



From Deposit to Concentrate: The Basics of Tungsten Mining

Part 1: Project Generation and Project Development

Steffen Schmidt, P. Geo, Wolfram Bergbau & Hütten AG, Austria

Introduction

The two ITIA newsletter excerpts *Part 1: Project Generation and Project Development* and *Part 2: Operational Practices and Challenges* provide an overview of the many facets of tungsten mining, tracing the path from tungsten resources through exploration, development and mine operation to the production of tungsten concentrates that provide the feedstock for refineries and APT production. Some steps in the overall process are specific to tungsten, others are of a general technical nature.

Since the first edition of this paper from 2012, several industrial tungsten mines have been developed, some failed, mainly due to poor process design, others succeeded, and some moved new countries onto the tungsten landscape. Some existing mines had to close due to exhaustion of reserves. Examples in this paper have been adapted where necessary or annotated. The quest remains the same: assure reliable ethical and sustainable supply of tungsten concentrate to the mid-stream industry (the smelter/refinery level of the supply chains).

In addition, since 2012, the subject of “conflict-free”, or better “responsible/ethical sourcing”, also gained significant momentum. Tungsten is one of the four “conflict minerals” defined in the US Dodd-Frank Act, the others being tantalum, tin and gold. This is now reflected in an additional chapter.

Development and operation of tungsten mines are governed by a multitude of often interlacing factors, which can be grouped in a number of categories:

- Geological Factors: what is in the ground?
- Technical Factors: how can it be recovered?
- Social and Environmental Factors: cost and benefit for society and impact on the natural environment?
- Economic Factors: what does it cost?

Compared to other metals such as copper, lead or zinc, annual mine production of tungsten concentrates is modest. According to ITIA’s Statistical Overview for 2022, primary mine production of tungsten totaled 101,000t WO₃. Tonnage-wise, this is just 10% of the copper output of La Escondida in Chile, the world’s largest copper mine, or a quarter of Morenci, the largest US copper mine, which has also feed grades comparable to many larger tungsten mines. Or, if we look at value rather than tonnage, the metal value recovered annually in tungsten mining, stemming from dozens of industrial mines and hundreds of semi-industrial and artisanal operations around the world is not even half of that of La Escondida and approximately on par with Morenci.

Despite its modest size, the tungsten mining industry is very diverse, exploiting deposits in different geological settings, and using a wide range of mining and beneficiation methods to produce saleable concentrates.

Currently, more than 80% of primary mine production for tungsten stems from operations in China. However, significant tungsten deposits can be found on all continents.

Part 1 covers the geological background, the stages of project development and mining and beneficiation techniques applied in the tungsten industry.

There are currently a number of Junior Resource companies promoting the possible development of tungsten deposits. To avoid inadvertently favoring the one or other of these opportunities, the current article draws examples mainly from past-producing or active tungsten mines.

Note: In order to improve clarity for the non-technical reader, usage of words like “ore” and “reserve” does not follow necessarily the conventions of International Reporting Standards for the Mineral Industry.

Geological Background

Average abundance of tungsten in the earth's crust is around 1.5ppm, and thus much less than, for example, most of the Rare Earth elements such as neodymium. Tungsten is a lithophile element, which means it is more abundant in granitic (around 2ppm) than basaltic (1ppm) and ultra-mafic rocks (0.5ppm).

Mineralogy

There are numerous tungsten minerals, but only scheelite (CaWO_4) and the wolframite ($(\text{Fe},\text{Mn})\text{WO}_4$) solid-solution

series between the end members ferberite and hübnerite are of economic importance.

Weathering and other alteration processes lead to secondary tungsten minerals. Typical examples are hydro-tungstite ($\text{H}_2\text{WO}_4 \cdot \text{H}_2\text{O}$), anthoinite ($\text{AlWO}_3(\text{OH})_3$) and cerotungstite ($\text{CeW}_2\text{O}_6(\text{OH})_3$), which together often form whitish to yellowish earthy masses colloquially named as tungstic ochre. Presence of these minerals might lead to lower process recovery and/or lower concentrate grade and thus, could have an important negative economic impact.

For additional information about the mineralogy of tungsten, refer to the ITIA Newsletter 06/2006.

Scheelite – CaWO_4

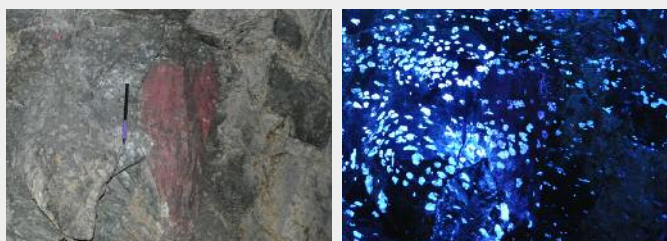
Specific gravity: 5.9–6.1
Hardness: 4.5–5
Tenacity: brittle crystal system: tetragonal
Colour: colourless, whitish, ochre, yellow, grey
Other properties: strong fluorescence under short-wave UV light: whitish blue, turning into yellow with increasing molybdenum content.

Scheelite is a calcium-tungstate with theoretical 80.5% WO_3 content. The mineral forms a solid-solution series with powellite (CaMoO_4), and naturally occurring scheelite contains often up to several % of Mo. This has an impact on usability as raw material.

Large crystals often show the typical bi-pyramidal (pseudo-octahedral) habit and are sought-after collector items.

Properties that influence use as ore material:

- high density: can be enriched with gravitational methods.
- brittle: not a good placer mineral; risk of overgrinding during comminution.
- Mo content: not suitable for certain downstream processes.
- fluorescence: easy to identify in exploration and mining.
- amenable to flotation.



Scheelite as miners see it: skarn ore at Bonfim mine, Brazil, under normal light (left) and UV light (right). Image width about 80 cm.

Wolframite – $(\text{Fe}, \text{Mn})\text{WO}_4$

Solid-solution series between ferberite (FeWO_4) and hübnerite (MnWO_4)

Specific gravity: 7.0–7.5
Hardness: 4–4.5
Tenacity: brittle crystal system: monoclinic
Colour: greyish black (feberite), brownish to reddish black, dark red (hübnerite)

Wolframite is an iron/manganese-tungstate with theoretical 76.3–76.6% WO_3 content. Crystals are usually tabular or prismatic. Pseudomorphs of wolframite after scheelite are called reinite: the wolframite replaces earlier scheelite and retains thus the bi-pyramidal shape of scheelite.

Properties that influence use as raw material:

- high density: can be enriched with gravitational methods.
- brittle: not a good placer mineral; risk of overgrinding during comminution.
- not amenable to flotation.
- paramagnetic – can be upgraded by high-intensity magnetic separation.



Wolframite as miners and collectors see it: prismatic ferberite at Panasqueira, Portugal (left, image width 50 cm) and hübnerite from Pasto Bueno, Peru (right, image width 12 cm).

Tungsten Deposits

Tungsten deposits occur world-wide (**Figure 1**). There are some noticeable clusters, where deposits of similar age and type are concentrated, such as the scheelite skarn deposits in NW Canada and the western USA, wolframite quartz vein deposits in Bolivia and Peru and the Hercynian skarn and vein deposits of the western Iberian Peninsula. The world's largest accumulation of tungsten deposits is found in Eastern Asia, extending from Korea, Japan and China into Vietnam and Thailand. This includes the countless, in part giant tungsten deposits of the Jiangxi and Hunan provinces in China.

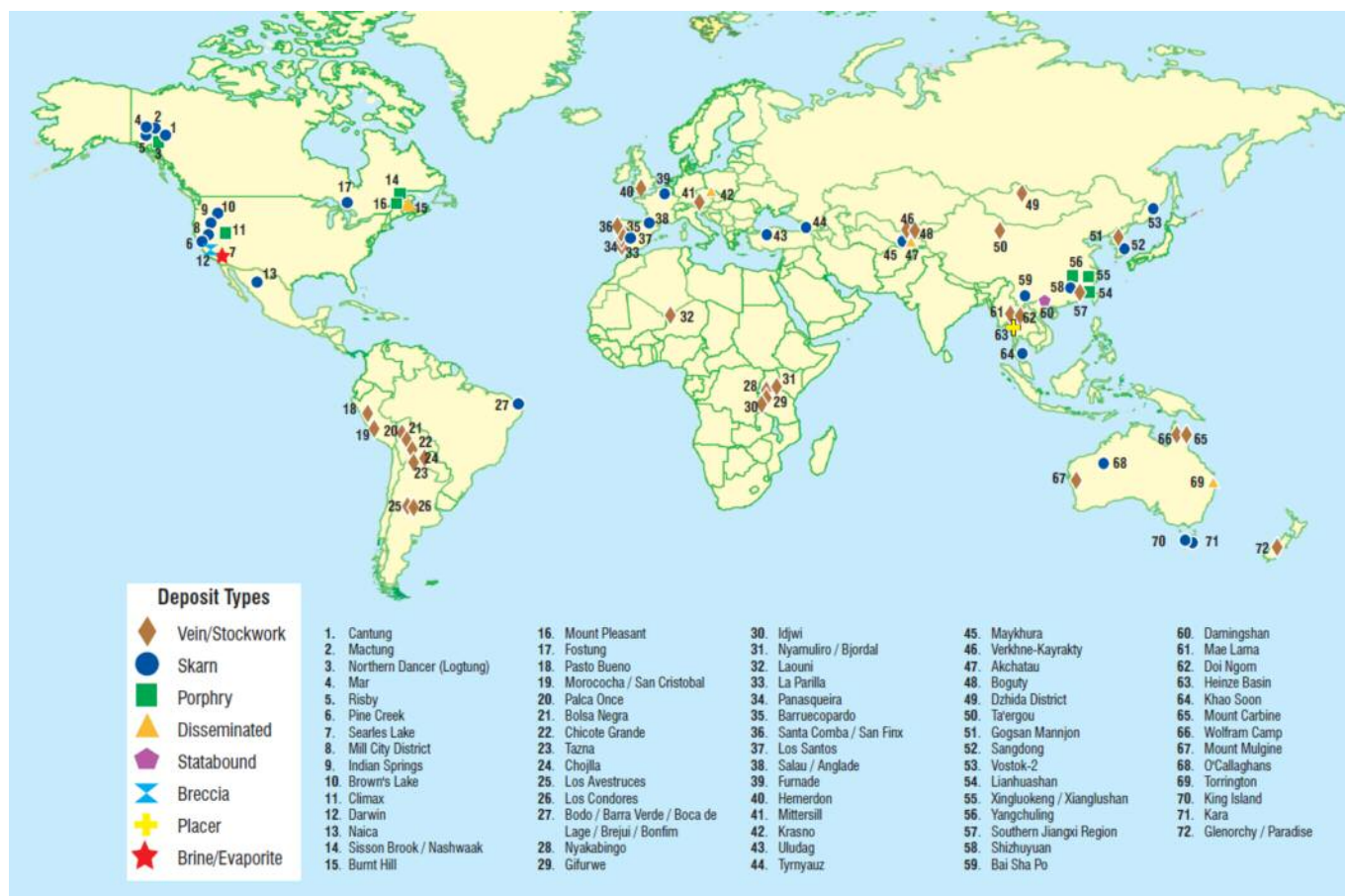
Tungsten deposits are generally formed by magmatic-hydrothermal processes in relation to granitic intrusions. The deposits can be found either within the peripheral part of the intrusive itself (greisen, porphyry, stockwork

and vein deposits), or in its vicinity (stockwork, vein and skarn deposits). Tungsten deposits are often associated with tin or molybdenum mineralisation.

There are some exotic deposit types such as breccia pipes or brine (salt lake) deposits, but these are of subordinate economic importance (refer to ITIA Newsletter 12/2006). One well-known deposit type was the group of "stratabound deposits relating to mafic volcanism" with the Mittersill deposit in Austria as type location. It appears, however, that the Mittersill deposit is better described as stockwork deposit relating to a granitic intrusive, and as this, it would be a classic tungsten deposit as described above.

In general, the exact mechanism for the formation of ore deposits is often controversially discussed.

Figure 1: Location and type of major tungsten deposits and districts, redrawn and updated after BRITISH GEOLOGICAL SERVICE [2011].



Scheelite and wolframite are rather stable with respect to chemical weathering, and thus might be enriched in laterites and eluvial placers (immediately above or close to the origin of the original mineralisation). However, due to their friable character, both minerals disintegrate swiftly during transport in water, and alluvial placers (similar to typical gold placers) are rare.

The classification of greisen, porphyry and stockwork deposits is often ambiguous, and it might just be a question of scale or scope whether an occurrence is described as (multiple-) vein or stockwork deposit.

While simplification does not allow encompassing all deposits, it appears practical to distinguish three main groups of deposits, which have a distinct relation between deposit type and technical challenges for their exploitation. In order of increasing tonnage (and generally decreasing grade):

Classical vein deposits

- More or less continuous veins of decimetres to metres in thickness, mainly comprising quartz. In granite itself or in surrounding host rock. Connection to granite not always clear. Most deposits have ferberite or hübnerite mineralisation, but scheelite vein deposits do also occur (**Figures 2 and 3**).
- Typical tonnages: few 10s to few 100,000s of tonnes of ore.
- Typical grades: 0.5–5% WO₃
- Typical by-product: Sn
- Object of mining is the individual quartz vein with its content of tungsten mineralisation.
- Examples of active mines: Panasqueira, Portugal; Nyakabingo, Rwanda; Chollja, Bolivia.

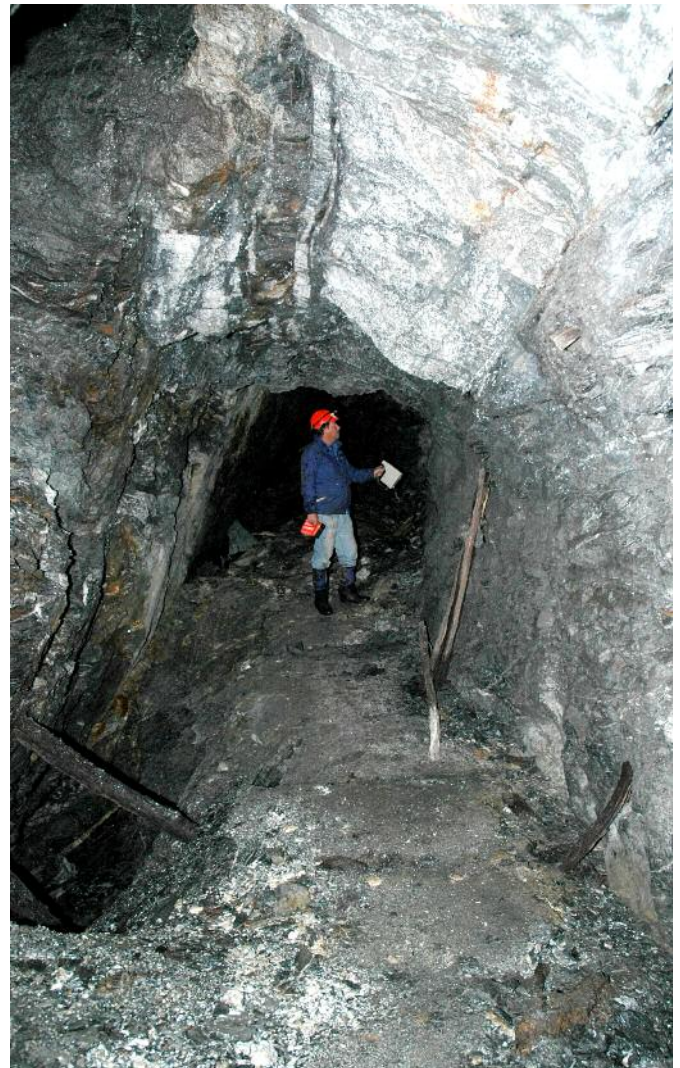
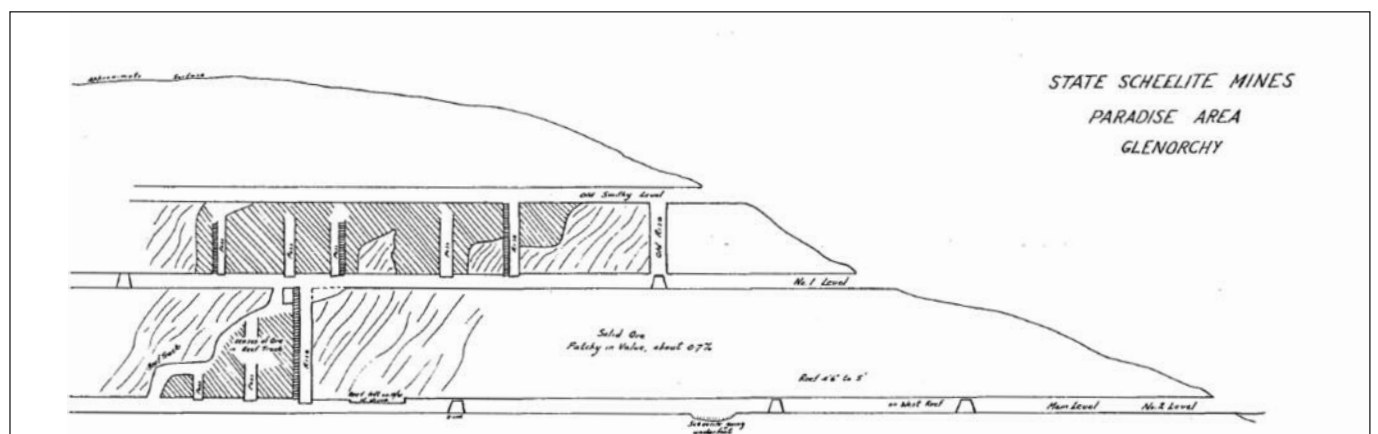


Figure 2: Quartz-scheelite vein deposit: Paradise Mine, New Zealand.

Figure 3: Vertical longitudinal projection of the quartz-scheelite vein from figure 10 with old mine development, Paradise mine, New Zealand, from JEFFERY [1986]. Narrow hatching indicates stoped (mined out) material.



Skarn deposits

- Replacement of carbonate rock (e.g. limestone) by calc-silicate minerals (garnet, epidote, amphiboles and others) near to the contact of a granitic/felsic intrusion (**Figures 4 and 5**).
- Mineralisation might be mono-metallic tungsten (almost exclusively as scheelite) or polymetallic (often with Mo or base metals: Pb, Zn, Cu), also together with gold, fluorite or magnetite. In some cases, tungsten is only by-product.
- Typical tonnages: few million tonnes, but much larger deposits are known.
- Typical grades: 0.3–1% WO₃
- Examples of active mines: King Island (Dolphin), Australia; Shizhuyuan, China; Vostok-2, Russia; Barra Verde/Boca de Laje and Brejui, Brazil.

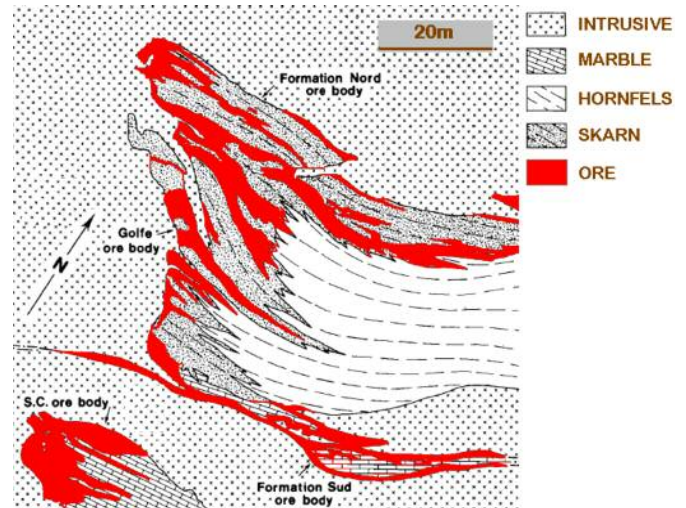


Figure 4: Scheelite skarn deposit: Map of level 1452 of the Anglade mine (Salau deposit), French Pyrenees modified from FONTEILLES et al [1989], showing the lithological control of skarn and scheelite mineralisation and relation to the intrusive sequence.



Figure 5: Low-profile room & pillar mining of the "A" orebody at the Bonfim mine, Brazil, showing strong scheelite mineralisation in a narrow band along the top of the skarn layer. With normal light (left), with UV light (right).



Bulk mineable deposits: greisen, porphyry, stockwork

- "Bulk mineable" is a mining term: it means that large volumes of low-grade material can be mined regardless of complex contacts of individual mineralised structures. Greisen and porphyry deposits are generally located in the apical parts of felsic intrusions, while stockwork vein deposits can be found either in the intrusions itself or in the surrounding country rock. Technically, some skarn deposits are also bulk mineable. Examples are shown in **Figures 6, 7 and 8**.
- These deposits are often either W-Sn or W-Mo deposits. Both, scheelite and wolframite occur in bulk mineable deposits, and some deposits contain both minerals together, which renders beneficiation more complex.
- Typical tonnages: dozens or hundreds of million tonnes.
- Typical grades: 0.1–0.3% WO₃
- Object of mining is not the individual mineralised vein but the entire rock mass including the quartz or greisen veins.
- Examples of active mines: Lianhuashan, China; Mittersill, Austria; Barruecopardo, Spain.

Figure 6: Quartz veins with wolframite and minor scheelite in the Mt Carbine pit, Australia. The quartz veins are too narrow to be mined individually, therefore bulk mining of the entire mineralised package is employed.

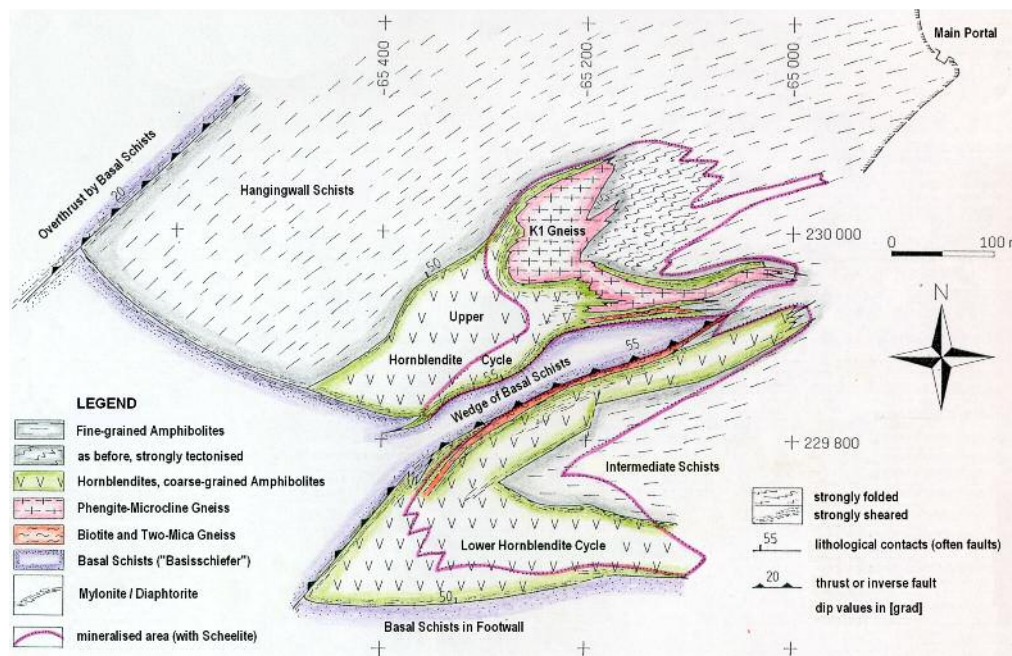


Figure 7: Mittersill scheelite deposit, Austria. Geological sketch of level 1175, Western Ore Zone, showing the extension of quartz-scheelite stockwork veining in basic and ultramafic rocks in the surrounding of a small granite intrusive (K1-Gneiss).



Figure 8: Quartz-scheelite stockwork veining at Mittersill under normal light (above) and UV light (right). This is an exceptionally rich exposure in the mine.



Project Development

The path from discovery to production is complex and time-consuming: It is rare that production occurs within the first ten years from initial discovery. Besides a “good”

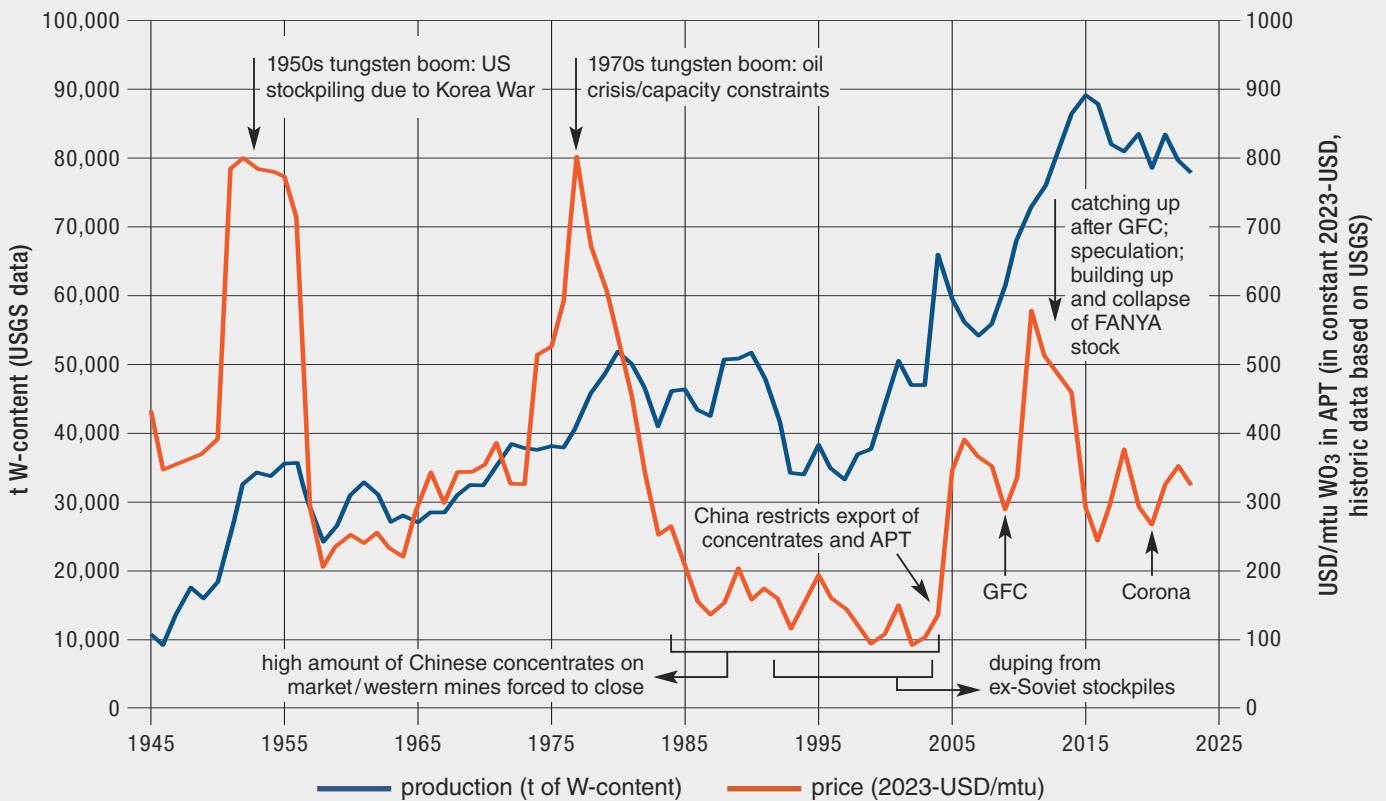
deposit, the right economic environment is needed to trigger interest in project development.

Economic constraints

The tungsten market might appear less cyclic than that of major metals, but there have been major fluctuations in price over time, and many of these are also reflected in general metal price indices: Two price peaks occurred in the mid- to late 20th century: the first in the 1950s, due to strategic stockpiling programs around the Korean War and in the 1970s, due to capacity constraints during a growth cycle together with the oil price crisis. The boom of the 1970s was followed by a prolonged period of depressed prices, due to flooding of the western market by Chinese concentrates (later Chinese APT, and finally Russian surplus material after the collapse of the Soviet Union). When China imposed an export ban for concentrates and quotas for export of APT in the mid-2000s, prices went up swiftly, causing renewed interest in development of tungsten operations.

Most of the tungsten projects developed since the first edition of this guide and/or now under consideration were originally discovered or had even already been mined in the mid to late 20th century before depressed prices from the 1980s onwards forced most western producers to mothball their mines or halt exploration and development projects. Many of these projects have passed through the hands of various owners since.

Junior Resource companies own most tungsten projects, and these need to raise specific interest in a given project to assure project funding, as financing from own funds is not possible. This means, the project itself does not need to be only economically interesting, but adequate promotion is required: A good “story” is needed, and to this end, the classification of tungsten as a critical raw material by the European Union and the US is helping to raise interest.



Relative mine production and prices in real terms for tungsten between 1945 and 2023, based on data from USGS. GFC stands for Global Financial Crisis.
















Once a deposit has been discovered, various studies are undertaken with the ultimate goal to establish a mine. This is a multi-phase process, in which each phase is designed to justify further expenses for the increasingly detailed and thus costly stages in the process leading to a Bankable Feasibility Study (**Figure 9**).

At the beginning, this is largely aimed to better understand the geological inventory through exploration and resource modelling, always keeping in mind the economic potential.

At later stages, engineering of extraction and beneficiation, environmental considerations, market studies and cost modelling are the main focus.

Smith (2023) provides an excellent overview over the engineering study requirements at the individual study level (conceptual (=scoping), pre-feasibility and feasibility level) in issue 146 of RPM Global’s Perspectives series of newsletters.

Figure 9: Typical steps of project generation and development from grass-root exploration through discovery and technical studies to production. Distribution of relative costs varies from project to project and depends on risk assessment and approach to feasibility work.

Stage	Operations, techniques, important issues	Relative risk	Relative costs
Production	Start-up, optimisation, routine operation, ongoing exploration to replace mined tonnages.	 *	
Construction	Mine development, construction of mill, tailings facilities and other infrastructure		
Pre-Construction	Financing, permitting, off-take negotiations, final engineering, tender & selection of contractors.		
Positive Outcome of Feasibility Study – Go-Ahead Decision			
Feasibility Study	Advanced engineering, detailed mine plan for first few years, Proven Mineral Reserves, Metallurgical testwork might include pilot plant processing, Environmental Management Plan, social studies, marketing studies, detailed calculation of operation and capital costs.		
Pre-Feasibility Study	Basic engineering, selection of mining method and basic mine plan, metallurgical testwork, Probable Mineral Reserves, Environmental Baseline Study. Additional detailed exploration to further upgrade resource/reserve classification.		
Resource Definition and Scoping	Extensive staged drilling campaigns leading initially to Inferred Resources and then to Indicated Resources at least for the central portion of the deposit; preliminary metallurgical testwork, Scoping Studies to define scale and economic merit of a possible operation (Preliminary Economic Assessment). Could include underground development and test mining.		
Discovery			
Grass-root exploration	Regional prospection, mapping, geochemistry, limited drilling, possibly geophysics.		
Exploration Concept	Data research and desktop review and so on to formulate targets.		

* denotes the risk relating to errors in the underlying studies and design that might be discovered upon start-up and that might even render the project uneconomic after it had been constructed.

Exploration

During the tungsten booms of the 1950s and 1970s, numerous deposits have been discovered world-wide which since have not or only partly been mined. This means that there is little incentive for grass-root exploration (the search for new deposits in virgin terrain), except in China, where the industry actively undertakes exploration to replace mined-out deposits.

More important than early-stage exploration is detailed exploration to better understand known deposits, bring them to Feasibility stage to attract financing and to extend the resources of active mines.

Exploration methods have to take the particularities of tungsten deposits into account, for example the low concentration of the valuable mineral and its often highly erratic grade distribution.

Besides specific tungsten exploration campaigns, for example during the tungsten boom in the 1970s, many

deposits have been discovered rather by chance, or as “by-product” of the exploration for deposits of other commodities. Historically, tungsten was even an unwelcome constituent of multi-element ore deposits – hence the name Wolfram (mineral that is “wolfing” away the tin).

Way to discovery

With exception of well-developed vein deposits, tungsten deposits tend to be inconspicuous: ore grades and thus the concentration of the ore mineral are low, there are no colourful oxidation zones (gossans) and generally no magnetic or gravity anomalies that would aid geophysical prospection.

Moreover, scheelite is “just” a whitish or pale-coloured mineral perfectly camouflaged by carbonates, quartz and feldspar. However, the mineral has a very strong fluorescence, and this property is used for exploration: field work is often undertaken as night prospection with UV lamps or by checking heavy mineral concentrates from stream sediments under UV light for scheelite content.

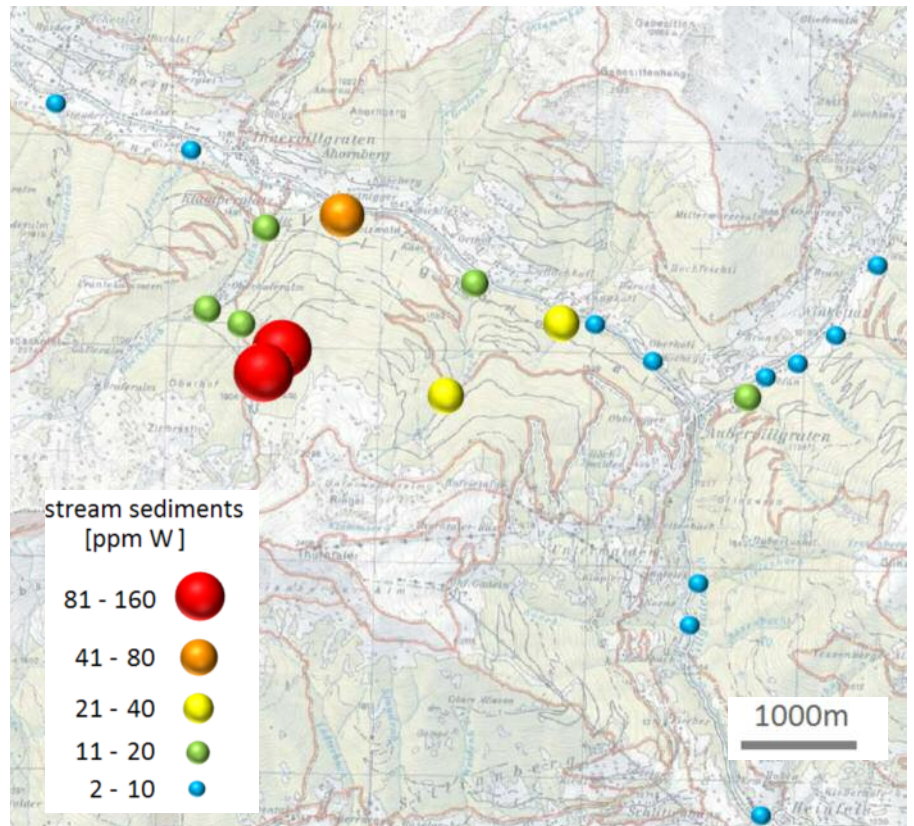


Figure 10: Exploration field work – Stream sediment sampling (left) and an anomaly map (right) for regional tungsten exploration in Austria.

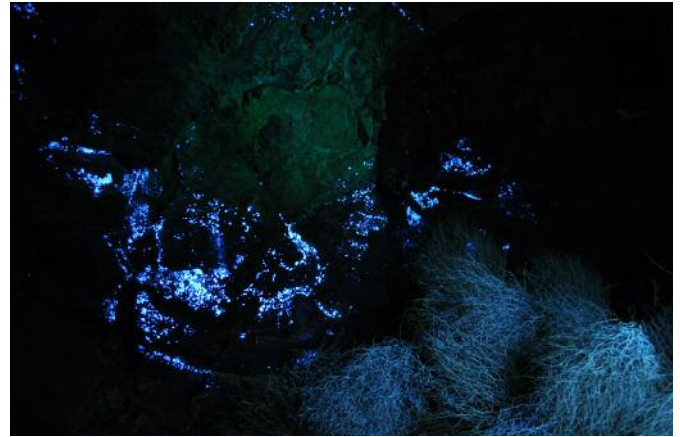


Figure 11: Exploration field work – Breccia-hosted scheelite during night prospection at Darwin in the Californian desert (left flash light, right UV light).

Thus, the main avenue to discovery is:

1. Selection of a prospective area (for example in one of the known deposit clusters, and near granites).
2. Geochemical prospection, for example, testing stream sediments for tungsten content (or scheelite) and then tracing the way of an anomaly back up-stream (**Figure 10**).
3. In case of scheelite: night-prospection with UV light. An example for successful systematic grass-root exploration was the discovery of the Mittersill deposit in the Austrian Alps in 1967 (**Figure 11**).

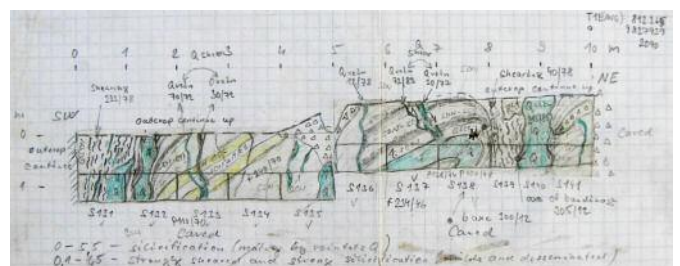
The latter is also an example for two other issues:

- Scheelite is easily overlooked, unless specifically explored for: the Mittersill deposit is a world-class high-grade deposit, directly outcropping, in a densely populated area: for any common commodity (such as iron, copper or lead-zinc), a deposit of this size, in such a setting, would have been discovered centuries earlier.
- Discovery of a deposit based on a specific scientific theory does not prove that the deposit is indeed of the envisaged deposit style.

Detailed Exploration

Once the deposit is discovered, staged exploration aims to provide the base for increasingly reliable estimates of the resource inventory: in order to plan mining, a reliable model of shape, tonnage and grade distribution within the deposit is required as well as information about the ground conditions (rock quality, geotechnical parameter). This is initially done by mapping (**Figure 12**).

The staged drilling campaigns are often the single most expensive item prior to mine development. In a typical case, the deposit would have been identified by sparse randomly oriented drill holes, and detailed exploration would tighten this to a regular grid. For example, in the initial phase of resource definition, one hole every 200 m might suffice, while determination of Proven Reserves at the same deposit requires holes in less than 25 m spacing.



Figures 12: Exploration field work – Mapping of a trench in Rwanda (top) and an excerpt of the geologist's field book (bottom).

The principal method of detailed exploration is drilling, in general diamond core drilling: in contrast to destructive drilling methods such as employed during exploration of hydrocarbons, core drilling allows to obtain an intact sample of the intersected ground, in the form of a drill core. This permits examining in detail mineralogy, lithology and ground conditions of the ore zone and assures that no contamination occurs. While advancing the drill hole, the core is recovered in a core barrel, which then is retrieved with help of a wire-line (Figures 14 and 15).

Another common exploration drilling method is reverse circulation (RC) drilling. Drill chips are recovered by compressed air blown down the rods through the centre void of the drill string. In the case of tungsten, the high density contrast between ore minerals and host rock and their high friability pose risks of biased results, and RC drilling is rarely used for detailed tungsten exploration.

Many tungsten deposits are “nuggety” and the problem of a high nugget effect (refer to info box “Nuggety Ore” and the Nugget Effect) is exacerbated by the comparatively small sample volume recovered during diamond core drilling. In general, for a very coarse-grained mineralisation, one would aim for the highest possible sample volume to assure representative results for individual samples.



Figure 13: Underground channel sampling at the Rudnik mine, Serbia, testing scheelite mineralisation.



Figure 14: Exploration drilling at the Mineração Nordeste Brasil's project near Serra Negra do Norte, Brazil.

“Nuggety Ore” and the Nugget Effect

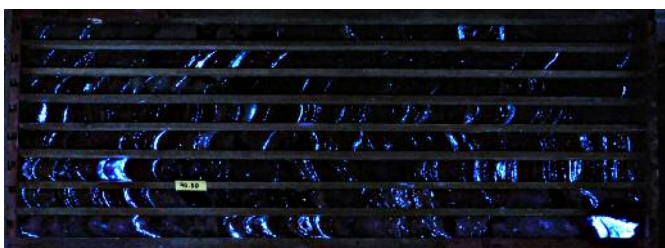
Nuggets are known from gold deposits, and the term describes the occurrence of comparatively large grains of the valuable mineral in an overall very low-grade deposit, such as in the case in many tungsten deposits, especially vein-type deposits. A deposit with the said characteristics is described as “nuggety”.

In practice, this means that a given sample (for example, a drill core) might or might not contain one of these larger grains, and thus does not give a valid estimate for the mineralisation as such (it is either – in most cases – too low, or – in rare cases – much too high).

In geostatistics, the nugget effect describes the variance between two samples taken at (virtually) the same position – this might also be due to sampling errors. The higher the individual sample volume, the lower the nugget effect.



Nuggety wolframite ore at the Panasqueira mine, Portugal. Visual estimates (surface of black wolframite in white quartz) are used to determine the grade. Note: a 2 mm thick “continuous seam” of wolframite would account for a grade higher than the average production grade of the mine.



Figures 15: Drill core from the Mittersill scheelite mine, seen at normal (top) and UV light (bottom).

Trenching, underground channel sampling (**Figure 13**) and test mining of small ore blocks provide better results, but might be prohibitively costly. Trenching is only possible along the surface outcrop, and results might be influenced by weathering and supergene enrichment.

Limitations and constraints of the sampling have to be taken into consideration during the subsequent stage of the investigation, notably for resource modelling.

Resource/Reserve Modelling

Determination of the (at the given time best possible) estimate for the quantity and quality of ore that can be mined from a given deposit is probably the most important parameter for the economic assessment of a proposed mining project (and justification to spend money on a mineral property, at any stage). These estimates and their reporting in the public domain generally follow certain industry standards (see info box Mineral Resources and Ore Reserves).

Mineral Resources and Ore Reserves

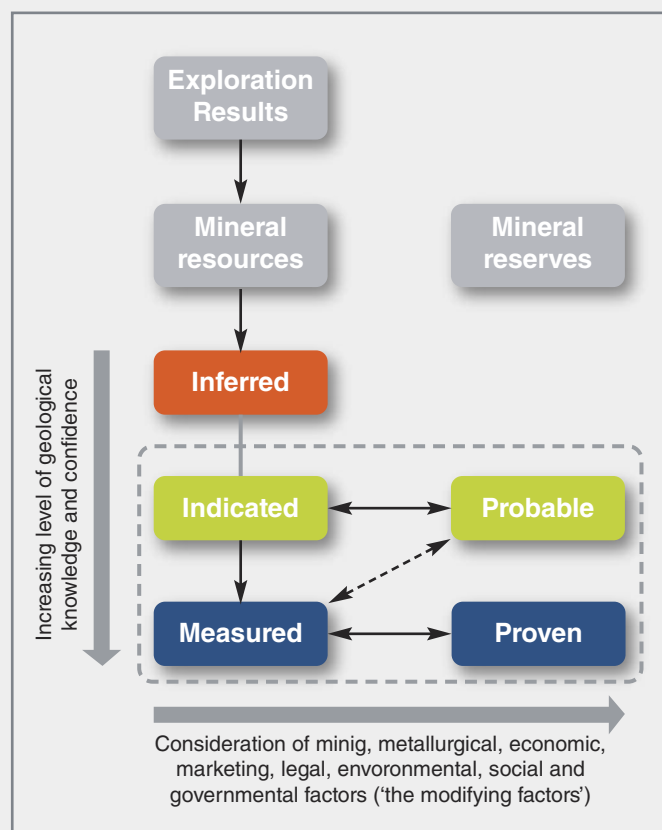
In the wake of the Bre-X scandal, a massive gold mining fraud that unravelled in 1995 (DANIELSON V & WHYTE J [1997]), rules for reporting of mineral resources and reserves by public companies were tightened in most jurisdictions. Several different resource reporting codes exist, but the main definitions were standardised in the late 1990s. The most wide-spread codes used are JORC (Australasian), CIM (Canadian) and SAMREC (South African). Somewhat different codes exist in Russia, other states of the former Soviet Union and China.

Companies listed on the principal international stock exchanges are generally obliged to follow the guidelines defined by these codes.

These codes all distinguish between resources and reserves as follows:

- Resource: the estimate of the quantity and quality of the mineralised material in-situ that has potential to be mined economically in future; and
- Reserve: the under current conditions economically mineable portion of the resource, including adjustments for dilution and mining losses and the application of modifying factors.

All these codes include the concept of Competent Persons. A Competent Person is a suitably experienced professional who has a minimum of five years' experience which is relevant to the style of mineralisation and scope of the report. The Competent Person must also be a member of a recognised professional association.



Relation between Mineral Resources and Mineral Reserves showing classification with increasing quality of data. Redrawn after CIM [2014]

The estimate is based on “hard facts” (like assay values and density measurements at sample points) and a diligent interpretation and interpolation how the ore grades are distributed in the three-dimensional space between these measurement points. It is important that continuity of the mineralisation can be assumed between the individual sample locations points. Therefore, a sound understanding of the deposit type is required. Subsequently, statistical and geostatistical methods are used to describe the data distribution and assess whether sample spacing is sufficiently tight within the given domain.

Traditional (“paper-based”) estimates have now been largely replaced by computerised block models, which allow not only global estimates but provide insight into the local grade distribution and thus aid mine planning and production scheduling. However, there are a number of risks attached to computer-aided modelling:

- Black box: the operator relies too much on the data processing of the computer without being able to follow-up step-by-step.
- Misinterpretation of the deposit model; lack of continuity between neighbouring samples; risk of modelling across “hard boundaries” (like geological contacts).
- In general, there is a tendency to model “unconstrained” if the morphology of the deposit is complex.
- Over-reliance on local estimates: other than in paper-based models, it is easy to forecast production in small increments: however, even if the global estimate is indeed correct, local estimates might be completely erratic. Blocks are filled with information, but the information might be nonsensical.

A computer-aided resource model can only be as good as the geological understanding. If individual quartz vein intersections in a stockwork deposit are interpreted as continuous quartz veins and modelled as a high-grade narrow vein deposit, the estimate is meaningless even if all statistical parameters indicate the opposite (**Figures 16 and 17**).

The finer-grained and more homogeneous a mineralisation is, the easier it is to provide reasonable grade estimates. In case of skarn deposits, the often complex shape has to be modelled due to the strict lithological control of the mineralisation: grades are not allowed to “float” across boundaries as in unconstrained models (**Figure 18**).

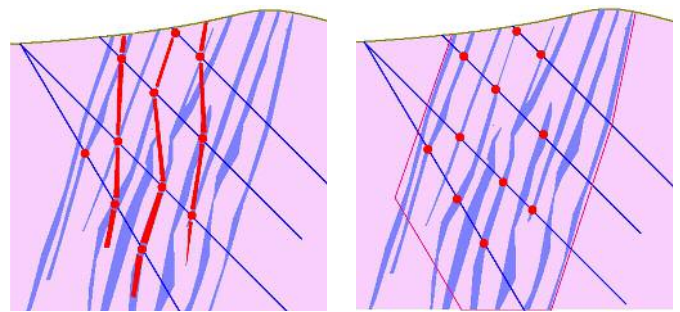


Figure 16: Erroneous interpretation of a stockwork as deposit comprising individual continuous high-grade quartz veins that could be mined in an underground mine (left: red dots = individual intersections above cut-off, assumed “orebodies” = red); valid interpretation of the same results as bulk mineable deposit suitable for open pitting (right: assuming average diluted grade is sufficiently high – resource estimate would encompass all material within purple outline).

The grade distribution of vein-type deposits is particularly difficult to model, due to the erratic (“nuggety”) distribution of the ore minerals. Reliable data can often only be obtained from underground development, not from drilling. Vein-type deposits are often operated with very little Ore Reserves “on the books”, but long-term experience shows that mined resources will be replaced in the course of day-to-day mining by newly defined resources.

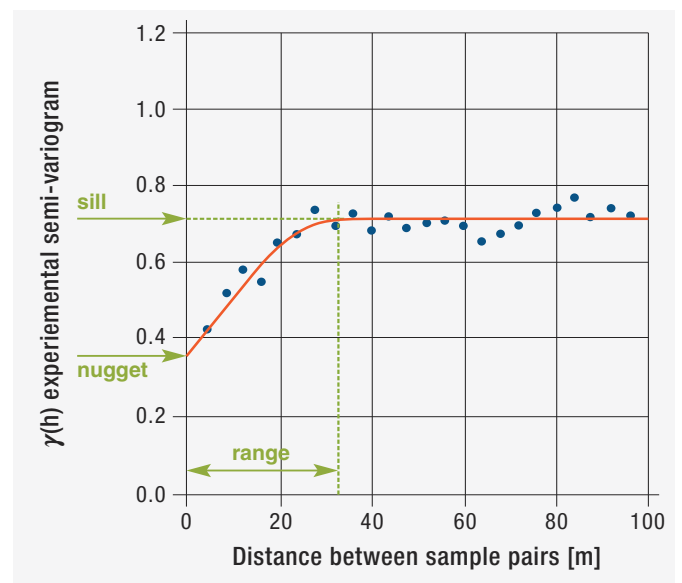


Figure 17: Semi-variogram (short: variogram), an important tool for the geostatistical interpretation of orebodies. Simply speaking, the range indicates the maximum acceptable drillhole spacing; at this spacing, the sill is reached, which means that sample results are independent of each other. The sill value equals the variance of the data set. The nugget describes the expected discrepancy of the result for drillholes drilled at (almost) the same place. Tungsten deposits, especially vein-type deposits have typically a high nugget effect.

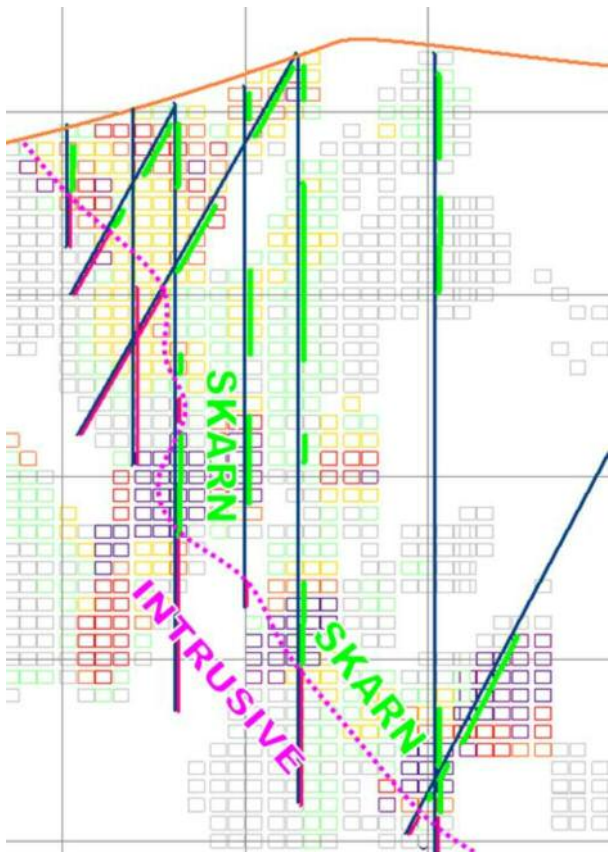


Figure 18: Erroneous interpretation of a skarn mineralisation due to unconstrained block modelling, not taking lithological boundaries into account: grades are allowed to “float” into the granite domain, which is completely sterile. Grid spacing =50 m

In case of vein-type deposits, required sample volumes to obtain reliable grade values might be prohibitive, and graphical methods (measuring the surface of ore minerals per square meter) are used instead. There might be also rule-of-thumb relations between vein thickness and mineral endowment, which aid in resource estimation.

Vein deposits can be seen as two-dimensional features, and, depending on their orientation, are still often shown in “traditional” VLP (vertical longitudinal projection) (**Figure 19**) or horizontal projection.

Once the geological inventory is determined with the required level of detail, modifying factors have to be applied to convert resources to reserves, i.e., to estimate the “mineable” portion of the geological (in-situ) inventory. These comprise mainly planned and an adequate allowance for unplanned dilution (where waste is taken instead of ore) and planned and unplanned losses (ore left behind in pillars or after blasting in stopes) (**Figure 20**). The parameter take ground conditions, mining method and legal requirements into account.

Where valid 3D block models exist (**Figure 21**), pit optimisation programmes allow establishing the most economic open pit outline, based on input parameters like operation costs, revenue and slope angle.

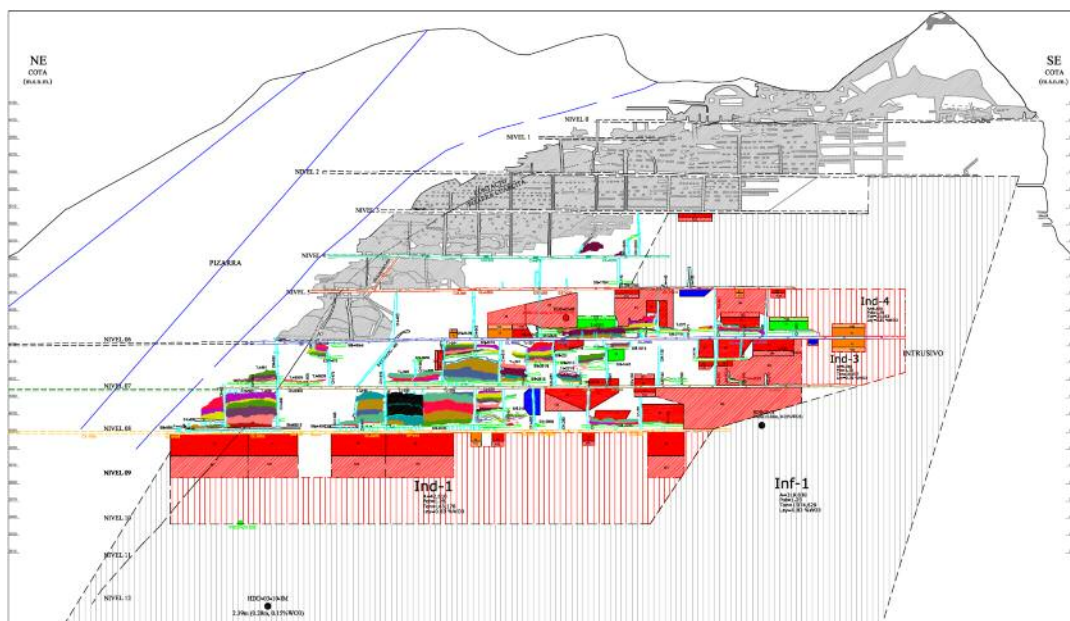


Figure 19: Classic presentation of the resource inventory of a narrow vein quartz-wolframite deposit on a VLP (vertical longitudinal projection), Pasta Bueno mine, Peru. From company documentation of Malaga Inc., Canada, prepared by Pincock, Allen & Holt in 2012. Grey areas = historic mining; solid blocks in red & orange = Proven Reserves; dense hatch pattern in orange & red = Probable Reserves, vertical wide hatching = Inferred Resources. Various colours in stoped areas = recent production in shrinkage stopes. Level spacing = 50 m.

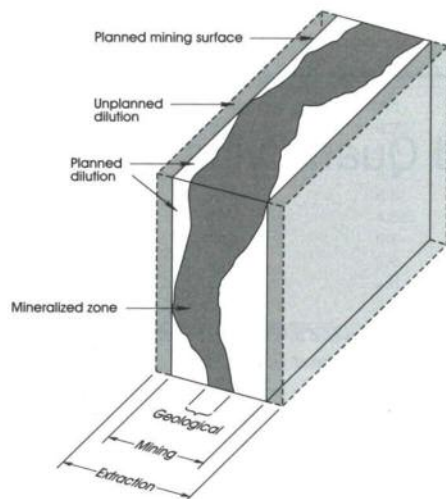


Figure 20: Conceptual view of planned and unplanned dilution when mining a tabular deposit: The planned layout for mining includes an irregular geological body and expected dilution by host rock; in reality, there will be likely some further overbreak into the sterile rock – so real extraction includes both, planned and unplanned dilution, both of which has to be accounted for in a realistic ore reserve estimate. From SINCLAIR & BLACKWELL [2002].

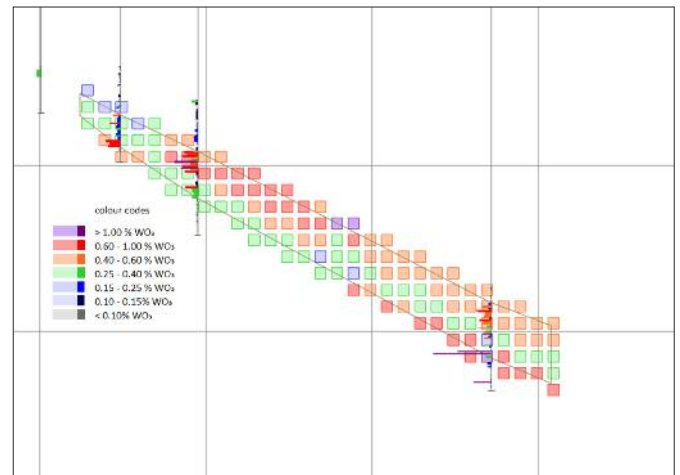


Figure 21: Resource estimation with three-dimensional block model, sectional view of grade interpolation between widely-spaced drillhole intersections, grid spacing = 50 m. This shows the relation between measured data along the drillholes and data interpretation in the block model.

Engineering Studies

From initial scoping to Bankable Feasibility Study, increasingly detailed engineering studies are required to provide a solid foundation for financial decisions. Initially, rule-of-thumb estimates might suffice, but in the later stages of the process, design, scheduling and cost estimation of mining methods, beneficiation techniques, the set-up of the entire infrastructure including tailings management and water supply and so on do require a vast specialist knowledge. Except in the largest international mining houses, this knowledge is not available in-house.

The engineering studies are therefore generally undertaken by specialist consultancy groups, and often outsourced to various specialists, especially where knowledge of such particular matters as flotation of scheelite is required. Mining and infrastructure of tungsten mines are not specific to the commodity, but beneficiation is highly sensitive, especially with respect to concentrate specifications. It might prove almost impossible to overcome certain ore dressing challenges, and in-depth metallurgical testwork, using representative samples from the deposit, is a must for a robust design of the beneficiation plant – and the overall economic model.

Together with resource definition drilling, metallurgy is the most expensive part of the engineering studies. Essentially,

resource definition and metallurgy go hand-in-hand: by definition a mineralisation is only a resource if potential economic extraction can be demonstrated. And the drilling and sampling of the orebody required to estimate the inventory are also the principal source of feed material for the metallurgical test work.

Given the low tenor of tungsten deposits, only a small quantity of concentrates can be produced per tonne of sample. Therefore, test mining or bulk sampling are likely to be required to supply additional material to supplement initial testwork based on drill core samples (**Figures 22 and 23**).



Figure 22: Pilot plant equipment at the Aachen Mining University, Germany used to undertake metallurgical studies for tungsten mining projects. In foreground a laboratory concussion table.



Figure 23: Pilot and lab-scale processing equipment at the metallurgical testwork facilities at the Nyakabingo mine, Rwanda. (left = spirals, right = super-panner)

Environmental and Social Studies

Environmental and social impacts of any mining operation are extremely sensitive issues, and they are not specific to tungsten mining. In fact, tungsten operations have often a smaller environmental impact than the more common base metal (lead, zinc, copper) or gold mining operations: beneficiation requires generally much lower or no usage of chemicals, and the levels of hazardous metals as arsenic and lead in the deposits are often low.

Mining projects have often a significant impact on the local communities. It is important to minimise negative impacts on one side, but promote reasonable and sustainable projects on the other side. Critics of mining in many industrialised countries are pushing the problems to less developed countries, which have lesser control on the possible impact management. It is important to assure the right balance between environmental impact, impact mitigation, social advantages (creation of employment) and possible disadvantages (eg, relocation), tax revenue, regional development opportunities and the economic benefit for the mine owner.

One common issue of mine development is the NIMBY attitude – “not in my backyard”: Mine development is stopped by local issues rather than being politically supported to assure supply with critical raw materials.

The level of environmental studies required to advance a mining project are often prescribed by legislation. In addition, funding of projects is often dependent on the adherence to the so-called Equator Principles, a set of standards to assess and manage environmental and social risk in project financing. Similarly, the seventeen United Nations’ Sustainability Development Goals (SDGs) are often covered in project studies for mines in order to demonstrate that the given project takes adequately care of sustainability issues.

Environmental studies can be divided into three overlapping areas: baseline studies that describe the current status, the assessment of the impact of the mine on the natural environment, and a management plan to mitigate the impact. An important issue is timing: the baseline studies require generally to record data covering an entire annual cycle of climate, ground water and natural habitat in the surrounding of the mine. Therefore, baseline studies are often started

early in the evaluation process, in order to collect the required data without undue time pressure.

Social impact depends largely on the scope and location of the proposed mine. In the case of a medium-scale underground mine in an industrialised country, social impact might be almost nil, while a larger-scale open pit mine in an area with an indigenous population having a traditional life-style might have a huge social impact: relocation, loss of ancestral values, alcohol-related problems and similar, which need to be minimised and offset by adequate management systems and significant efforts in direction of training, schooling, improved health care and regional development (respecting cultural heritage).

In the end, a mine will only then be fully successful, when it obtains a “social licence” – all stakeholders, and especially the local population, need to be convinced that benefits offset (and ideally exceed) the detriments of mine development.

While engineering studies are often undertaken by consultancy groups in the main mining countries, social and environmental studies require local knowledge and in their best case are developed jointly by experienced expatriates together with local or regional experts, and thus promote knowledge transfer.

Permitting

Permitting can be a very time-consuming and frustrating process for the prospective operator. While the original exploration permits are clearly issued with the intention to progress a discovery to an operating mine, authorities outside of the traditional mining countries are sometimes taken by surprise when this actually happens. The historically often poor track record of the mining industry (numerous abandoned mine sites require public funding because the operators simply “disappeared” and a number of well-publicised environmental disasters related to mining) caused understandably a skeptical approach to new mining applications, and the permitting authorities try to play safe by imposing very stringent regulations.

It is a must for the potential miner to involve from the outset all stakeholders and good communication is invaluable to build trust and obtain support from the local population and regional governments. This mutual trust and the feeling

that the operation is actually beneficial for the region can help to overcome unspecific opposition by anti-mining groups.

In general, permits are required from various authorities, and beside the actual “mining” cover issues like construction, water supply and discharge, environmental compliance, explosives and might involve tricky issues like employment of expatriates and knowledge transfer.

There is also a tendency to oblige operators to strive for value adding by not exporting concentrates, but going further down-stream. In the case of tungsten, a significant annual capacity, long lifetime of the resources and suitable infrastructure including stable electricity supply is required to justify downstream upgrading to APT. This needs to be communicated.

Permitting is a staged process, and while many permits can be obtained rather early in the process, final permits might only be available after construction, and thus a residual risk remains throughout financing and construction. Permitting risks are also detrimental to off-take commitments, which rely on prompt delivery according to a pre-approved schedule. It is thus of the utmost interest to the mining company to handle the entire permitting process with greatest care – and that might prove to be particularly challenging to inexperienced Junior Resource companies as typical for the tungsten sector.

Marketing, Financing and Construction

Tungsten is not traded on a metal exchange, and it is not possible to hedge concentrates. Most concentrate is traded directly between mines and APT/down-stream producers. Therefore, the market is fairly opaque, which makes it difficult for a newcomer to get a good idea of the expected revenue for his product. However, various journals (London Metal Bulletin, Metal Pages, Ryan's Notes, ...) publish price indications for APT and concentrate.

Due to the small size of the market, it is difficult to assure off-take – even if the price is right. For example, during the Global Financial Crisis in 2009, the APT quotation did not decrease as much as the prices for more common metals; however, not because the market remained intact but rather due to the absence of any market.

The tungsten mining sector is a playground for Junior Resource companies – major mining companies are generally not interested in this market. This, and the limited understanding of the tungsten market by investors, makes financing even more challenging. Preliminary Economic Assessments and Feasibility Studies recently completed for a number of projects show very favourable economic indicators (Internal Rate of Return, Net Present Value), but this is based on the assumption of guaranteed off-take of the entire production – which is illusory if several of the large-scale projects would be developed contemporaneously. Projects currently under consideration have partly planned capital investments of several USD 100M.

At the same time, there is persistent hesitation of the downstream companies to go upstream and look for backward integration.

In summary, these factors limit access to financing, which will minimise the risk of sudden oversupply followed by yet another wave of renewed mine closures. However, the development of some additional tungsten concentrate capacity is a must to balance the supply of the downstream industry. The most promising avenue to financing is for promising projects to collaborate with the downstream industry and have solid off-take contracts in place.

In most cases, once a larger-scale mining project obtains financing, construction will still take two to three years before initial production commences.

Part 2 of this article looks into operational practices in tungsten mining and features with many examples from the worldwide industry.



Wolframite from artisanal mining in Burundi.

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