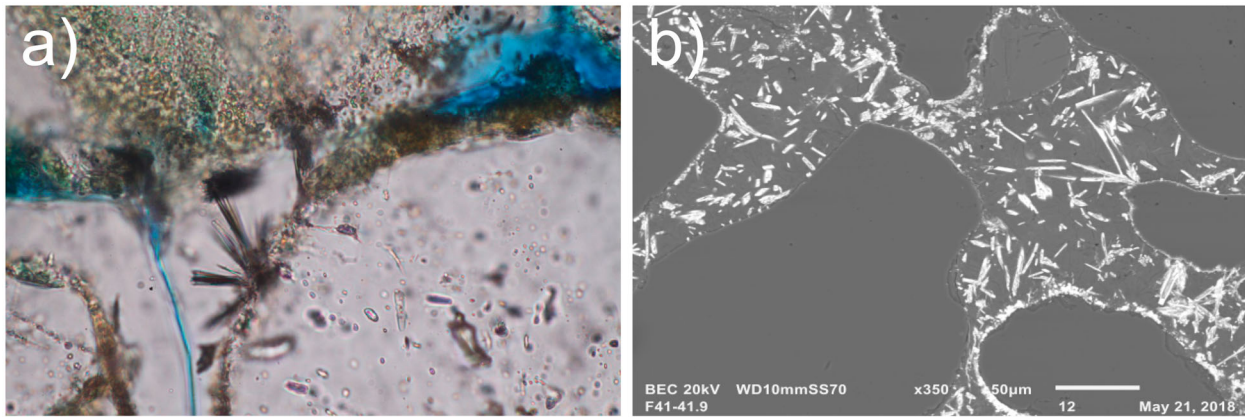


Figure 3. Salt Wash type vanadium-uranium deposit textures; (a) Montroseite needles growing on detrital quartz grain and forming inclusions in its euhedral overgrowth, 50× magnification, conoscopic light; vertical dimension of the photo is 150 microns; (b) Mixed montroseite and uraninite needles (possibly uvanite) in a matrix of vanadinite needles, backscattered SEM image (from Barton et al. 2018a).

including detrital fraction related to continental weathering; trace metals assimilated by organisms which after their death accumulated in favourable reducing depositional settings; authigenic, seawater-derived metals incorporated into shales during diagenesis under redox conditions; interaction of metal-bearing hydrothermal brines with sediments during diagenesis, late hydrothermal (epigenetic activity); and any combination of above processes (Coveney 2003; Pagès et al. 2018 ; Henderson et al. 2019; Hints et al. 2021; Xu and Mao 2021, and references therein).

Table 2. Summary of vanadium and uranium production from Salt Wash member of the Morrison Formation within the Paradox Basin as indirect indicator of grade and tonnage. Entries are per district rather than individual deposits. Data converted from Thamm et al. (1981) to metric units. The tonnage of contained V_2O_5 was calculated based on tonnes of ore and V_2O_5 content. Not entire mineralised zones were necessarily mined.

District	Tonnes of Ore	Tonnes U_3O_8	Tonnes V_2O_5	% U_3O_8	% V_2O_5
Urvan Mineral Belt	12 688 793	31 112	163 685	0.25	1.29
La Sel-La Sal Creek District	897 206	2915	13 099	0.32	1.46
Lukachukai-Carrizo District	767 478	1818	8826	0.24	1.15
Green River District	607 814	1194	1155	0.20	0.19
East Canyon-Dry Valley	441 799	692	5743	0.16	1.30
Cottonwood Wash District	267 619	406	2569	0.15	0.96
Thompson District	122 470	259	1421	0.21	1.16
Henry Mts. Mineral Belt	71 668	215	968	0.30	1.35
Moab District	75 296	207	1129	0.28	1.50
Montezuma Canyon District	28 123	40	352	0.14	1.25
Meeker District	34 473	103	390	0.30	1.13
Other areas	4536	6	58	0.15	1.27
Totals and weighted averages	16 007 275	38 969	200 091	0.24	1.25

Consequently, the trace element assemblages and the concentrations of enriched metals vary significantly by location and there is no universal explanation for these relationships. While there are hundreds, if not thousands, of studies addressing the origin of HMBS, there are only a few potentially economically mineable deposits under current market conditions outside of China. Despite its checkered mining history, the metamorphosed Talvivaara black schist-hosted Ni-Zn-Cu-Co (not producing V) deposit in Finland described by Kontinen and Hanski (2015) is probably the most important example currently in production outside of China.

The vanadium-bearing black shales of economic interest can be considered a subset of HMBS. They are found mainly in late Proterozoic and Phanerozoic marine successions and may contain more than 0.18 wt-% V_2O_5 and up to 1.7 wt-% V_2O_5 (Kelley et al. 2017). Regarding the origin of vanadium-rich horizons, recent research of black shales along the southeastern margin of the Yangtze Platform in South China suggests that these horizons formed under euxinic and intermittently suboxic to euxinic conditions at the basin slope, probably with some terrestrial input. Related, yet far less common, polymetallic (Ni-Mo-enriched) horizons are devoid of any signature of terrestrial input and appear to be constrained to iron-deficient euxinic conditions (Xu and Mao 2021). A recent study of the Alum Shale in Denmark, Sweden, Norway, and Estonia suggests that vanadium hyper-enrichment during the Lower Ordovician resulted from the upwelling of deep oceanic water (Bian et al. 2021). These examples, together with many other studies, clearly indicate that while there are fundamental similarities in the depositional environments, there may be more than one way to reach a favourable depositional environment for the formation of hyper-vanadium-enriched black shales.

In common geological settings, vanadium (V^{3+}) substitutes for Al in the octahedral sites of 2:1 phyllosilicates such as roscoelite (Gaines et al. 1997; Peacor et al. 2000), smectite, illite-smectite, illite, and muscovite (Meunier 1994; Peacor et al. 2000); however, more recently, it became evident that some shales consisting of trioctahedral mica such as phlogopite and biotite may also contain high concentrations of vanadium (Zheng et al. 2019). Besides some of the previously mentioned minerals, patrónite, chernykhite [phyllosilicate, muscovite subgroup $(Ba,Na)(V^{3+},Al)_2(Si,Al)_4O_{10}(OH)_2$], and phengite were reported as vanadium-bearing minerals at the Balasauskandyk V–Mo–U deposit in Kazakhstan (Komekova et al. 2017). Furthermore, vanadium is also found as V^{4+} in organic material attached on sedimentary particles (Breit and Wanty 1991) and depending on the nature of the thermal stability of organic material, vanadium may remain associated with organic material during diagenesis and low-grade metamorphism (Zhang et al. 2015). For example, at Mecca Quarry Shale at Velpen, Indiana (Figure 4(a,b)), illite is reported to account for 65% of the vanadium, whereas organic material accounts for the remaining 35% (Peacor et al. 2000). There is a lot of scientific speculation regarding the processes by which vanadium was incorporated into metalliferous black shales, as discussed by Peacor et al. (2000) and Hints et al. (2021). The effect of weathering distribution of vanadium on vanadium-bearing black shales is important, but not well-documented. Uncommon vanadium oxysalts [metahewettite ($CaV_6O_{16}\cdot H_2O$), bokite ($KAl_3Fe_6V_2O_{76}\cdot 30H_2O$)], compound phosphate minerals [schoderite ($Al_2PO_4VO_4\cdot 8H_2O$), and metaschoderite ($Al_2PO_4\cdot VO_4\cdot 6-8H_2O$)] were reported in oxidised zones of the Gibellini project (Hanson et al. 2018). At the Julia Creek vanadium deposit (Queensland, Australia) hosted by the Cretaceous organic-rich Toolebuc Formation, most of the vanadium (60%) was remobilised and incorporated into Fe oxide and oxyhydroxide phases during the supergene enrichment (Lewis et al. 2010).

Examples of black shales considered as potential sources of recoverable vanadium include the Woodruff Formation (Nevada, U.S.A.; notably the Gibellini project; Hanson et al. 2018), the Alum Shale (southern Sweden, particularly the Scania area; Bian et al. 2021), the Devonian Shangling deposit (Guangxi Province, China; Zhang et al. 2015), the Baiguoyuan Ag–V deposit (Hubei Province, China; Yi et al. 2017), and other mineralised lower Cambrian black shale horizons in South China (Lehmann et al. 2016; Shi et al. 2021; Xu and Mao 2021). The late Devonian–Early Mississippian Bakken black shales in the Williston Basin of Montana, North Dakota, Saskatchewan, and Manitoba are enriched in vanadium and zinc (Scott et al. 2017) and may also contain stratigraphic

intervals of interest as a potential source of vanadium. Table 3 provides the V_2O_5 grade and tonnage estimates for selected deposits derived in compliance with the NI-43-101 or JORC guidelines. It also lists potential vanadium co-products. The Häggån deposit is of particular interest as it indicates the importance of cut-off grade in resource estimation.

Vanadiferous black shales represent the largest vanadium resource in China (Li et al. 2010) and their vanadium content typically varies between 0.13% and 1.2% V_2O_5 (Qi 1999), leading to numerous attempts to extract commercially vanadium from black shales. Most of these attempts were at a small scale (less than 100 tonnes of V_2O_5 per year), focused on weathered ores (Zheng et al. 2019), and took place during periods of high vanadium prices and fewer environmental regulations relative to western industrialised countries (Zhang et al. 2011). The recovery of vanadium from black shales, which is commonly referred to by Chinese authors as ‘stone coal’ (Dai et al. 2018), was based on a roasting process emitting HCl and Cl_2 into the environment (Li et al. 2010). A summary of the extraction methods used during those time periods is provided by Zhang et al. (2011). The intensity of ongoing research in this domain by China (e.g. Wang et al. 2020; Chen et al. 2021) and other countries (e.g. Olson 2019) combined with the fact that most of the previously mentioned Chinese plants closed suggests that an ideal method for extracting vanadium from shales at a commercial scale has not yet been developed, is not considered cost-competitive under current market conditions, or is not compatible with current environmental regulations in western industrialised countries. This assessment agrees with the most recent review by Li et al. (2021).

To our knowledge, currently there is no commercial vanadium recovery from black shales outside of China. There are very few authoritative studies addressing actual proportions of vanadium in aluminosilicates and in organic material from vanadium-rich shales. Many site-specific metallurgical, geological, and even review studies either sidestep this issue, do not discuss this issue, or simply assume that most, if not all vanadium are in phyllosilicates. However, this is not the case at the Mecca Quarry Shale (Indiana, U.S.A.; Peacor et al. 2000) and more importantly at the Gibellini vanadium project (Nevada, U.S.A.). The Gibellini project appears to differ significantly from most of the other above-listed deposits in terms of vanadium distribution. In the reduced portion of the Gibellini deposit, the vanadium is found largely in organic material consisting of fine-grained ($<15\mu m$), flaky, and stringy organic fragments, while in the oxidised portion of the deposit, metahewettite, bokite, schoderite, and metaschoderite occur as fracture fillings (Hanson et al. 2018).

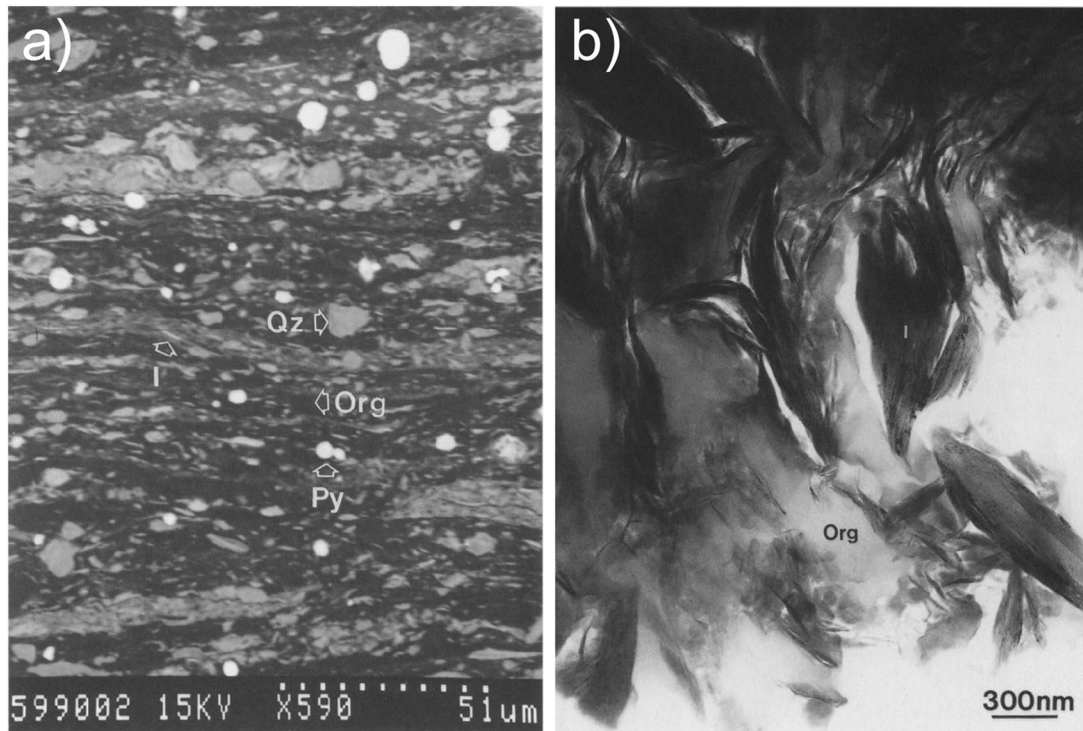


Figure 4. Mecca Quarry Shale; (a) BSE image of a thin section. Bright round objects are pyrite (Py) framboids, black material is kerogen (Org). Most material of intermediate contrast is detrital quartz (Qz) and illite (I); (b) transmission electron microscopy (TEM) image showing the textural relationship between kerogen (Org; light grey), and authigenic V-rich illite (from Peacor et al. 2000).

Surprisingly, based on preliminary metallurgical studies, the highest recovery rates are expected from the transition zone separating the oxidised and reduced zones. The envisaged extraction process consists of heap leaching and solvent extraction followed by acid stripping and precipitation of final product (Hanson et al. 2018).

The development of the first successful operation extracting vanadium from a given vanadium-rich shale outside of China will require innovation, perseverance, and pioneering spirit. Determining if the vanadium is predominantly contained in phyllosilicates, compound phosphates, vanadium oxy salts, iron oxides, and oxyhydroxides or organic materials

Table 3. Grades and tonnages of selected, relatively well-documented, HMBS considered as potential future sources of vanadium.

Deposit	Country	Category	Resources			References
			Tonnage (Million tonnes) [†]	Grade (% V ₂ O ₅)	Potential co-product(s)	
Häggån	Sweden	Indicated and inferred #	2000	0.30	±Ni ± Zn ± Mo (±U)*	Aura Energy (2019)
		Indicated and inferred ##	124	0.43	±Ni ± Zn ± Mo (±U)*	
Viken	Sweden	Indicated	24	0.31	±Mo ± Ni (±U)*	American Battery Metals Corp. (2019)
Green Giant	Madagascar	Inferred	2831	0.27	±Mo ± Ni (±U)*	
		Indicated	50	0.69	**	NextSource Materials (2021)
Gibellini	U.S.	Inferred	10	0.63		Hanson et al. (2021)
		Measured and indicated***	23	0.29		
Julia Creek	Australia	inferred***	15	0.18		QEM Limited (2021) Lewis et al. (2010)
		Indicated	220	0.30	Oil in shale	
		inferred	2540	0.30		

0.2% V₂O₅ cut-off.

0.4% V₂O₅ cut-off.

* Vanadium is closely associated with uranium; however, Swedish Mineral Act prevents the recovery of uranium and requires it to be treated as waste.

** Hosted by metapelites (metamorphosed shales) containing the Molo Graphite deposit; however, graphite is not listed as a possible byproduct at Green Giant.

*** Includes oxidised, transition, and reduced portions of mineralised zone.

[†] Rounded to nearest million.

is essential before attempting to select the optimal extraction method for any given project and for project ranking according to development potential. Furthermore, the studies by Zheng et al. (2019) suggest that the distinction between shales consists of specific vanadium-bearing phyllosilicates such as dioctahedral mica (e.g. muscovite and illite) and trioctahedral mica (e.g. phlogopite and biotite) will be important, especially in the case of unweathered ores.

Base metal vanadate deposits

Base metal vanadate occurrences are characterised by lead-, zinc-, and copper-vanadate minerals in the oxidised portions of base metal deposits. They share spatial and genetic similarities with classical Pb–Zn supergene nonsulphide carbonate-hosted base-metal occurrences (Boni and Large 2003 ; Hitzman et al. 2003) which are relatively widespread (Fischer 1975). The classical carbonate-hosted Pb–Zn nonsulphide deposits do not contain abundant vanadate minerals. They are found in both arid and tropical environments/paleo-environments; however, many of the best supergene nonsulphide deposits recognised to date formed in semi-arid environments, and some are found in cold, wet climates at higher latitudes (Paradis and Simandl 2011). Where base metal vanadates occur within the mineralised nonsulphide zone, they appear to post-date both sulphide and nonsulphide base metal-bearing minerals. The vanadium required for crystallisation of vanadates is commonly believed to be brought in by late supergene fluids; however, the provenance of vanadium is not universally agreed upon.

Deposits of the Otavi Mountainland, Namibia, hosted by Neoproterozoic carbonates of the Abenab and Tsumeb Subgroups of the Otavi Group in the Damara Supergroup (Boni et al. 2007; Kamona and Gunzel 2007) are the best-known examples of base metal vanadate mineralisation. They were first mined in 1919, with increasing production between 1943 and 1960 (Wartha and Schreuder 1992). Most vanadium mineralisation in the Otavi Mountainland is spatially associated with (overly) primary sulphide and nonsulphide Pb–Zn carbonate-hosted deposits, or other base metal deposits. Most prior Zn–Pb–V production came from the Berg Aukas and Abenab West dolostone-hosted deposits forming stratiform lenses, breccia zones, and cavity fillings (Figure 5 (a)). The remaining ore reserves at Berg Aukas were reported to be at 1.65 million tonnes grading 17% Zn, 5% Pb and 0.6% V_2O_5 (Misiewicz 1988). The Abenab West deposit was a stratiform karst zone consisting mainly of nonsulphide Pb–Zn minerals, secondary copper minerals, descloizite, and vanadinite within unconsolidated, ferruginous clay (red mud) containing quartz and detrital galena

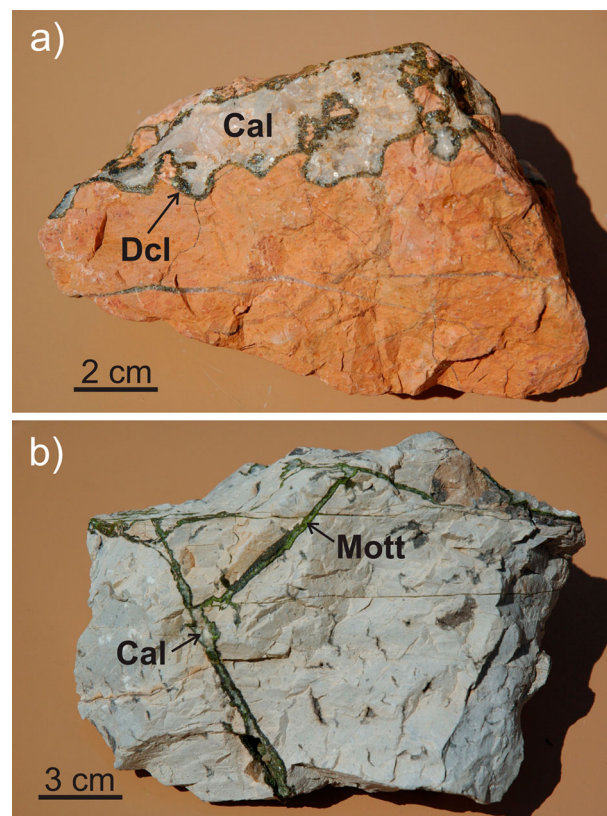


Figure 5. Base metal vanadate mineralisation from Otavi Mountainland, Namibia; (a) Cavity filled with descloizite (Dcl) crystals and sparry calcite (Cal) in limestone of the Maieberg Formation from the Okorundu pit, west of the Abenab mining area (Boni et al. 2007); (b) Veinlets of motttramite (Mott; green) and calcite (Cal; white) cutting the dolostone of the Hüttenberg Formation at Gross Otavi vanadium occurrence (from Boni et al. 2007).

(Boni and Large 2003) filled with fragments of collapsed country rocks and compacted red muds, cemented by coarse calcite and descloizite–vanadinite concretions. From 1939 to 1958, it supplied more than 50 000 tonnes of Pb, 5000 tonnes of V and an unknown quantity of Zn concentrates (Kamona and Gunzel 2007, and references herein). The pertinent geological information on these and other deposits in the Otavi area is summarised by Boni et al. (Boni and Large 2003; Boni et al. 2007) and Kamona and Gunzel (2007).

The spatial association between vanadium mineralisation and nonsulphide Pb–Zn deposits in combination with field observations, textures, and mineral paragenesis led to the conclusion that the vanadium mineralisation in the Otavi Mountainland was supergene in origin, a hypothesis supported by studies from Boni et al. (2007) and Kamona and Gunzel (2007). According to Bannister and Hey (1933) and Palache et al. (1951), the vanadate mineralisation of the Otavi Mountainland commonly consisted of mineral species belonging to the isomorphic series between descloizite $[PbZn(VO_4)(OH)]$ and motttramite $[PbCu(VO_4)(OH)]$ and to a lesser extent vanadinite

[$\text{Pb}_5(\text{XO}_4)_3\text{Cl}$], where X represents the elements P, As, and V (Figure 5(b); from Boni et al. 2007). Also in the Otavi Land area, the Abenab vanadium deposit, hosted by the carbonate rocks of the Maieberg Formation which belongs to the Tsumeb Supergroup, produced 1.85 million tonnes of ore averaging 1.03% V_2O_5 (Cairncross 1997). The deposit is described as a cylindrical breccia pipe consisting of descloizite and vanadinite cemented by calcite (Kamona and Gunzel 2007). Other examples of the vanadate-bearing deposits include Kabwe Mine (formerly known as ‘Broken Hill’), Zambia (Skerl 1934; Taylor 1954; Southwood et al. 2019) and Kihabe Zn–Pb–V prospect, Botswana (Mondillo et al. 2020). The Kabwe Mine and related processing plant operated from 1906 to 1994 and produced 0.8 million tonnes of Pb, 1.8 million tonnes of Zn with silver (79 tonnes), V_2O_5 (7820 tonnes), cadmium (235 tonnes) and copper (64 tonnes) as a byproduct (Kamona and Friedrich 2007). The Kabwe area in Zambia is currently considered as one of the most polluted sites in the world, due largely to wind dispersion of dust from extensive piles of slag (Baieta et al. 2021). Non-African examples are the St. Anthony mine in Arizona (644 tonnes of vanadium, 1934–44; Fischer 1975), and Los Lamentos and San Antonio mines in Mexico (211 tonnes of vanadium, 1938–40; Fischer 1975).

Within relatively well-documented deposits of the Otavi Mountainland, vanadium was present only in the nonsulphide portions of the mineralised zones and is suspected to have been introduced into the nonsulphide Pb–Zn zones from outside by late supergene or hypogene fluid.

The most likely sources of vanadium were the siliclastic country rocks, or mafic rocks of the underlying Paleoproterozoic basement (Boni et al. 2007). The need for external source of vanadium, in combination with a slightly higher temperature of formation for vanadates than for coexisting Zn–Pb–Cu nonsulphides, as suggested by stable isotope studies mentioned by Boni et al. (2007) may explain why vanadates are relatively uncommon in association with nonsulphide base metal deposits in other parts of the world.

The discovery of high-grade, large tonnage Pb–Zn vanadate mineralisation is not expected to happen by the exploration community; however, the possibility of a new discovery cannot be entirely discounted. In the meantime, efforts are underway to optimise the methods for the production of vanadium concentrate from small lead vanadate deposits (Silin et al. 2020a), metallurgical treatments of lead vanadate ores (Silin et al. 2020b), and potential recovery of vanadium from historic slags produced by smelting of African Pb–Zn ores (Ettler et al. 2020).

Other deposit types

As indicated by Kelley et al. (2017), vanadium was also reported in anomalous concentrations in a variety of ore deposit types including gold-telluride quartz veins (e.g. Mueller and Muhling 2020) and surficial uranium deposits. Surficial deposits are described by the International Atomic Energy Agency (2020) as mostly Tertiary to recent, near-surface uranium occurrences in sediments and soils and they share a number of similarities with sandstone-hosted uranium–vanadium deposits. The largest of the surficial uranium deposits are calcrete-hosted and occur in valley-fill sediments along drainage channels and in playa-style sediments in areas of deeply weathered, uranium-rich granites. Good examples of such surficial uranium deposits with significant vanadium content are Langer Heinrich uranium mine in Namibia (Hartleb 1988; Iilende 2012; World Nuclear News 2019), Amarillo Grande and Laguna Salada projects in Argentina (de Klerk et al. 2014; Edwards 2020), and Southern High Plains physiographic region in U.S.A. (Hall et al. 2019).

Heavy mineral sands (‘iron sands’) in New Zealand (Figure 2(b)), derived by weathering and sedimentary processes from volcanic rocks (Brathwaite et al. 2021), are a valuable source of vanadiferous titanomagnetite used by New Zealand Steel (2021a, 2021b) to produce iron and vanadium-bearing slag. Heavy mineral sand/placer deposits in other parts of the world may also contain recoverable vanadium resources (Perks and Mudd 2021). New discoveries, similar to high-grade Minas Ragra type patrónite (vanadium sulphide)-bearing deposit, Peru, described by Hillebrant (1907) and Lamey (1966), should not be discounted. The recovery of vanadium and/or other elements (e.g. REE, yttrium, and uranium) as byproducts of phosphoric acid from phosphate rock has been proposed many times in the past; more recently by Chen and Graedel (2015). While such recoveries are theoretically and technically possible (Weterings and Janssen 1985) and favourably looked upon from the circular economy and environmental points of view, it remains to be seen if such efforts are justifiable even after environmental and criticality benefits are accounted for, under current market conditions.

Summary

When located in favourable geopolitical and environmental settings near developed infrastructure and sources of inexpensive energy, vanadiferous magnetite, sandstone-hosted uranium–vanadium, shale-hosted vanadium, and lead–zinc–copper vanadate deposits may be acceptable exploration targets (Table 1).

Most vanadium is currently produced from vanadiferous titanomagnetite deposits hosted in mafic-ultramafic layered intrusions; extraction may be directly from vanadiferous titanomagnetite concentrate, or from vanadium-enriched slags. Some producers outside China exploiting this type of deposit currently have the flexibility to increase their production levels. Several known deposits of this type which are currently under exploration, or in development outside of China may come into production within the next 3 years. The reactivation of historic mines (e.g. Mustavaara V–Fe–Ti mine, Finland, which closed in 1985 due to low vanadium prices; Taipale 2013) represents additional options. Vanadiferous titanomagnetite deposits represent an attractive exploration and development target because they have relatively high grades and tonnages, vanadium extraction technology from vanadiferous magnetite is well-established, and because, a well-designed exploration programme targeting this deposit type may also result in the discovery of significant Ni, Cr, and PGE deposits within the same intrusive complex.

Tabular, Salt Wash type, sandstone-hosted uranium-vanadium deposits were historically a significant source of both vanadium and uranium and significant resources were identified outside of U.S.A. Depending on the future uranium and vanadium market conditions, they may become a highly sought-after exploration and development targets once again. However, most of the deposits where vanadium was (or is) successfully extracted as a byproduct of uranium have relatively small vanadium ore reserves in comparison to currently producing vanadiferous titanomagnetite type and some vanadium-rich black shale type deposits. This deposit type is a non-ideal exploration and development target in jurisdictions that have strict restrictions or a moratorium on uranium exploration or production. On the positive side, these deposit types typically occur in clusters and belts, respond well to inexpensive radiometric surveys, and where environmentally permissible, could be exploited by *in-situ* leaching technologies.

Vanadium-rich black shales, a subset of HMBS, represent the largest Chinese, and possibly global, vanadium resources. Under current market conditions and environmental constraints however, they represent a very small fraction of vanadium mine production. If ongoing intensive research into the optimisation of extracting vanadium from these rocks (currently concentrated in China based on the number of recently published scientific papers) is successful, and related environmental concerns are addressed, this deposit type may become truly competitive with the mafic-ultramafic layered intrusions vanadiferous titanomagnetite deposits. If the development of vanadium-bearing black shales goes

ahead, in many cases, vanadium is likely to be a co-product of other metals. Important aspects in the early ranking of vanadium-rich black shales projects (relative to each other) are the mineralogy of the deposit, and the proportions of the vanadium within the crystal structure of minerals, to that adsorbed to mineral particles, and that found within or adsorbed to organic material (as was attempted for the Gibellini project). This has important implications on the need for ore sintering, the selection of vanadium extraction method, rate of recovery, and consequently, extraction costs.

Copper–lead–zinc vanadate deposits were historically, a significant source of vanadium. These deposits are spatially and genetically linked to traditional sulphide or nonsulphide base metal deposits (predominantly carbonate-hosted). They are not recommended as primary exploration targets; however, these deposits may be considered as valid secondary exploration targets within exploration programmes targeting sedimentary rock-hosted Cu–Pb–Zn-bearing sulphide and/or nonsulphide deposits assuming appropriate climatic or paleo-climatic settings.

Other deposit types that are potential vanadium sources that explorationists should be aware of are surficial vanadium-bearing uranium deposits (e.g. Langer Heinrich, Namibia), and high-grade patrónite-bearing deposits (e.g. Minas Ragra, Peru). The concepts and technical parameters used in project evaluations such as vanadium resource availability, market base, market projections, environmental aspects, social aspects, all technical economic aspects related to exploration and development (e.g. availability of infrastructure, ore tonnage/grade, proximity to the surface, geometry of the deposit, and mining, processing, and waste disposal aspects) remain extremely important in the traditional ranking of exploration and development projects under free market conditions.

Because vanadium is considered a ‘critical’, ‘battery’, and ‘specialty material’ (sensu Simandl et al. 2021), at least in some western jurisdictions, free-market conditions may not apply or could be curtailed to some extent by government initiatives and long-term contracts between producers and end-users to secure reliable supply chains. Furthermore, as the concept of the circular economy is increasingly evoked by governments, financial institutions, and multinational companies, projects involving recycling, and the rehabilitation of historic mines and processing sites (tailings and mine waste dumps) may benefit from preferential treatment by funding agencies. These aspects cannot be ignored during the short-term ranking of projects according to their development potential. However, history has shown us that in the long term, current geopolitical tensions and conflicts will subside and the law of

supply and demand will be re-established. Therefore, regardless of current hype, fundamental technical and economic aspects of traditional project ranking should not be ignored, and development efforts should be concentrated on technically and economically sound projects located in stable, mining-friendly countries.

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References

- Abzalov MZ. 2012. Sandstone-hosted uranium deposits amenable for exploitation by in situ leaching technologies. *Appl Earth Sci.* 121:55–64.
- American Battery Metals Corp. 2019. American Battery Metals announces LOI to acquire the development-stage Viken Project in Sweden and Financing. Newsfile Corp. [accessed 2021 Dec 07]. <https://www.newsfilecorp.com/release/44374/American-Battery-Metals-Announces-LOI-to-Acquire-the-DevelopmentStage-Viken-Project-in-Sweden-and-Financing>.
- Arguin J-P, Pagé P, Girard R, Barnes S-J. 2017. The spatial variation of mineralogy in the vanadiferous magnetite deposit of the Lac Doré Complex (Chibougamau, Québec) and its implications on the chemical purity of magnetite concentrates. In: Proceedings of the 14th SGA Biennial Meeting 2017, the Mineral Resources to Discover, Quebec, QC, Canada, 20–23 [accessed 2017 Aug 4]:[247–250 p.].
- Atlantic. 2021. Geology reserves and resources. Atlantic. [accessed 2021 Dec 08]. <https://atlanticptyltd.com.au/projects/windimurra/geology-reserves-resources>.
- Aura Energy. 2019. Häggån battery metals project resource upgrade estimate successfully completed. Aura Energy Limited. [accessed 2021 Dec 07]. https://www.rns-pdf.londonstockexchange.com/rns/4628P_1-2019-10-10.pdf.
- Australian Vanadium Limited. 2021. The Australian Vanadium Project. Australian Vanadium Limited; [accessed 2021 Dec 08]. <https://www.australianvanadium.com.au/our-assets/the-australian-vanadium-project/>.
- Bai Z-H, Zhong H, Hu R-Z. 2021. World-class Fe-Ti-V oxide deposits formed in feeder conduits by removing cotectic silicates. *Econ Geol.* 116:681–691.
- Bai ZJ, Zhong H, Naldrett AJ, Zhu WG, Xu GW. 2012. Whole rock and mineral composition constraints on the genesis of the giant Hongge Fe-Ti-V oxide deposit in the Emeishan large igneous province, southwest China. *Econ Geol.* 107:507–524.
- Baieta R, Ettler V, Vaněk A, Penížek V, Trubač J, Kříbek B, Svoboda M, Sracek O, Nyambe I. 2021. Depicting the historical pollution in a Pb-Zn mining/smeltering site in Kabwe (Zambia) using tree rings. *J Afr Earth Sci.* 181:104246. <https://doi.org/10.1016/j.jafrearsci.2021.104246>.
- Bannister FA, Hey M. 1933. The identity of mottramite and psittacinite with cuprififerous descloizite. *Mineral Mag.* 23:376–386.
- Barnes S-J, Maier WD, Ashwal LD. 2004. Platinum-group elements in the Upper Zone of the Bushveld Complex. *Chem Geol.* 208:293–317.
- Barton IF, Barton MD, Thorson JP. 2018a. Characteristics of Cu and U-V deposits in the Paradox Basin (Colorado Plateau) and associated alteration. Society of Economic Geologists, Inc. Guidebook Ser. 59:73–102.
- Barton MD, Barton IF, Thorson JP. 2018b. Paleofluid flow in the Paradox Basin: introduction. Society of Economic Geologists, Inc. Guidebook Ser. 59:1–12.
- Bian L, Schovsbo NH, Chappaz A, Zheng X, Nielsen AT, Wang X, Dai S, Galloway JM, Małachowska A, Xu X, Sane H. 2021. Molybdenum-uranium-vanadium geochemistry in the lower paleozoic alum shale of Scandinavia: implications for vanadium exploration. *Int J Coal Geol.* 239:103730. <https://doi.org/10.1016/j.coal.2021.103730>.
- Boni M, Large D. 2003. Nonsulfide zinc mineralization in Europe: an overview. *Econ Geol.* 98:715–729.
- Boni M, Terracciano R, Evans NJ, Laukamp C, Schneider J, Bechstädt T. 2007. Genesis of vanadium ores in the Otavi Mountainland, Namibia. *Econ Geol.* 102:441–469.
- Brathwaite RL, Christie AB, Gazley MF. 2021. Stratigraphy, provenance and localisation of the titanomagnetite placer at Waikato North Head, South Auckland, New Zealand. *Miner Deposita.* 56(2):343–362. <https://doi.org/10.1007/s00126-020-00968-8>.
- Breit GN, Wanty RB. 1991. Vanadium accumulation in carbonaceous rocks: a review of geochemical controls during deposition and diagenesis. *Chem Geol.* 91:83–97. [https://doi.org/10.1016/0009-2541\(91\)90083-4](https://doi.org/10.1016/0009-2541(91)90083-4).
- Brough C, Bowell RJ, Larkin J. 2019. The geology of vanadium deposits. In: R. Bowell, editor. An introduction to vanadium. Nova Science Publishers, Inc; p. 87–117.
- Bushveld Minerals. 2021. Annual Report and Financial Results December 2020. [accessed 2022 Jan 20]. <https://www.bushveldminerals.com/wp-content/uploads/2021/07/Bushveld-Minerals-Annual-Report-Financial-Results-2020.pdf>.
- Cairncross B. 1997. The Otavi Mountainland Cu-Pb-Zn-V deposits, Namibia. *Mineral Rec.* 28:109–130.
- Cawthorn RG, Barnes S-J, Ballhaus C, Malitech KN. 2005. Platinum group element, chromium, and vanadium deposits in mafic and ultramafic rocks. In: Hedenquist

- JW, Thompson JFH, Goldfarb RJ, Richards JP, editors. Economic geology one hundredth anniversary. Vol. 1905–2005. Littleton (CO): Society of Economic Geologists; p. 215–249.
- Cawthorn RG, Molyneux T. 1986. Vanadiferous magnetite deposits of the Bushveld Complex. In: Anhaeusser CR, Maske S, editors. Mineral deposits of Southern Africa. Johannesburg: Geol Soc S Afr; p. 1251–1266.
- Chen B, Bao S, Zhang Y. 2021. Synergetic strengthening mechanism of ultrasound combined with calcium fluoride towards vanadium extraction from low-grade vanadium-bearing shale. *Int J Min Sci Technol.* 31 (6):1095–1106. <https://doi.org/10.1016/j.ijmst.2021.07.008>.
- Chen M, Graedel T. 2015. The potential for mining trace elements from phosphate rock. *J Clean Prod.* 91:337–346.
- Chenoweth W. 1981. Uranium-vanadium deposits of the Uravan mineral belt and adjacent areas, Colorado and Utah: New Mexico Geological Society Guidebook, 32nd Field Conference, p. 165–170.
- Chenoweth WL. 2018. The geology, exploration and production history of the Uranium-Vanadium Mines of George R Simpson and Gloria Emerson, Northwestern Carrizo Mountains, Apache County, Arizona. [accessed 2021 Aug 15]. http://repository.azgs.gov/sites/default/files/dlio/files/nid1887/simpson_permit_-_chenoweth.pdf.
- Coveney RJ. 2003. Metalliferous paleozoic black shales and associated strata. In: Lentz DR, editor. Inorganic geochemistry of sediments and sedimentary rocks: evolutionary considerations to mineral deposit-fanning environments. *GeoText: Geological Association of Canada*; p. 135–144.
- Croll R, Reichhardt FJ, Witley J, Roberts R, Rabe J, Weissenberger A, Wiid GJ, Trussler GE, Longridge L, Greve K. 2016. Mookopane vanadium project pre-feasibility study. Bushveld Minerals Limited. [accessed 2021 Dec 07]. <http://www.bushveldminerals.com/wp-content/uploads/2017/08/201602040458050.pdf>.
- Crowson P. 2001. Mineral handbook 2000–2001. Edenbridge: Mining Journal Books; p. 486.
- Cuney M, Mercadier J, Bonneti C. 2022. Classification of sandstone-related uranium deposits. *J Earth Sci.* 33:236–256. <https://doi.org/10.1007/s12583-021-1532-x>.
- Dahlkamp FJ. 2010. Uranium deposits of the world USA and Latin America. Berlin Heidelberg: Springer-Verlag.
- Dai S, Zheng X, Wang X, Finkelman RB, Jiang Y, Ren D, Yan X, Zhou Y. 2018. Stone coal in China: a review. *Int Geol Rev.* 60:736–753. <https://doi.org/10.1080/00206814.2017.1378131>.
- da Silva Lima L, Quartier M, Buchmayr A, Sanjuan-Delmás D, Laget H, Corbisier D, Mertens J, Dewulf J. 2021. Life cycle assessment of lithium-ion batteries and vanadium redox flow batteries-based renewable energy storage systems. *Sustain Energy Technol Assess.* 46:101286.
- de Klerk L, Goode J, Véliz P, van der Westhuysen J. 2014. Ni 43-101 preliminary economic assessment of the Laguna Salada uranium-vanadium deposit, Chubut Province, Argentina (Technical Report). U3O8 Corp. [accessed 2021 Sep 6]. http://www.u3o8corp.com/wp-content/uploads/2016/07/u3o8corp_preliminary.economic.assessment.laguna.salada.2014.pdf.
- Edwards C. 2020. Process design for the Ivana uranium-vanadium mill. *CIM Journal.* 11(4):231–237. <http://dx.doi.org/10.1080/19236026.2020.1833650>.
- Energy Fuels Inc. 2019. Energy fuels provides update on vanadium production. Energy Fuels Inc. [accessed 2021 Sep 30]. <https://www.energyfuels.com/2019-04-01-Energy-Fuels-Provides-Update-on-Vanadium-Production>.
- EPA. 2021. Contaminant Candidate List 5 (CCL 5). [accessed 2021 Nov 10]. <https://www.epa.gov/ccl/contaminant-candidate-list-5-ccl-5>.
- Ettler V, Jarošíková A, Mihaljeviča M, Kříbek B, Nyambed I, Kamonae F, Mapanif B. 2020. Vanadium in slags from smelting of African Pb-Zn vanadate ores: mineralogy, extractability and potential recovery. *J Geochem Explor.* <https://doi.org/10.1016/j.gexplo.2020.106631>.
- European Commission. 2020. Critical raw materials resilience: charting a path towards greater security and sustainability: communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions – Commission of the European Communities – COM 474, Document 52020DC0474. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0474>.
- Fischer RP. 1975. Geology and resources of base-metal vanadate deposits. *US Geol Surv. Professional Paper* 926-A. <https://doi.org/10.3133/pp926A>.
- Forge Resources Ltd. 2011. Forge resources to purchase Balla Balla magnetite, vanadium and titanium project from Atlas Iron Limited (ASX:AGO). Australian Securities Exchange. [accessed 2021 Dec 08]. <https://www.asx.com.au/asxpdf/20111216/pdf/4239v45c02k79t.pdf>.
- Gadd MG, Peter JM, Hnatyshin D, Creaser R, Gouwy S, Fraser T. 2020. A middle Devonian basin-scale precious metal enrichment event across northern Yukon (Canada). *Geol.* 48:242–246. <https://doi.org/10.1130/G46874.1>.
- Gadd MG, Peter JM, Jackson SE, Yang Z, Petts D. 2019. Platinum, Pd, Mo, Au and Re deportment in hyper-enriched black shale Ni-Zn-Mo-PGE mineralization, Peel River, Yukon, Canada. *Ore Geol Rev.* 107:600–614. <https://doi.org/10.1016/j.oregeorev.2019.02.030>.
- Gaines RV, Skinner HCW, Foord EE, Mason B, Rosenzweig A, King VT, Dowty E. 1997. Dana's new mineralogy. New York: John Wiley & Sons, Inc.
- Gao F, Olayiwola AU, Liu B, Wang S, Du H, Li J, Wang X, Chen D, Zhang B. 2022. Review of vanadium production Part I: primary resources. *Miner Process Extr Metall Rev.* 43:466–488. <https://doi.org/10.1080/08827508.2021.1883013>.
- Gao M-l, Xue X-x, Li L-j, Yang H, Bai R-g, Wang H-x. 2018. A novel method to extract vanadium from vanadium-bearing steel slag using sodium carbonate solution. *Physicochem Probl Miner Process.* 54:911–921.
- Geldenhuis IJ. 2020. Feasibility of fluxless smelting of titaniferous magnetite ore in a pilot-plant open-arc dc furnace. Dissertation, Stellenbosch University.
- Geldenhuis IJ, Reynolds QG, Akdogan G. 2020. Evaluation of titania-rich slag produced from titaniferous magnetite under fluxless smelting conditions. *JOM.* 72:3462–3471. <https://doi.org/10.1007/s11837-020-04304-3>.
- Gilligan R, Nikoloski AN. 2020. The extraction of vanadium from titanomagnetites and other sources. *Miner Eng.* 146:106106. <https://doi.org/10.1016/j.mineng.2019.106106>.
- Girard R, Allard GO. 1998. The lac Doré vanadium deposits, Chibougamau. In: Pilote P, editor. Geology and metallogeny of the Chapais-Chibougamau Mining District: a new vision of the discovery potential. Proceedings of the Chapais Chibougamau 1998 symposium. p. 99–102.

- Hall SM, Van Gosen BS, Paces JB, Zielinski RA, Breit GN. 2019. Calcrete uranium deposits in the Southern High Plains, USA. *Ore Geol Rev.* 109:50–78.
- Hansley PL, Spirakis CS. 1992. Organic matter diagenesis as the key to a unifying theory for the genesis of tabular uranium-vanadium deposits in the Morrison Formation, Colorado Plateau. *Econ Geol.* 87:352–365.
- Hanson K, Orbock EJC, Peralta E, Gormely L. 2018. Gibellini Vanadium Project, Nevada, USA, NI 43-101 Technical Report, Amec Foster Wheeler. Project Number: 198505.
- Hanson K, Wakefield T, Drake A. 2021. Gibellini Vanadium Project Eureka County, Nevada NI 43-101 Technical Report on Preliminary Economic Assessment Update. <https://www.silverelef.com/pdf/October-2021-Preliminary-Economic-Assessment-for-the-Gibellini-Project.pdf>.
- Hartleb JWO. 1988. The Langer Heinrich uranium deposit: southwest Africa/Namibia. *Ore Geol Rev.* 3:277–278.
- Henderson KM, Williams-Jones AE, Clark JR. 2019. Metal transport by liquid hydrocarbons: evidence from metalliferous shale and pyrobitumen, Yukon. In: N. Rogers, editor. Targeted geoscience initiative: 2018 report of activities. Geological Survey of Canada, Open File 8549; p. 179–187. <https://doi.org/10.4095/313650>
- Hillebrand WF. 1907. The vanadium sulphide, patronite, and its mineral associates from Minasragra, Peru. *J Am Chem Soc.* 29:1019–1029.
- Hints R, Pajusaar S, Urtson K, Liiv M, Kallaste T. 2021. Metal enrichment in lithologically complex black shales: a case study from the Tremadocian of NE Estonia. *Estonian J Earth Sci.* 70(1):36–50.
- Hitzman MW, Reynolds NA, Sangster DF, Allen CR. 2003. Classification, genesis, and exploration guides for non-sulfide zinc deposits. *Econ Geol.* 98:685–714.
- Hughes H, Andersen JC, O'Driscoll B. 2021. Mineralization in layered mafic-ultramafic intrusions. In: *Encyclopedia of geology*. 2nd ed.. Amsterdam: Elsevier; p. 823–839.
- Hulbert LJ, Gregoire DC, Paktunc G, Carne RC. 1992. Sedimentary nickel, zinc, and platinum-group-element mineralization in Devonian black shales at the Nick property, Yukon, Canada: a new deposit type. *Explor Min Geol.* 1:39–62.
- Hund K, La Porta D, Fabregas TP, Laing T, Drexhage J. 2020. Minerals for climate action: the mineral intensity of the clean energy transition: World Bank Group, Washington, DC, 112 <https://pubdocs.worldbank.org/en/961711588875536384/Minerals-for-Clean-Energy-Transition-The-Mineral-Intensity-of-the-Clean-Energy-Transition.pdf>.
- Huyck HLO. 1989. When is a metalliferous black shale not a black shale? U.S. Geological Surv Circular. 1058:42–56.
- Iilende A. 2012. The source of uranium and vanadium at the Langer Heinrich and Klein Trekkopje uranium deposits – genesis and controlling factors for uranium mineralization. MSc. Dissertation, University of Namibia.
- International Atomic Energy Agency. 1993. Uranium extraction technology. Technical Reports Series, 359 [accessed 2021 Sep 1] [p. 358]. https://www-pub.iaea.org/MTCD/publications/PDF/trs359_web.pdf.
- International Atomic Energy Agency. 2001. Manual of acid in situ leach uranium mining technology. Vienna, IAEA-technical document-1239: IAEA; p. 283.
- International Atomic Energy Agency. 2009. World distribution of uranium deposits (UDEPO) with uranium deposit classification. IAEA-TECDOC-1629. Vienna: IAEA; p. 109.
- International Atomic Energy Agency. 2018. Geological classification of uranium deposits and description of selected examples, Technical Document 1842 [accessed 2021 Sep 1]. [p. 428]. <https://www.iaea.org/publications/12346/geological-classification-of-uranium-deposits-and-description-of-selected-examples>.
- International Atomic Energy Agency. 2020. Descriptive uranium deposit and mineral system models. [accessed 2021 Sep 2] [p. 313]. https://www-pub.iaea.org/MTCD/Publications/PDF/DES_MOD_web.pdf.
- International Energy Agency. 2021. The Role of Critical World Energy Outlook Special Report Minerals in Clean Energy Transitions. [accessed 2021 Sep 15]. <https://iea.blob.core.windows.net/assets/24d5dfbb-a77a-4647-abcc-667867207f74/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf>.
- Johnson SC, Large RR, Coveney RM, Kelley KD, Slack JF, Steadman JA, Gregory DD, Sack PJ, Meffre S. 2017. Secular distribution of highly metalliferous black shales corresponds with peaks in past atmosphere oxygenation. *Miner Deposita.* 52:791–798. <https://doi.org/10.1007/s00126-017-0735-7>.
- Jowitt SM, Keays RR. 2011. Shale-hosted Ni-(Cu-PGE) mineralisation: a global overview. *Appl Earth Sci Trans Inst Min Metall, Sect B.* 120:187–197.
- Kamona AF, Gunzel A. 2007. Stratigraphy and base metal mineralization in the Otavi Mountain Land, Northern Namibia – a review and regional interpretation. *Gondwana Res.* 11:363–413.
- Kamona F, Friedrich GH. 2007. Geology, mineralogy and stable isotopes geochemistry of the Kabwe carbonate-hosted Pb–Zn deposit, Central Zambia. *Ore Geol Rev.* 30:217–243.
- Karinen T. 2010. The Koillismaa Intrusion, northeastern Finland – evidence for PGE reef forming processes in the layered series. *Geol Surv Finland, Bull.* 404:176.
- Karinen T, Hanski E, Taipale A. 2015. The Mustavaara Fe-Ti-V oxide deposit. In: Maier W.D., O'Brien H, Lahtinen R, editors. *Mineral deposits of Finland*. Amsterdam: Elsevier; p. 179–192.
- Kelley KD, Scott CT, Polyak DE, Kimball BE. 2017. Vanadium. In: Schulz KJ, DeYoung JH Jr, Seal RR II, Bradley DC, editors. *Critical mineral resources of the United States – economic and environmental geology and prospects for future supply*: U.S. Reston (Virginia): US Geological Survey, Professional Paper 1802. p. U1–U36., <https://doi.org/10.3133/pp1802U>.
- King River Resources Limited. 2021. Speewah Project High Purity TiO₂. King River Resources Limited. [accessed 2021 Dec 08]. <https://app.sharelinktechnologies.com/announcement/asx/cdd8a621dad0bf866a9c4ad8f237aada>.
- Kinnunen P, Karhu M, Yli-Rantala E, Kivikytö-Reponen P, Mäkinen J. 2022. A review of circular economy strategies for mine tailings. *Cleaner Eng Technol.* 8:100499.
- Komekova NM, Kozlov VA, Smirnov KM, Shayakhmetova RA, Nesterov KN. 2017. Autoclave leaching of vanadium from black shale. *Metall.* 60:1186–1190. <https://doi.org/10.1007/s11015-017-0427-7>.
- Kontinen A, Hanski E. 2015. The Talvivaara black shale-hosted Ni-Zn-Cu-Co deposit in eastern Finland. In: Maier WA, Lahtinen R, O'Brien H, editors. *Mineral deposits of Finland*. Amsterdam: Elsevier. <https://doi.org/10.1016/B978-0-12-410438-9.00022-4>.
- Lamey CA. 1966. *Metallic and industrial mineral deposits*. New York: McGraw-Hill.

- Largo Inc. 2021. The Maracás Menchen Mine. Largo Inc. [accessed 2021 Dec 07]. <https://largoinc.com/English/about-us/maracas-menchen-mine/default.aspx>.
- Lee J-c, Kurniawan, Kim E-y, Chung KW, Kim R, Jeon H-S. 2021. A review on the metallurgical recycling of vanadium from slags: towards a sustainable vanadium production. *J Mater Res Technol.* 12:343–364.
- Lehmann B, Frei R, Xu L, Mao J. 2016. Early Cambrian black shale hosted Mo-Ni and V mineralisation on the rifted margin of the Yangtze platform China: reconnaissance chromium isotope data and a refined metallogenic model. *Econ Geol.* 111:89–104.
- Lewan MD, Maynard JB. 1982. Factors controlling enrichment of vanadium and nickel in the bitumen of organic sedimentary rocks. *Geochim Cosmochim Acta.* 46:2547–2560. [https://doi.org/10.1016/0016-7037\(82\)90377-5](https://doi.org/10.1016/0016-7037(82)90377-5).
- Lewis SE, Henderson RA, Dickens GR, Shields GA, Coxhell S. 2010. The geochemistry of primary and weathered oil shale and coquina across the Julia Creek Vanadium deposit. *Miner Deposita.* 45:599–620. <https://doi.org/10.1007/s00126-010-0287-6>.
- Li C-x, Wei C, Deng Z-g, Li M-t, Li X-b, Fan G. 2010. Recovery of vanadium from black shale. *Trans Nonferrous Met Soc China.* 20:127–131.
- Li LJ, Zhang L, Zheng SL, Lou TP, Zhang Y, Chen DH, Zhang Y. 2011. Acid leaching of calcined vanadium titanomagnetite with calcium compounds for extraction of vanadium. *Chin J Process Eng.* 11:573–578.
- Li W, Ma C, Gong W, Zhu X. 2021. Clean production technology for effective recovery of vanadium from shale: interaction between activators and vanadium-loaded minerals. *J Clean Prod.* 315. <https://doi.org/10.1016/j.jclepro.2021.1281700>.
- Longridge L, Martinez A. 2020. Lac Doré Project, Chibougamau, Québec, Canada NI 43-101 technical report. [accessed 2021 Dec 08]. <https://www.vanadiumcorp.com/wp-content/uploads/2020/12/R441.2020-VCOMRE01-VanadiumCorp-Lac-Dore-NI-43-101-Technical-Report.pdf>.
- Maier WD, Barnes S-J, Groves DI. 2013. The Bushveld Complex, South Africa: formation of platinum–palladium, chrome-and vanadium-rich layers via hydrodynamic sorting of a mobilized cumulate slurry in a large, relatively slowly cooling, subsiding magma chamber. *Miner Deposita.* 48:1–56.
- Mathieu L. 2019. Origin of the vanadiferous serpentine–magnetite rocks of the Mt. Sorcerer Area, Lac Doré Layered Intrusion, Chibougamau, Québec. *Geosci.* 9:110. <https://doi.org/10.3390/geosciences9030110>.
- Merritt RC. 1971. The extractive metallurgy of uranium. Boulder (CO): Colorado School of Mines Research Institute.
- Meunier JD. 1994. The composition and origin of vanadium-rich clay minerals in Colorado Plateau Jurassic sandstones. *Clay Miner.* 42:391–401.
- Misiewicz JE. 1988. The geology and metallogeny of the Otavi Mountain Land, Damara orogen, SWA/Namibia, with particular reference to the Berg Aukas Zn-Pb-V deposit: a model of ore genesis. Dissertation, Rhodes University.
- Mondillo N, Boni M, Balassone G, Forrester N, Putzolu F, Santoro L. 2020. Mineralogy and genesis of the Kihabe Zn-Pb-V Prospect, Aha Hills, Northwest Botswana. *Miner.* 10:685.
- MSA Group. 2021. Vametco Inferred & Indicated Mineral Resource and Ore Reserve update for Annual Reporting Purposes. Bushveld Minerals Limited. [accessed 2021 Dec 07]. <http://www.bushveldminerals.com/wp-content/uploads/2021/02/Vametco-Mineral-Resources-and-Ore-Reserves-31-December-2020.pdf>.
- Mueller AG, Muhling JR. 2020. Early pyrite and late telluride mineralization in vanadium-rich gold ore from the Oroya Shoot, Paringa South mine, Golden Mile, Kalgoorlie: 3. Ore mineralogy, Pb-Te (Au-Ag) melt inclusions, and stable isotope constraints on fluid sources. *Miner Deposita.* 55:733–766. <https://doi.org/10.1007/s00126-019-00876-6>.
- Naldrett AJ, Wilson A, Kinnaird J, Yudovskaya M, Chunnnett G. 2012. The origin of chromitites and related PGE mineralization in the Bushveld Complex: new mineralogical and petrological constraints. *Min Deposita.* 47:209–232.
- Namur O, Abily B, Boudreau AE, et al. 2015. Igneous layering in basaltic magma chambers. In: Charlier B, Namur O, Latypov R, Tegner C, editors. *Layered intrusions*. Springer; p. 75–152.
- Navarro R, Guzman J, Saucedo I, Revilla J, Guibal E. 2007. Vanadium recovery from oil fly ash by leaching, precipitation and solvent extraction processes. *Waste Manage.* 27:425–438.
- Neometals. 2018. Neometals commences update of Barrambie definitive feasibility study. Australian Securities Exchange. [accessed 2021 Dec 08]. <https://1wcm0741r5ad1d1r7j17fvxq-wpengine.netdna-ssl.com/wp-content/uploads/2018/11/Neometals-11-16.pdf>.
- New Zealand Steel. 2021a. The mining operation. [accessed 2021 Sep 30]. <https://www.nzsteel.co.nz/sustainability/our-environment/the-mining-operation/>.
- New Zealand Steel. 2021b. Iron making. [accessed 2021 Sep 30]. <https://www.nzsteel.co.nz/new-zealand-steel/the-story-of-steel/the-steel-making-process/iron-making/>.
- NextSource Materials. 2021. The Green Giant Vanadium Project. NextSource Materials Inc. [accessed 2021 Dec 07]. <https://www.nextsourcematerials.com/vanadium/green-giant-vanadium-project/>.
- Northrop HR, Goldhaber MB, Landis GP, Unruh JW, Reynolds RJ, Campbell JA, Wanty RB, Grauch RI, Whitney G, Rye RO. 1990. Genesis of the tabular-type vanadium-uranium deposits of the Henry basin, Utah. *Econ Geol.* 85:215–269. <https://doi.org/10.2113/gsecongeo.85.2.215>.
- Olson J. 2019. Vanadium Extraction and Recovery by Alkaline Heap Leaching of Mineralized Material from the Gibellini Project in Eureka County, Nevada. M.Sc. thesis, University of Nevada.
- Pagès A, Barnes S, Schmid S, Coveney RM, Schwark L, Liu W, Grice K, Fan H, Wen H. 2018. Geochemical investigation of the lower Cambrian mineralised black shales of South China and the late Devonian Nick deposit, Canada. *Ore Geol Rev.* 94:396–413. <http://dx.doi.org/10.1016/j.oregeorev.2018.02.004>.
- Palache C, Berman H, Frondell C. 1951. *The system of mineralogy*. 7th ed. Vol. 2. New York: Wiley.
- Paradis S, Simandl GJ. 2011. Carbonate-hosted, Nonsulphide Zn–Pb (supergene) Mineral Deposit Profile B09. British Columbia Ministry of Energy, Mines, and Petroleum Resources, Paper 2011-1:189–193.
- Peacor DR, Coveney RM, Zhao G. 2000. Authigenic illite and organic matter: the principal hosts of vanadium in the Mecca Quarry Shale at Velpen, Indiana. *Clays Clay Miner.* 48:311–316.

- Perks C, Mudd G. 2021. Soft rocks, hard rocks: the world's resources and reserves of Ti and Zr and associated critical minerals. *Int Geol Rev.* 64:987–1008. <https://doi.org/10.1080/00206814.2021.1904294>.
- Petranikova M, Tkaczyk AH, Bartl A, Amato A, Lapkovskis V, Tunsu C. 2020. Vanadium sustainability in the context of innovative recycling and sourcing development. *Waste Manag.* 113:521–544.
- Polyak DE. 2020. Vanadium. Mineral Commodity Summaries: United States Geological Survey, 180–181, [accessed 2021 Sep 30]. <https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-vanadium.pdf>.
- Polyak DE. 2021. Vanadium. Mineral Commodity Summaries: United States Geological Survey, 180–181, [accessed 2021 Sep 30]. <https://pubs.usgs.gov/periodicals/mcs2021/mcs2021.pdf>.
- Polyak DE. 2022. Vanadium. Mineral Commodity Summaries: United States Geological Survey, [accessed 2022 Feb 10]. <https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-vanadium.pdf>.
- Prevec SA. 2018. Igneous Rock Associations 23. The Bushveld Complex, South Africa: New insights and paradigms. *Geosci Can.* 45:117–135.
- QEM Limited. 2021. The Julia Creek Vanadium/Oil Shale Project. Surfers Paradise (Queensland): QEM Limited. [accessed 2021 Dec 07]. <https://www.qldem.com.au/project/>.
- Qi MJ. 1999. The current situation and prospect of the vanadium extraction from stone coal. *Hydrometall Chin.* 4:1–10.
- Rapple D, Haun R. 2021. Production of pure vanadium: industry review and feasibility study of electron beam melt refining of V–Al alloys. *J Sustain Metall.* 7:755–766.
- Reynolds IM. 1985. The nature and origin of titaniferous magnetite-rich layers in the Upper Zone of the Bushveld Complex: a review and synthesis. *Econ Geol.* 80:1089–1108.
- Rodriguez PC, da Silva LA, Xavier FV, Campbell RA, Ferreira GG. 2017. Maracás Menchen Project, Bahia, Brazil Independent Technical Report – an updated mine plan, mineral reserve and preliminary economic assessment of the inferred resources. Prepared by GE21 Ltd on behalf of: Largo Resources Ltd.
- Roskill. 2021. Vanadium, Outlook to 2030, 19th Edition, Roskill. [accessed 2021 July 20]. <https://roskill.com/market-report/vanadium/>.
- Rudnick RL, Gao S. 2003. Composition of the continental crust. In: Rudnick RL, editor. *The Crust*, vol. 3. Amsterdam: Elsevier; p. 1–64.
- Sá JHS, Barnes S-J, Prichard HM, Fisher PC. 2005. The distribution of base metals and platinum-group elements in magnetite and its host rocks in the Rio Jacaré Intrusion, Northeastern Brazil. *Econ Geol.* 100:333–348.
- Sahoo PK, Kim K, Powell MA, Equeenuddin SM. 2016. Recovery of metals and other beneficial products from coal fly ash: a sustainable approach for fly ash management. *Int J Coal Sci Technol.* 3:267–283.
- Schlesinger WH, Klein EM, Vengosh A. 2017. Global biogeochemical cycle of vanadium. *Proc Natl Acad Sci U.S.A.* 114(52):201715500. <https://doi.org/10.1073/pnas.1715500114>.
- Schmid S, Taylor WR, Jordan DP. 2020. The Bigryli Tabular Sandstone-Hosted Uranium–Vanadium Deposit, Ngalia Basin, Central Australia. *Miner.* 10:896. <https://doi.org/10.3390/min10100896>.
- Scoon RN, Costin G, Gräbe PJ. 2017. Geology and origin of the vanadiferous Fe-Ti oxide-rich Kennedy's Vale discordant body, Eastern limb of the Bushveld Complex, South Africa. *South Afr J Geol.* 120:251–270.
- Scott C, Slack JF, Kelley KD. 2017. The hyper-enrichment of V and Zn in black shales of the Late Devonian-Early Mississippian Bakken Formation (USA). *Chem Geol.* 452:24–33.
- Seppä V-M, Rantala E, Lovén P. 2021. NI 43-101 technical report preliminary economic assessment on the Mustavaara Vanadium Project, Finland. [accessed 2021 Dec 08]. https://www.strategic-res.com/site/assets/files/3721/ni43-101_technical_report_pea_on_the_mustavaara_vanadium_project_finland.pdf.
- Shawe DR. 2011. Uranium-vanadium deposits of the Slick Rock district, Colorado: U.S. Geological Survey Professional Paper 576-F, p. 80.
- Shi C, Cao J, Han S, Hu K, Bian L, Yao S. 2021. A review of polymetallic mineralization in lower Cambrian black shales in South China: Combined effects of seawater, hydrothermal fluids, and biological activity. *Palaeogeogr Palaeoclimatol Palaeoecol.* 561:110073. <http://dx.doi.org/10.1016/j.palaeo.2020.110073>.
- Silin I, Gürsel D, Kremer D, Hahn KM, Wotruba H. 2020a. Production of vanadium concentrate from a small-scale lead vanadate deposit by gravity concentration: a pilot plant study. *Miner.* 10:957. <https://doi.org/10.3390/min10110957>.
- Silin I, Hahn KM, Gürsel D, Kremer D, Gronen L, Stopič S, Friedrich B, Wotruba H. 2020b. Mineral processing and metallurgical treatment of lead vanadate ores. *Miner.* 10:197. <https://doi.org/10.3390/min10020197>.
- Simandl L, Simandl GJ, Paradis S. 2021. Specialty, critical, battery, magnet and photovoltaic materials: market facts, projections and implications for exploration and development. *Geosci Can.* 48:73–91. <https://doi.org/10.12789/geocanj.2021.48.17>.
- Skerl AC. 1934. Vanadium at the Rhodesia Broken Hill. *Miner Mag.* 50:280–283.
- Smith WD, Maier WD. 2021. The geotectonic setting, age and mineral deposit inventory of global layered intrusions. *Earth Sci Rev.* 220:103736. <https://doi.org/10.1016/j.earscirev.2021.103736>.
- Southwood M, Cairncross B, Rumsey MS. 2019. Minerals of the Kabwe ('Broken Hill') Mine, Central Province, Zambia. *Rocks Miner.* 94:114–149. <https://doi.org/10.1080/00357529.2019.1530038>.
- Taipala A. 2013. Composition of magnetite in gabbros of the Mustavaara Fe-Ti-V Deposit. M.Sc. Dissertation, University of Oulu. [accessed 2021 Aug 15]. <https://jultika.oulu.fi/files/nbnfioulu-201303081088.pdf>.
- Taner MF, Ercit TS, Gault RA. 2000. Vanadium bearing magnetite from the Matagami and Chibougamau mining districts, Abitibi, Québec, Canada. *Explor Min Geol.* 7:299–311.
- Taylor JH. 1954. The lead–zinc–vanadium deposits at Broken Hill, Northern Rhodesia. *Colon Geol Miner Resour.* 4:335–365.
- Taylor PR, Shuey SA, Vidal EE, Gomez JC. 2006. Extractive metallurgy of vanadium-containing titaniferous magnetite ores: a review. *Min Metall Explor.* 23:80–86. <https://doi.org/10.1007/BF03403340>.
- Technology Metals Australia Limited. 2021a. Gabanintha mineral resources & reserves. Subiaco (WA): Technology Metals Australia Limited. [accessed 2021 Dec 08]. <https://www.tmtlimited.com.au/mineral-resource-reserves>.
- Technology Metals Australia Limited. 2021b. Yarrabubba geology and mineral resource & reserve. Subiaco (WA):

- Technology Metals Australia Limited. [accessed 2021 Dec 08]. <https://www.tmtlimited.com.au/geology-and-mineral-resource-reserve>.
- Tegner C, Cawthorn RG, Kruger FJ. 2006. Cyclicality in the main and Upper Zones of the Bushveld Complex, South Africa: crystallization from a zoned magma sheet. *J Petrol.* 47:2257–2279.
- Thamm JK, Kovsach AA, Adams SS. 1981. Geology and recognition criteria for sandstone uranium deposits of the Salt Wash type, Colorado Plateau province – Final report, prepared for the U.S. Department of Energy, Grand Junction Office, Colorado [accessed 2022 Jan 10]. <https://www.osti.gov/servlets/purl/6512174>.
- TNG Limited. 2017. Updated feasibility study and financial model confirms robust business case for development of Mount Peake vanadium-titanium-iron project. TNG Limited. [accessed 2021 Dec 08]. <https://www.tngltd.com.au/wp-content/uploads/2019/11/6861157.pdf>.
- U.S. Department of the Interior. 2018. Final list of critical minerals 2018: Federal Register Document Number 2018-10667, 83:23296–23297, <https://www.govinfo.gov/content/pkg/FR-2018-05-18/pdf/2018-10667.pdf>.
- Vanadium Price.com. 2021. V₂O₅ Vanadium Pentoxide Flake 98% Price USD / lb [accessed 2021 Dec 08]. <https://www.vanadiumprice.com/>.
- Viers J, Dupre B, Gaillardet J. 2009. Chemical composition of suspended sediments in World Rivers: new insights from a new database. *Sci Total Environ.* 407:853–868.
- Von Gruenewaldt G. 1993. Ilmenite-apatite enrichments in the Upper Zone of the Bushveld Complex: a major titanium-rock phosphate resource. *Int Geol Rev.* 35:987–1000.
- Voyager Metals Inc. 2021. Mont Sorcier iron. Toronto (ON): Voyager Metals Inc. [accessed 2021 Dec 08]. <https://voyagermetals.com/mont-sorcier-iron/>.
- Wang G, Diao J, Liu L, Li M, Li H, Li G, Xie B. 2019. Highly efficient utilization of hazardous vanadium extraction tailings containing high chromium concentrations by carbothermic reduction. *J Clean Prod.* 237. <https://doi.org/10.1016/j.jclepro.2019.117832>.
- Wang M, Huang S, Chen B, Wang X. 2020. A review of processing technologies for vanadium extraction from stone coal. *Miner Process Extr Metall.* 129:290–298. <https://doi.org/10.1080/25726641.2018.1505207>.
- Wartha RR, Schreuder CP. 1992. Vanadium - Minerals resource series 30. Windhoek (Namibia): Ministry of Mines and Energy. *Geol Surv Namibia*; p. 16.
- Watt AJ, Burke IT, Edwards RA, Malcolm HM, Mayes WM, Olszewska JP, Pan G, Graham MC, Heal KV, Rose NL, et al. 2018. Vanadium: a re-emerging environmental hazard. *Environ Sci Technol.* 52:11973–11974. <https://doi.org/10.1021/acs.est.8b05560>.
- Weterings K, Janssen J. 1985. Recovery of uranium, vanadium, yttrium and rare earths from phosphoric acid by a precipitation method. *Hydrometall.* 15:173–190.
- White DJ, Levy LS. 2021. Vanadium: environmental hazard or environmental opportunity? A perspective on some key research needs. *Env Sci Processes Impacts.* 23:527–534.
- Whitley J, Garner R, van der Merwe AJ. 2019. Competent Persons Report on the Brits Vanadium Project North West and Gauteng Provinces, South Africa. Bushveld Minerals Limited. [accessed 2019 Dec 07]. http://www.bushveldminerals.com/wp-content/uploads/2020/01/Independent-CPR_Brits-Vanadium_January_2020_Final.pdf.
- Willemse J. 1969. The vanadiferous magnetic iron ore of the Bushveld igneous complex. *Econ Geol, Monograph.* 4:187–208.
- World Nuclear News. 2019. Paladin looks to rapid restart for Langer Heinrich. World Nuclear Association. [accessed 2021 Sep 11]. <https://world-nuclear-news.org/Articles/Paladin-looks-to-rapid-restart-for-Langer-Heinrich>.
- Xu L, Mao J. 2021. Trace element and C-S-Fe geochemistry of early Cambrian black shales and associated polymetallic Ni-Mo sulfide and vanadium mineralization, south China: implications for paleoceanic redox variation. *Ore Geol Rev.* 135:104210. <https://doi.org/10.1016/j.oregeorev.2021.104210>.
- Yi Y, Pia D-H, Jiang S-Y. 2017. Occurrence, source and enrichment mechanism of silver in black shale-hosted Baiguoyuan Ag-V ore deposit, Hubei Province, China. *J Geochem Explor.* 183:79–87. <http://doi.org/10.1016/j.gexplo.2017.10.005>.
- Zhang Y, Zhang Q, Cai Y, Wang D, Li K. 2015. The occurrence state of vanadium in the black shale-hosted vanadium deposits in Shangling of Guangxi Province, China. *Chin J Geochem.* 34:484–497.
- Zhang Y-M, Bao S-X, Liu T, Chen T-J, Huang J. 2011. The technology of extracting vanadium from stone coal in China: history, current status and future prospects. *Hydrometall.* 109:116–124. <https://doi.org/10.1016/j.hydromet.2011.06.002>.
- Zhao TC. 2002. Non-ferrous extractive metallurgy handbook. Beijing: Metallurgy Industry Press.
- Zheng Q, Zhang Y, Xue N, Liu T, Huang J. 2019. Vanadium occupation and its leachability differences in trioctahedral and dioctahedral mica. *RSC Adv.* 9:27615–27624.
- Zhou M-F, Robinson PT, Leasher CM, Keays RR, Zhang C-J, Malpas J. 2005. Geochemistry, petrogenesis and metallogenesis of the Panzhihua gabbroic layered intrusion and associated Fe-Ti-V deposits. *J Petrol.* 46:2253–2280.