



# GRAPHITE

## NOT ALL FLAKES ARE CREATED EQUAL

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### Properties, Geology and Abundance

Graphite is one of the three common allotropes of carbon (the other two are amorphous and diamond). It forms with a hexagonal crystal structure arranged in layers and is the most stable form of carbon under standard conditions. It is very soft, an excellent lubricant, basically inert, is an excellent electrical and thermal conductor. It is light (SG of 2.267 g/cm<sup>3</sup>, with the highest natural strength and stiffness and maintains strength and stability in excess of 3,600°C).

These unique properties support a 1.2 million tonne a year market with the demand in batteries expected to drive consumption up by 9%. This will require an increase in annual production of 500,000 tonnes by 2020.

The most important form of graphite is flake. These are flat, plate-like particles and are crystalline in nature. It is typically found in host rocks such as marble, gneiss and schists and is formed as a result of the reduction of sedimentary carbon compounds during metamorphic activity.

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In terms of Supply Risk Ranking, it is classified as a Strategic Mineral by the EU and a Critical Supply Mineral by the USA.

The other form of graphite, namely amorphous, is typically produced by thermal metamorphism of coal, and exhibits a low degree of crystallinity, very fine particle size and usually lower purity than crystalline flake.

The graphite market is 50 times larger than either the lithium or rare earth markets. More than 50% of the world's graphite production comes from just 10 companies, with 6 located in China. In 2015, China produced 780,000 tonnes (66%), followed by India 170,000 tonnes (14.2%) and Brazil 88,000 tonnes (6.7%). 70% of the world's graphite production is a flake product, with over 60% produced in China. While six graphite operations exceed production of 50,000 tpa, a typical operation produces 20,000 to 30,000 tpa of graphitic product.

Due to commitments to environmental reforms, China is cutting back on graphite production with more than 200 mines being closed. In addition, China has imposed a 20% graphite export tax along with an export licensing system as well as a 17% VAT. There is an increased focus on downstream processing and value-added graphite products such as expanded graphite (refer to Markets).

Graphite deposits are not uncommon and are found in many parts of the world. In 2015, the world reserves of graphite were estimated at 230 Mt, with the largest located in Turkey (99Mt), followed by Canada (72 Mt), China (55 Mt) and India (8 Mt).

Worldwide inferred resources exceed 800 million tonnes of recoverable graphite, which include the deposits discovered in eastern and south eastern Africa. With regard to assaying, it should be noted that Total Carbon (CT) includes Graphitic Carbon (Cg), Organic Carbon (COrg) and Inorganic Carbon (CInorg) (e.g. carbonates). It is very important to identify the Cg content rather than just total carbon at the resource stage to support the Feasibility Study and economic assessment, since it is unlikely that all the carbon present will be graphitic.

After processing, most of the non-graphitic carbon has been rejected and producers commonly report CT for the concentrate (although it is rarely 100% Cg). In the case of the battery market, not only is the Cg content measured but also the degree of crystallinity using X-Ray Diffraction (XRD). This is essential since only crystalline carbon (Cg) is conductive and close to 100% Cg is required for use as an anode in a battery.

## Markets

Like most industrial minerals, the market is relatively opaque and secretive, with a large range of niche markets built on long term relationships. Potential graphite products need to be 'qualified' with an interested customer before marketing arrangements and product prices can be locked in.

The graphite market, and thus pricing, is based on flake size and purity with higher grades and larger sizes generally commanding a premium. High purity is classified as  $\geq 94\%$  graphitic carbon (Cg, although producers typically report Total Carbon, CT) and in

2015, typical prices

- Jumbo : USD2,000 (>50 mesh [>300 microns]);
- Large : USD1,400-1,500 (>80 mesh [>180 microns]);
- Medium : USD1,200-1,300 (<80mesh/ >100 mesh [<180 microns/>150 microns]);
- Fine : USD1,000-1,100 (<100 mesh/>150mesh [<150 microns/>100 microns]); and
- Very fine : USD500 (<150 mesh [<100 microns]).

The largest market by tonnage is refractories (~39%, growth market) for steel making, such as magnesia-carbon bricks (25% graphite), foundry moulds, crucibles, etcetera. This market requires large and medium high purity (~94% Cg) graphite flakes.

Batteries are the second largest market (~21%, strong growth): anode in batteries e.g., nickel-metal hydride, lithium-ion batteries, fuel cells and requires high purity (>99.9% Cg), specially prepared graphite. (The main substitute is synthetic graphite (which is typically twice the cost of natural graphite)).

Not surprisingly, lubricants is a significant market (~14%, growth market): as a solid lubricant, additive to oils and polymer coatings as well as drilling muds as is the automotive market (~14%): brake linings, shoes and clutches: brake drums, brake pads and clutches.



Other markets include pencils (~4%), electrodes, steelmaking, graphite foil, carbon fibre reinforced polymer composites, carbon brushes, carbon additives and neutron moderator. There are a number of future markets for natural graphite including graphitic products (e.g. expanded graphite, graphene, fullerenes ('Bucky balls') and nanotubes) and substitution (existing carbon and synthetic graphite markets).

Expanded graphite is made by treating graphite with acids (chromic then sulphuric) to force apart the lattice planes. A potential use is in insulation applications offering fire resistance. The Chinese are developing this market through regulation. It also has potential as high temperature gaskets, foil for use in fuel cells, heat sinks (laptop computers) and valve packing. Graphene was discovered in 2004 and consists of a single layer of carbon,



one atom thick in a hexagonal lattice. It has a stunning range of properties, including strength (100x stronger than steel), lightness, highest electrical and thermal conductivity (exhibits the highest current density), almost transparent, no band gap (photovoltaic applications), stiffest material known (yet shows 20% elasticity) and highly impermeable.

While a number of production methods have been identified, the challenge of commercial production and manufacturing methods for graphene remains unresolved.

## Processing

Graphite deposits typically range from 2% to 8% Cg, with 15% to 20% Cg considered high grade. With the exception of vein deposits, which can be selectively mined (often by hand), all other graphitic ores require processing. The flowsheet is determined by both the mineralogy and the target market and aims to maximise the recovered flake size whilst achieving the desired concentrate purity as well as separating the graphitic carbon from the other forms of carbon present.

- Graphite flakes are often found encapsulating gangue such as silica as well as having surface inclusions on the edges.
- Graphite is hydrophobic, and like other natural 'floaters' such as molybdenite it will float readily from a milled slurry when contacted with air bubbles. This is enhanced by the addition of kerosene or diesel while gangue recovery is controlled by depressants and a dilute slurry. In the case of the battery market, a high grade (>95% Cg) flotation concentrate is required and is subjected to further treatment such as micronisation /spheroidisation, chemical/thermal treatment and finally carbon coating to produce spherical graphite for use in batteries (10-30 micron and 99.9% Cg).
- The typical concentrator flowsheet employs a primary milling and classification stage followed by several stages of flotation employing a number of concentrate regrinding stages. Unlike most processing flowsheets, these regrinding stages consist of attritioning rather than size reduction, whereby the edges and surface inclusions of graphite- rich particle are removed.

## Mineral Resource Reporting

It has become common practice to report the in-situ flake size distribution as a proxy for saleable product (refer to Markets) when reporting a graphite Mineral Resource in line with the recommended guidelines of JORC or similar international resource reporting codes. Interestingly, the JORC Code's preference is that, if the saleable product is reported, it should be in conjunction with the reporting of the Ore Reserve rather than a Mineral Resource.

However this approach is deficient and the in-situ flake size measure is only meaningful if the in-situ flakes are basically pure graphite and can be recovered without any size reduction, which is very unlikely. Mining and handling practices initially degrade flake size, while processing can have a particularly significant impact on the product flake size. In RPM's experience, there are numerous examples where the in-situ flake size distribution had a significant jumbo and coarse flake component and the resultant marketable product flake size was fine to very fine.

Another issue is the accuracy of the reported in-situ flake size, which is commonly measured by Mineral Liberation Analysis (MLA – X-ray Diffraction methodology) conducted on a number of representative composited diamond drill core samples.

The MLA provides two size determinations – the Equivalent Circle, where a particle diameter is calculated by the particle area, and the Maximum Diameter, which measures the largest dimension. These measurements are in two dimensions and are of particles which can present at any orientation to the measurement plane. Unless the graphite particle geometry is regular, circular and presented in the measurement plane, both measurement methods are an approximation. The Equivalent Circle measurement is likely to underestimate flake size because of particles presenting at high angles to the measurement plane while Maximum Diameter is likely to overestimate particle size. This occurs due to the presence of non-circular particles presenting along their longest axis in the measurement plane. Since the nature of the size determination method and interpretation is rarely reported, the graphite particle size can be ambiguous. It is also noted that sample preparation for the particle size measurement involves milling, which will have reduced the maximum particle size.

Since the MLA does not measure the particle purity when determining the particle size, the reported in-situ flake size distribution does not assist with the market purity specifications which is a major factor affecting the likely product value for some applications. RPM concludes that it is not practical to quantitatively report product specification at the Resource stage since they can only be determined reliably after extensive testing to a Pre- Feasibility Study level of confidence.