Graphite minerasl notes. Published on LinkedIn May 6th 2019. Andrew Scogings.

Vein graphite in charnockite from Sri Lanka. Sample approximately 8 cm wide

Graphite is an allotrope of carbon and is grey to black, opaque, very soft, has a low density and a metallic lustre. It is flexible and exhibits both non-metallic and metallic properties, making it suitable for diverse industrial applications. Physical properties include specific gravity of 2.2, and Mohs hardness of 1-2. Flake graphite is produced and sold according to specifications, the most basic of which is size faction for which there commonly accepted market descriptions such as Fine, Small, Medium, Large and Extra Large (see table below).

Global natural graphite production is approximately 1 to 1.2 million tonnes (Mt) per annum, of which **flake** graphite is estimated to be about 600-800 kt per year, **amorphous** graphite about 300 kt and **vein** graphite around 4 kt.

The leading world producers of flake graphite in 2018 were China and Brazil. Mozambique is ramping up production significantly, having produced around 0.1 Mt in 2018 - it is anticipated to overtake Brazil and become the second largest global producer in 2019. China is also seeing increased flake graphite production, mainly from Heilongjiang Province, to supply the battery anode market.

Amorphous graphite is produced mainly in China and Mexico. Sri Lanka is the sole producer of vein graphite.

The major usages of graphite are in refractories, batteries, expandable graphite, plus brake linings, lubricants and steelmaking / foundry operations.

Batteries are the fastest growing market for flake graphite. Chinese producers use small / fine flake (China Specification LG -194; 80% < 100 mesh, Carbon >94%, moisture <0.5%) to make spherical graphite for battery anode applications. The conversion ratio for flake to spherical graphite is estimated to be around 30-40%, hence the production of spherical graphite is expected to generate significant tonnages of fine ('amorphous') graphite by-product and drive prices down at that end of the market. Exports of spherical graphite from China increased by around 40% in 2018 compared with 2017 (Benchmark Mineral Intelligence, 12 December 2018).

Expandable graphite is another market expected to grow, for applications such as fire retardation, insulation and heat transmission applications. As a rule of thumb, the highest expansion rates are achieved by large and extra large flake products generally >80 mesh (>180 micron).

Commonly accepted flake graphite product nomenclature		
Sizing (micron)	**Sizing (mesh)**	**Market terminology**
>300	>48	Extra-Large or 'Jumbo' Flake
180 to 300	80 to 48	Large Flake
150 to 180	100 to 80	Medium Flake
75 to 150	200 to 100	Small Flake
<75	<200	Fine Flake

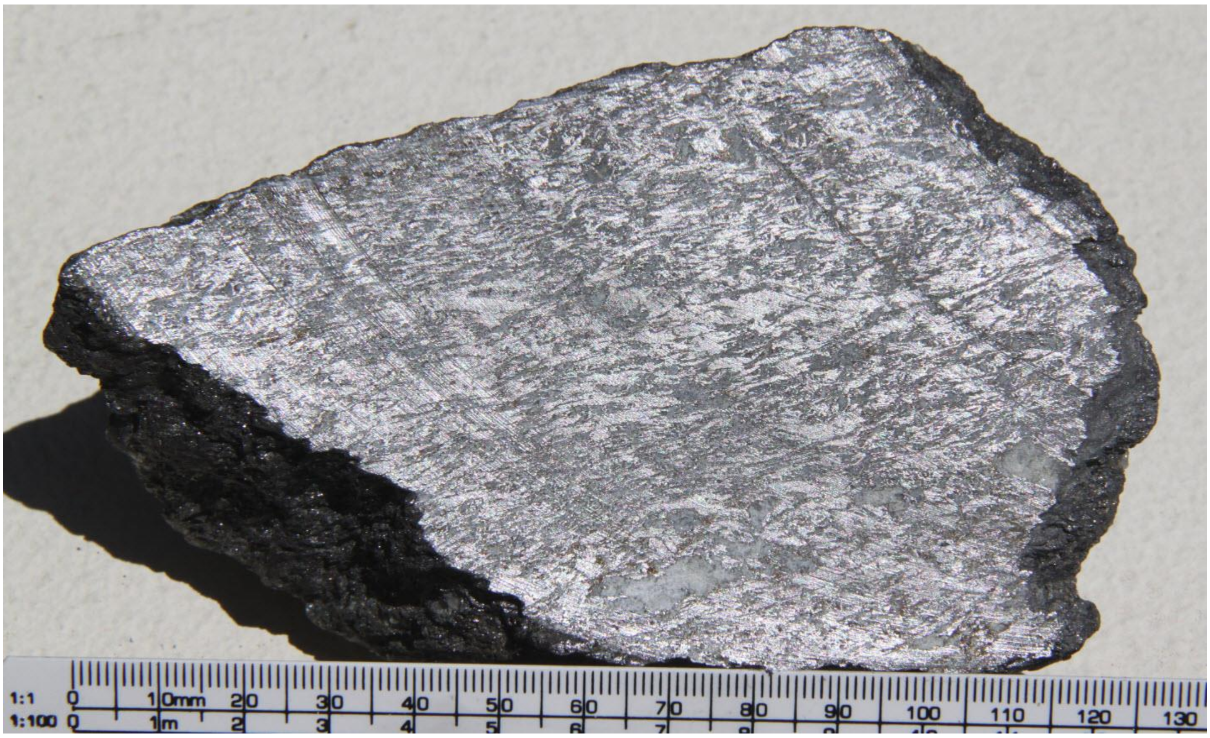
Geology and mineralogy

Natural graphite deposits occur in three main geological settings: **flake graphite** disseminated in metamorphosed sedimentary rocks such as gneiss or schist, **amorphous graphite** formed by metamorphism of coal or carbon-rich sediments, and **vein** or **lump** graphite filling fractures in granitic country rock.

The term 'amorphous graphite' is a commercial term and is misleading, as all graphite has a crystalline structure though the degree of crystallinity may vary. Fine crystalline flake is often described in the trade as 'amorphous', leading to confusion when analysing graphite production and markets.

Graphite may be manufactured synthetically from carbon-bearing raw materials such as petroleum coke. Synthetic graphite is far higher-priced than natural graphite.

Natural graphite products typically contain mineral impurities, which may include silicate and sulphide minerals such as quartz, mica or pyrite in the case of flake graphite. Amorphous graphite derived from coal may contain sedimentary rock impurities such as shale, sandstone, quartzite or limestone.



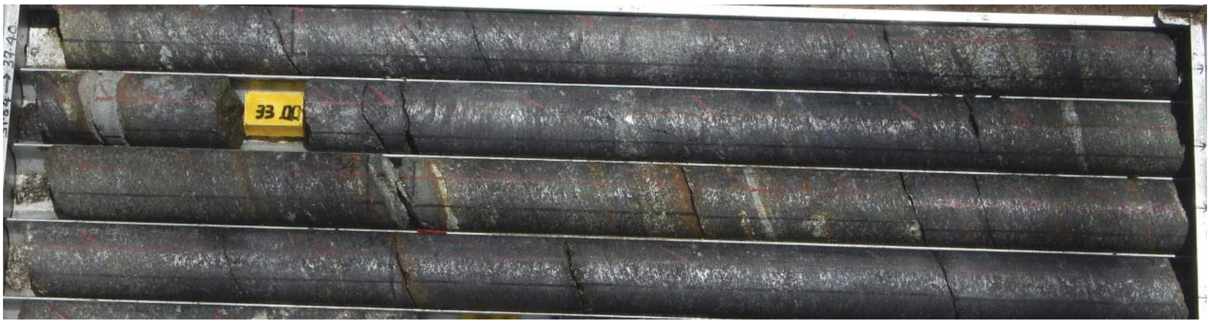
High grade flake graphite ore from an underground mine in Europe. Sample is approximately 12 cm in length.

Exploration methods

Graphite is explored for by methods such as field mapping, outcrop sampling, trenching, geophysics, drilling, and analysis of the graphite content followed by mineralogical and metallurgical testing. Given that graphite conducts electricity, various electromagnetic (EM) methods can be highly effective exploration tools for graphite mineralisation.

There are two main methods of drilling for natural graphite: reverse circulation percussion (RC) and diamond core drilling (DD). Auger drilling may occasionally be used to explore highly-weathered clayey mineralisation. RC is a useful way of infill drilling to demonstrate geological and grade continuity, as it is less costly than DD; however RC drill chips and powder are not suitable for metallurgical / process tests. DD is the preferred method of exploration drilling for graphite, as the graphite and host rock are relatively undisturbed when retrieved as core and hence appropriate for metallurgical testwork.

RC drill chips from a graphite deposit. The chips are about 5 mm length. Each compartment in the chip tray represents 1 metre.



DD core from a high grade graphite deposit. The core tray is 1 m long.

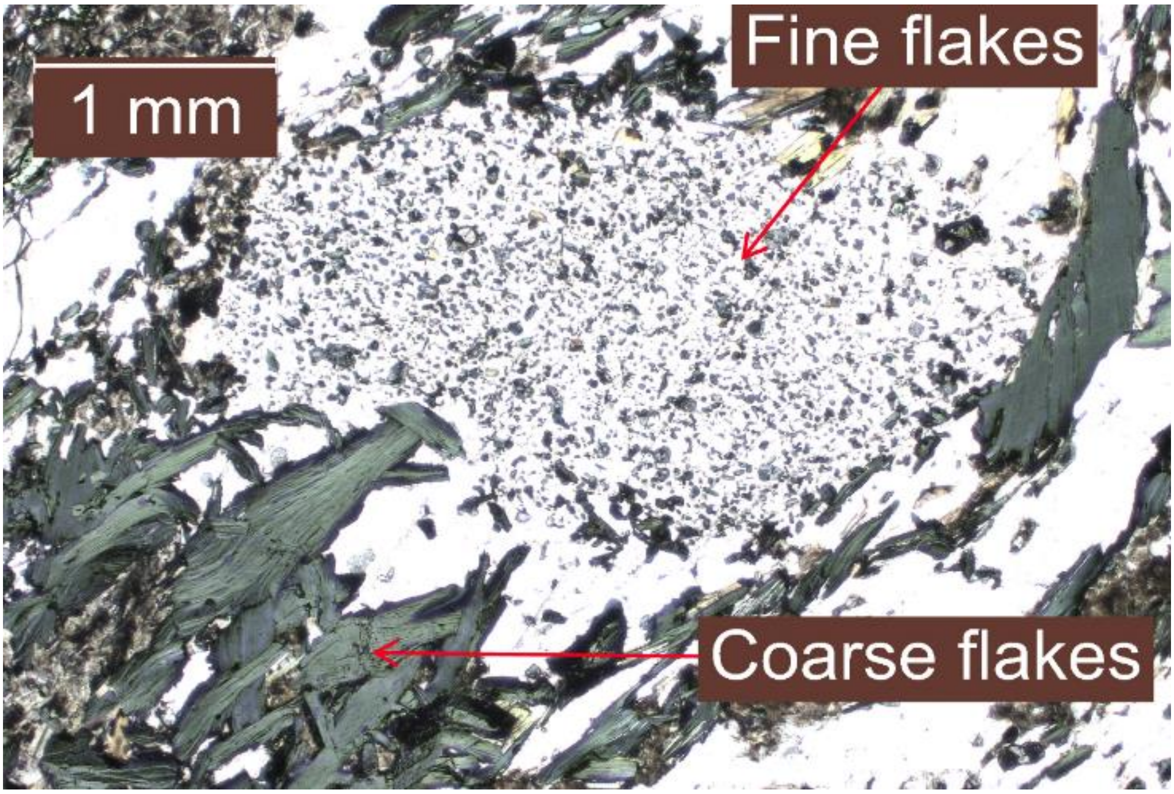
Sample analysis

Carbon may be present in rocks in various forms including organic carbon, carbonates or graphitic carbon. Carbon in rocks may be reported as total carbon (organic carbon + carbon in carbonate minerals + carbon as graphite) or as total graphitic carbon (total carbon – (organic + carbonate carbon).

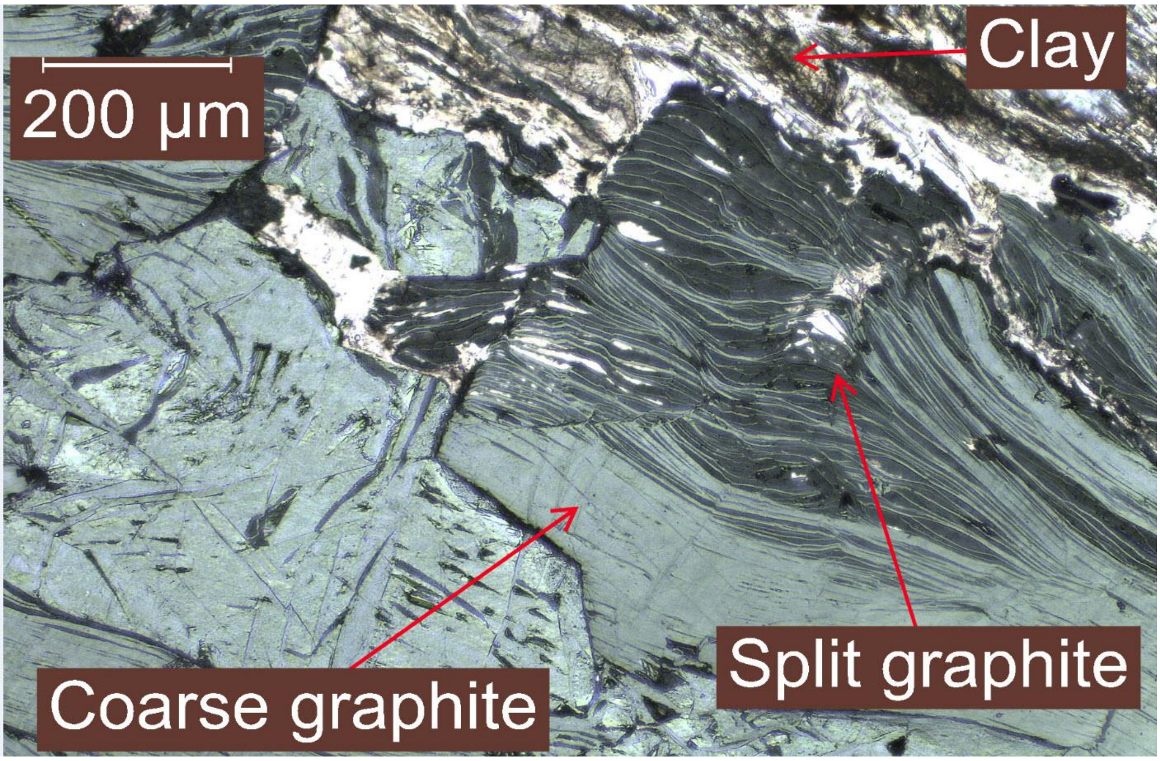
Therefore, when total graphitic carbon (TGC) is to be reported, organic carbon and carbon in carbonate minerals such as calcite should be removed before analysing TGC.

Exploration samples can be examined in thin section under a petrographic microscope, which is a relatively affordable and quick way of estimating the in situ graphite flake size distribution, gangue mineralogy and likely liberation characteristics. Optical microscopy may be complemented by methods such as XRD, QEMSCAN (Quantitative Evaluation of Minerals by Scanning Electron Microscopy) and MLA (Mineral Liberation Analyser, or automated SEM).

Thin section of graphite biotite hornblende gneiss. The black flakes are graphite, the small brown patches are bitotite and the pale green mineral is hornblende. Transparent minerals are quartz and feldspar. Thin section dimensions approximately 25 mm x 50 mm.



Flake graphite in thin section, illustrating a bimodal population. It is unlikely that the fine (very small) flakes can be recovered by flotation. Transmitted and reflected light, plane polarised.



Flake graphite in thin section, illustrating how graphite may be split where it comes into contact with weathering products such as clay derived from the breakdown of silicate minerals. Transmitted and reflected light, plane polarised.

Assaying for graphitic carbon quantifies the amount of graphite contained within a deposit, but does not indicate the amount, size distribution or purity of graphite that may be recoverable.

Therefore, samples should be tested at a metallurgical laboratory, which would typically run comminution and flotation tests to produce graphite concentrates (products) for further product performance tests and evaluation by potential customers.

Performance and characterisation tests include bulk density, crystallinity, Loss on Ignition (LOI), chemical purity, expandability and spheronisation amongst others.

Laboratory-scale flotation of flake graphite

Global flake graphite exploration

There has been intensive exploration for graphite by publicly-listed companies since about 2012, with most activities aimed at flake graphite deposits in Australia, Canada, **Mozambique** and **Tanzania**. The biggest Mineral Resource tonnages were discovered in northern Mozambique and southern / central Tanzania. Other target countries include Brazil, Finland, Madagascar, Malawi, Sweden and the USA.

Publicly reported exploration has added approximately 5.3 billion tonnes to the global flake graphite Mineral Resource base, at an average grade of just under 9% graphite. The reported deposits range in size from about 2 million tonnes (Mt) to over 1,000 Mt, while grades in individual deposits range from approximately 2% to as high as around 25% graphite (TGC).

Publicly reported global graphite Mineral Resources 2018

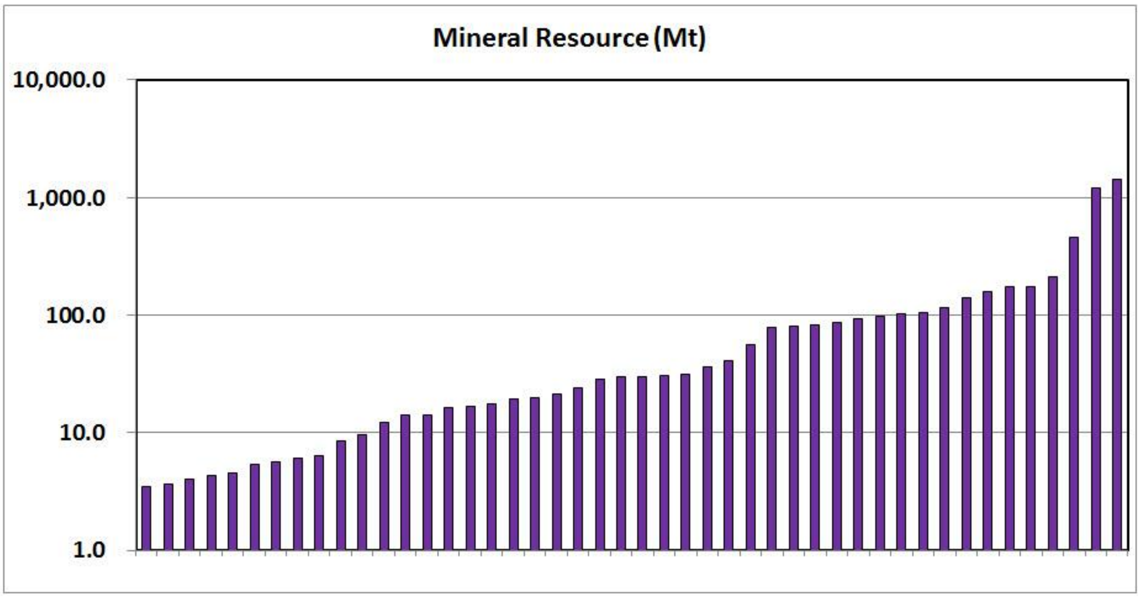
Country or Continent	Mineral Resource	Graphite	Contained graphite
	Mt	%	Mt
Africa	4,095	9	378
Australia	149	9	13
Canada	368	6	23
Madagascar	171	6	11
Russia	116	13	15
Scandinavia	77	13	10
USA	332	4	14
Total	5,308	8.7	464

Note 1: differences in tonnages and grades may occur due to rounding

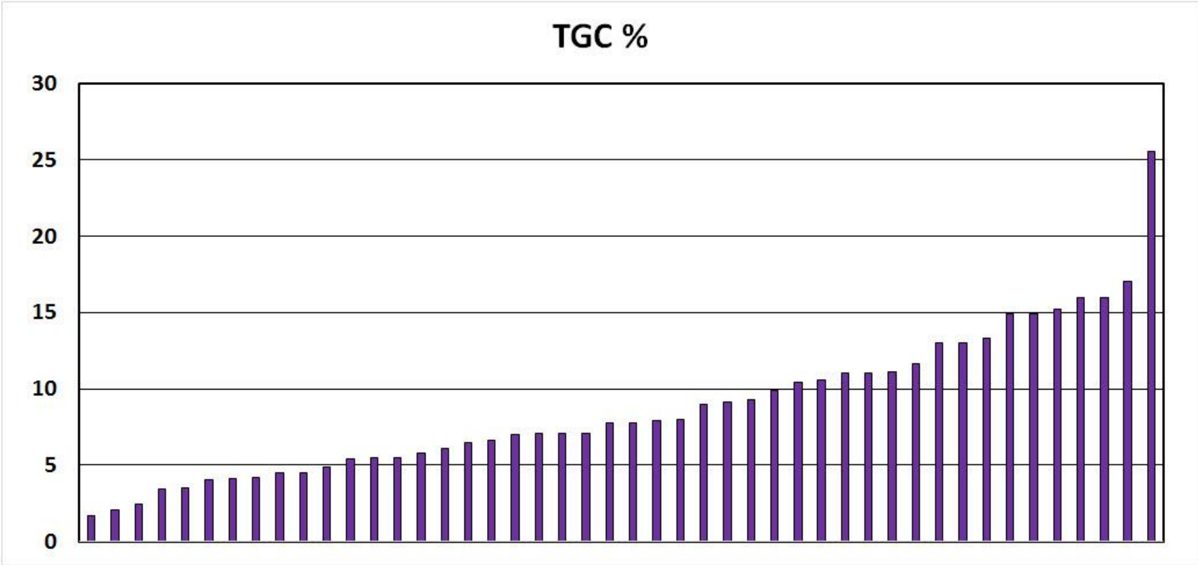
Note 2: tonnages and grades based on available information at the time of compilation and are not definitive

Individual flake graphite deposits vary widely in terms not only of tonnage and graphite grade, but also with respect to in situ and liberated graphite flake size. The investor should be aware that 'not all graphite deposits are created equal' and that neither tonnage, nor graphite grade, are specifically an indication of final product recoveries or quality.

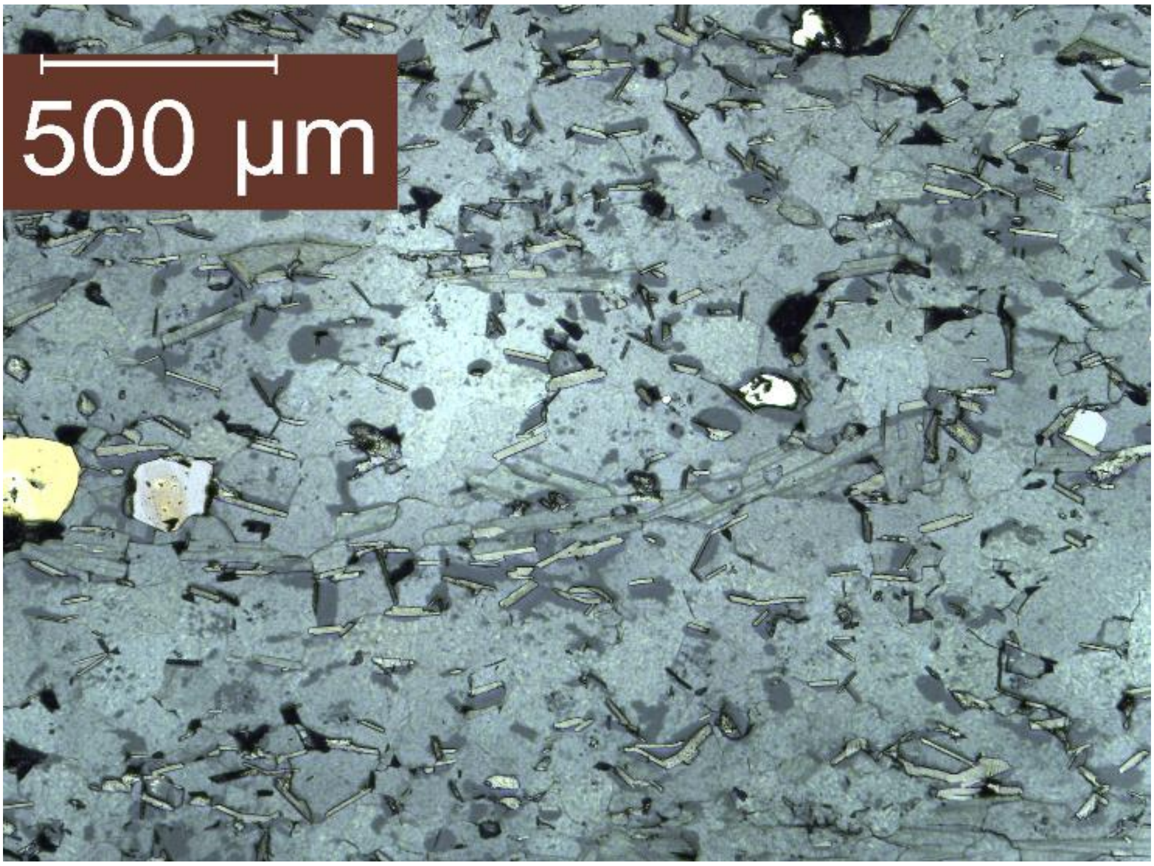
The size distribution and purity of liberated flakes is important to project economics, as this affects product marketability and sales price. As a general rule of thumb, larger flakes attract a higher price than small flakes, e.g. extra large flakes >300 micron may attract a price several times that of small flakes <150 micron.



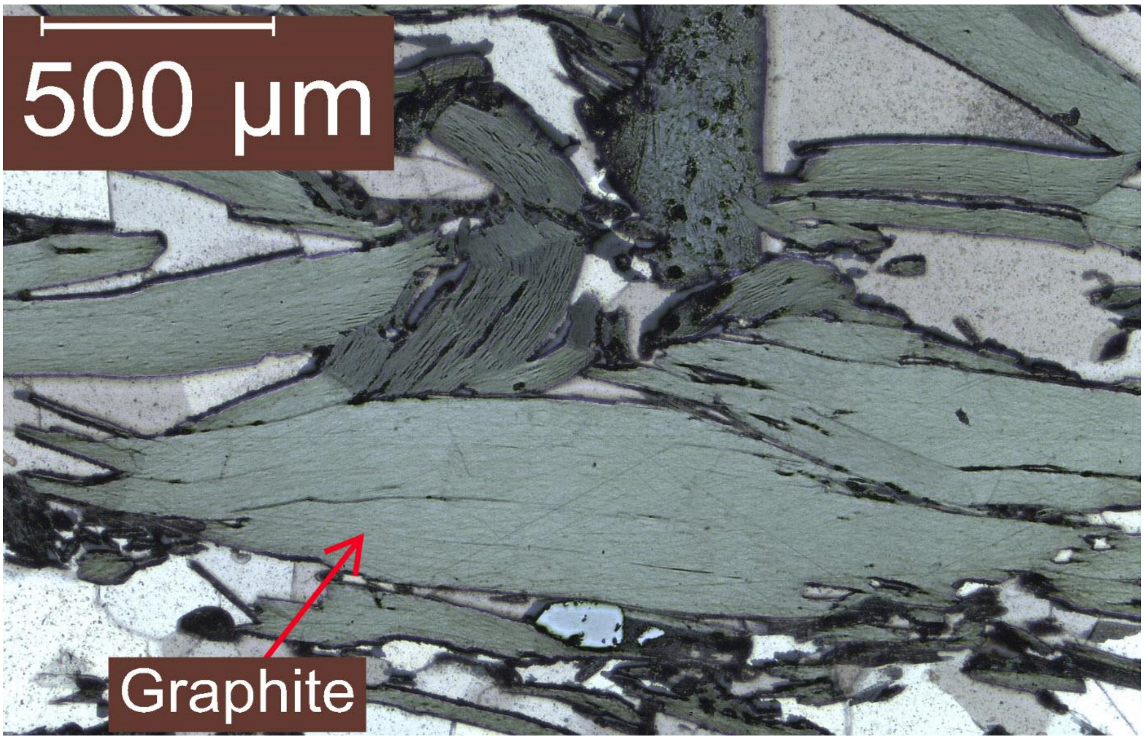
Publicly reported flake graphite deposits, ranked by Mineral Resource tonnes. Logarithmic scale, million tonnes.



Publicly reported flake graphite deposits, ranked by Mineral Resource grade (TGC %).



Very small in situ graphite flakes mostly less than 100 micron (0.1 mm) in length. This rock sample is from a relatively large deposit. Thin section, plane polarised transmitted and reflected light.

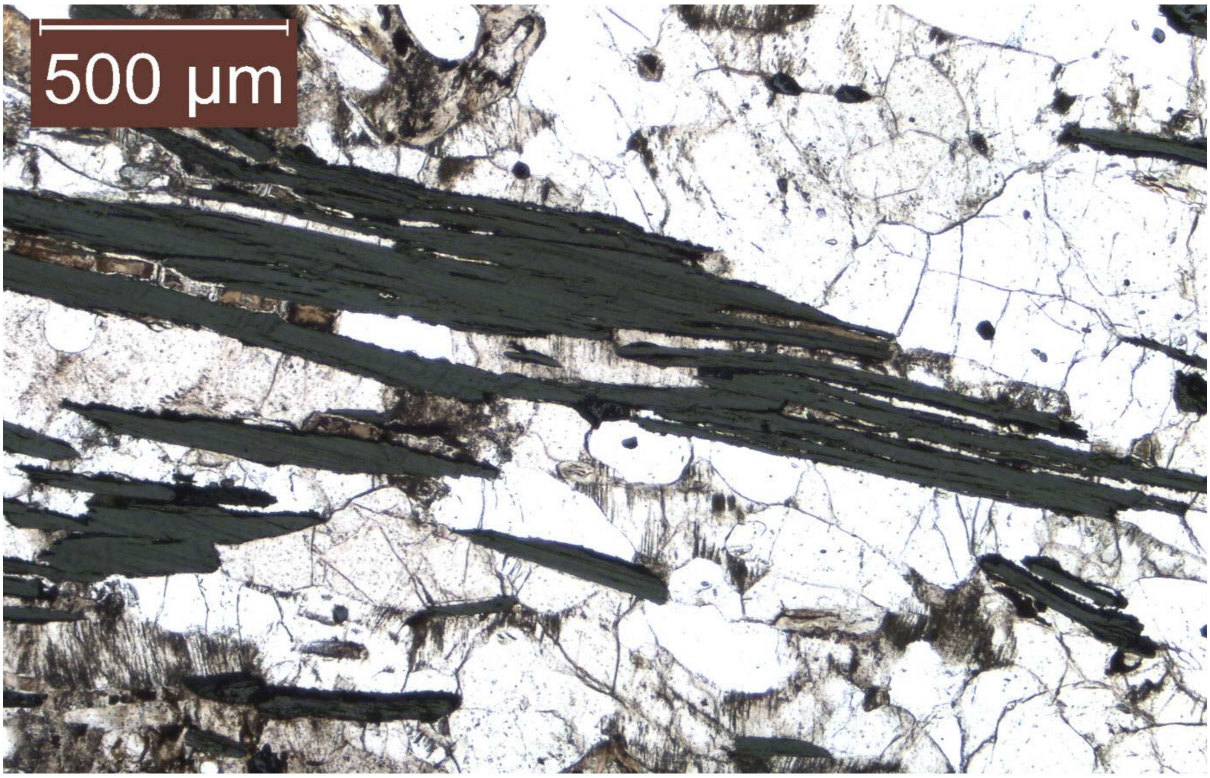


Large in situ flakes in excess of 500 micron (0.5 mm) in length. This rock sample is from a relatively small deposit. Thin section, plane polarised transmitted and reflected light.

Mining and production

Flake graphite deposits occur as lens-like to tabular bodies and are generally mined opencast, though some high-grade flake graphite deposits are mined underground in Germany and Norway and until recently, in Zimbabwe. Most flake graphite deposits mined opencast contain between about 5% and 15% graphite, whereas underground mines have grades of around 20-30% graphite.

Flake graphite mine near Luobei in Heilongjiang Province, NE China. Photo courtesy of Andrew Spinks, Kibaran Resources Ltd.



Flake graphite ore from a producing mine near Jixi in Heilongjiang Province, NE China. Thin section, plane polarised transmitted and reflected light.

Some flake graphite deposits are deeply weathered and described as 'free-dig' given that explosives are not needed to extract the ore – examples include producing mines in Brazil and Madagascar and some exploration projects in Malawi and Australia.

Vein deposits have complex geometry, are narrow and are selectively mined underground in Sri Lanka. Amorphous graphite is mined underground, mainly in China, using methods similar to coal mining.

The most commonly used beneficiation method for flake graphite is flotation, while acids or alkalis may be used to leach out impurities from concentrates. Graphite ore is crushed and ground in rod mills, before flotation, followed by several regrind and cleaner flotation stages and final drying, screening and packaging. Vein graphite is often purified by hand-sorting.

Most spherical graphite for lithium-ion battery anodes is manufactured in China and then exported to Japan or Korea for final coating. The process involves micronising and spheronising the graphite flakes followed by purification (commonly acid, alkaline or heat treatment) before being coated and made into anodes. The conversion ratio for flake to spherical graphite is estimated to be around 30-40%.

Spherical graphite plant

Rod mill at a flake graphite mine in China.

Flotation at a flake graphite mine in China.

Rotary dryer at a flake graphite mine in China.

Specifications

Graphite products are typically specified, at a minimum, by particle size distribution and carbon content (purity) as shown in the table below for some refractory products. There are no set industry specifications, although in countries such as China the government has established national standards based mainly on carbon content and size category.

Chinese flake graphite standards are based on four categories LC, LG, LZ and LD according to carbon content. These four categories are subdivided into 212 grades according to retained percentage by mesh size, fixed carbon, volatile content and moisture.

Other specifications agreed to by the producer and customer may be moisture, volatile content, bulk density, crystallinity, specific surface area, impurities, peak oxidation temperature and expansion volume for example.

Some refractory products and graphite specifications

Product	Flake size	Flake Graphite quality
Unshaped refractories	> 150 micron	85 to 94% C
Graphite-containing crucibles	> 150 micron	85 to 96% C
Magnesia / Dolomite Carbon bricks	< 150 to >300 micron	90 to 95% C
Alumina Magnesia Carbon bricks	< 150 micron	92 to 94% C

Source: Christoph Frey, Pro-Graphite (IM Graphite and Graphene Conference 2014)

China National Standards: flake graphite products categorised by carbon content

Category	Lower limit (% Carbon)	Upper limit (% Carbon)
LC (high purity)	≥ 99.9	100
LG (high carbon)	≥ 94.0	< 99.9
LZ (intermediate carbon)	≥ 80.0	< 94.0
LD (low carbon)	≥ 50.0	< 80.0

Source: GB/T 3518-2008 Flake Graphite Standards

China National Standards - examples of flake graphite product specifications

Mesh	Micron	Specification	Carbon %	Grade	Category
50	300	75 % > 50 mesh	99	599	LG
80	180	75 % > 80 mesh	95	895	LG
150	100	75 % > 150 mesh	90	15090	LZ
-100	-150	80 % < 100 mesh	94	-194	LG
-150	-100	80 % < 150 mesh	85	-15085	LZ

Source: GB/T 3518-2008 Flake Graphite Standards

Reporting graphite Mineral Resources and Ore Reserves

Clause 49 of the JORC Code 2012 requires that: "For minerals that are defined by a specification, the Mineral Resource or Ore Reserve estimation must be reported in terms of the mineral or minerals on which the project is to be based and must include the specification of those minerals."

Natural graphite is an industrial mineral produced to customer specifications and therefore ASX and NZX listed companies are required to report Mineral Resources, Ore Reserves (and Exploration Results) in accordance with Clause 49 of the JORC Code.

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