Graphite resources, and their potential to support battery supply chains, in Africa

Clive Mitchell and Eimear Deady

British Geological Survey

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Front cover photograph: Lindi Jumbo graphite deposit, Tanzania. © Walkabout Resources

Back cover photograph: Exploration drilling, Chilalo, Tanzania. © Marvel Gold

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Executive summary

Decarbonisation of energy and transport, to meet global net zero ambitions, will require significantly increased amounts of the raw materials used to manufacture batteries and other green technologies. This report focuses specifically on graphite, one of the major battery raw materials, for which demand is expected to grow rapidly in the coming decades. Graphite supply chains are complex and commonly global in their extent, with steps that include exploration, mining, processing, manufacturing, use and recycling.

The continent of Africa has significant graphite resources, which may provide an opportunity for many African countries to contribute to meeting increased demand whilst also supporting economic growth. This report reviews known resources of graphite and engagement in the battery supply chain across key African countries. Many African countries (most notably Mozambique, Madagascar, Tanzania and Namibia) have significant graphite resources and some operating graphite mines.

However, there is much less engagement in critical stages further along the supply chain. Currently, Africa has no capacity for the production of specialist products such as spherical graphite or manufacture of battery components. This leads to a typical situation where mineral concentrate is exported; value is added outside Africa; and products using graphite are then imported. There is clear potential for Africa's graphite resources to make a greater economic contribution, but this should be placed in the context of the wider supply chain; in particular, the potential for regional cooperation on the production of spherical graphite deserves further consideration.

There is currently limited data on the specific socio-economic and environmental impacts of graphite mining. Development of new graphite mines across Africa will be most successful if good governance, human rights, and minimising environmental impacts are all considered as priorities.

Introduction

The need to address climate change is a global priority, with countries across the world adopting policies for the rapid decarbonisation of the energy, industrial and transport sectors. This clean energy transition is driving the demand for metals and minerals such as lithium, cobalt and graphite. These are used in electric vehicles (EVs) and energy storage applications which mainly use lithium-ion batteries. The International Energy Agency (IEA) Sustainable Development Scenario estimates that, relative to 2020, demand for these metals and minerals will grow by at least thirty times by 2040, particularly in Asia, Europe and North America (International Energy Agency, 2021).

This report will focus specifically on graphite in Africa. Africa has significant graphite mineral resources and some production facilities but limited engagement with the supply chain beyond extraction and initial processing of the raw material. In this report, we summarise the potential for developing an integrated graphite supply chain for batteries in Africa.

Graphite is an industrial mineral which has, for many years, supplied a steady market as a raw material for refractory products particularly in steel manufacture, as well other uses including metal bearings, brake linings, lubricants, paint and pencil lead (Mitchell, 1992b). In recent years, its use in lithium-ion rechargeable batteries, where it is the dominant choice as anode material (Figure 1), has significantly impacted the demand for graphite.

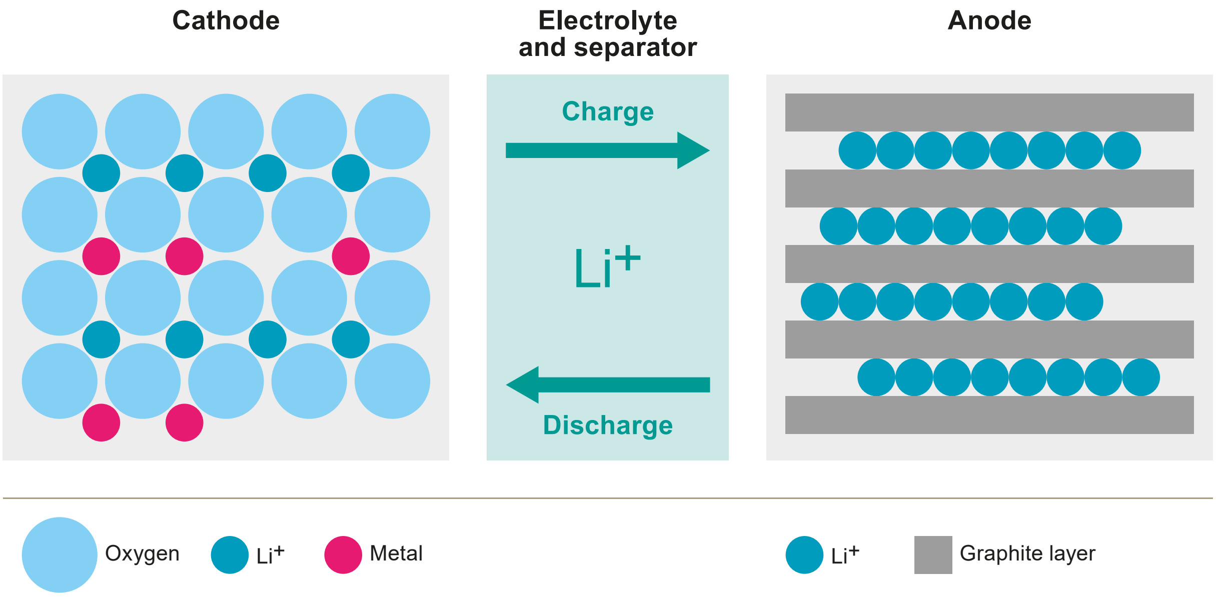

Figure 1 Simplified battery outline showing the basic constituents of a Li-ion battery. In the anode, graphite layers are used as host structures for the reversible intercalation of charged Li+ ions (figure derived from fig. 01 from www.superiorgraphite.com, 2021). The metals used in the cathode can be Co, Ni or Mn, or any combination of these metals (Gunn and Petavratzi, 2018).

Two types of graphite, natural and synthetic, compete in the battery anode market, with the demand split approximately 50:50 in 2018 (Asenbauer et al., 2020). Synthetic graphite is forecast to gradually replace natural graphite, particularly in premium batteries, due to its higher purity, lower electrical resistance and energy density (Asenbauer et al., 2020). Its share of the graphite anode market is expected to increase to 70%. However, synthetic graphite is more expensive to produce and is derived as a by-product of coal mining and oil refining. The greater CO2 emissions arising from the production of synthetic graphite provide a strong sustainability argument for continuing to produce natural graphite. Also, ironically the drive to decarbonise the economies of the world will reduce the supply of the key raw materials used to produce synthetic graphite (International Energy Agency, 2021; Whiteside J. Finn-Foley D., 2019).

The global supply of graphite is currently dominated by China. Africa has the potential to become a leading global producer of graphite as evidenced by the operation at Balama in Mozambique which has the capacity to produce 350,000 tonnes of graphite per year (Syrah Resources, 2019). There are more African graphite operations in the pipeline, as discussed below.

The global demand for graphite is set to rise dramatically from 1.1 million tonnes (Mt) a year in 2020 to 4 Mt a year by 2030 (Mining Journal, 2021). If historic production trends continue, demand will far outstrip supply by 2030 (Ballinger et al., 2019). The processing and manufacturing of battery components mostly takes place in China, Japan and South Korea (Grant, 2020). This concentration of key stages in the supply chain in a small number of countries represents a potential risk to the security of global graphite supply.

New sources and supply chains are needed to bridge the gap between supply and demand. Plans for the exploration and processing of these critical battery raw materials have accelerated in many parts of the world in an attempt to redress the imbalance in the supply chain, offering a potential opportunity for resource-rich developing countries in Africa (Hund, 2020).

Types of graphite deposit

Graphite, an allotrope of carbon, is predominantly concentrated into three types of mineral deposit: Amorphous graphite (microcrystalline graphite formed by metamorphism of coal, petroleum or carbon-rich sediments); flake graphite (disseminated graphite flakes associated with metamorphic rocks); and vein graphite occurring in veins or fracture-fillings in igneous and metamorphic rocks (Robinson Jr et al., 2017).

Amorphous graphite deposits are typically formed by the thermal metamorphism of coal, petroleum or carbon-rich sediments. The main suppliers of amorphous graphite are Mexico, China and Russia (Robinson Jr et al., 2017) (Michaux, 2018). A large proportion of worldwide graphite production is derived from deposits of disseminated flake graphite found in high-grade metamorphic rocks (Robinson Jr et al., 2017). Flake graphite forms when carbon-rich sedimentary rocks undergo regional metamorphism. Metamorphism to at least amphibolite facies (medium pressure and medium to high temperatures) is necessary to transform carbon to graphite (Hoefs and Frey, 1976). Vein graphite occurs in the form of lumps and chips, filling well-defined fissures in high-grade metamorphic or igneous rocks or along the intrusive contact of pegmatite with marble or paragneiss (Robinson Jr et al., 2017). The largest producer of vein graphite is Sri Lanka (Robinson Jr et al., 2017).

Flake graphite deposits are the most important deposit type in Africa, occurring in many countries across the continent. Flake graphite deposits occur as stratabound lenses or layers up to tens of metres thick and hundreds of metres in length mostly in metamorphosed sedimentary rocks of Archaean to Neoproterozoic age (Robinson Jr et al., 2017). Flake graphite ranges in particle size from fine-grained (50 microns diameter) to coarse-grained (greater than 800 microns diameter, 150 microns thick) flakes. The coarsest graphite flakes are up to 4 cm in diameter but are generally less than 1 cm. Flakes of graphite typically contain 90 to 95 per cent carbon.

Graphite is resistant to weathering. Mining of flake graphite is typically in open pits, where weathering of the gangue minerals facilitates the ease of mining.

The stages in the graphite supply chain for batteries

An estimated 1.1 Mt of graphite were produced globally in 2020 (USGS, 2021). Production is dominated by China, who in 2020 produced 650 000 tonnes, approximately 60% of the global market share. Significant production also comes from Brazil, India and North Korea (approximately 12% combined). Approximately 15% of global production comes from the continent of Africa, where mines in Mozambique and Madagascar are the largest producers. Currently there are eight operational flake graphite producers in Africa, four in Madagascar, two in Mozambique, and one each in Namibia and Tanzania; Zimbabwe ceased producing significant quantities of graphite in 2017 (Brown et al., 2019; Brown et al., 2021; USGS, 2021). The largest demand, around half of the current global total production of graphite, is from the steel and refractory industries. The fastest growing demand is in batteries, currently around 8–10% of demand. Growth of the lithium-ion battery (LIB) market is currently very newsworthy and graphite demand is an important aspect of this, as the ratio of graphite to lithium in LIBs is typically 10:1 (Pell, 2020).

Graphite deposits are known worldwide, but knowledge of their existence is only the starting point of a complex supply chain (Figure 2). The graphite supply chain for batteries can be considered to include the following stages:

1. Exploration stage: discovery and exploration of the mineral deposit, and progress to the point of opening the mine.

2. Mining stage: mining and initial processing to produce graphite concentrates.

3. Processing stage: processing to make specialised graphite products such as spheroidisation to make High Purity Spherical Graphite (HPSG) and coating.

4. Manufacturing stage: manufacturing of anode material for lithium-ion batteries.

5. Use stage: production and use of the consumer product.

6. End-of-life stage: Scrapping, reuse or recycling of graphite to graphene.

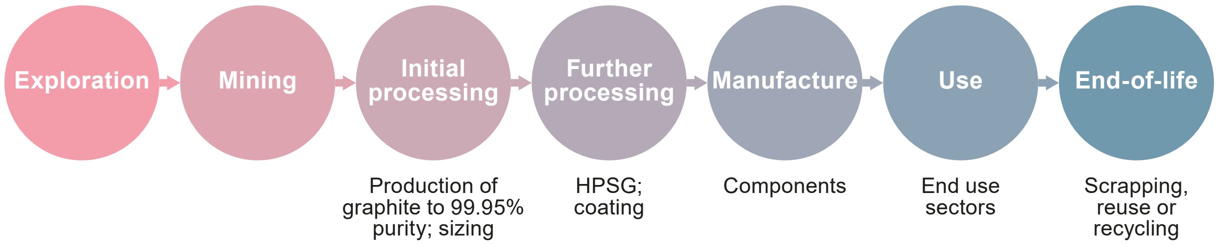

Figure 2 The stages in the graphite supply chain.

Stage 1: the exploration stage. This stage of the supply chain is essential for commodities like graphite where demand is expected to grow significantly in the coming years and so new deposits will need to be identified and developed. This stage includes initial discovery of a deposit (Figure 3), and then progresses through scoping and resource definition, pre-feasibility and definitive feasibility studies as the deposit becomes better characterised (usually through drilling). During this process the resource[1], and then the reserve[2], is gradually established with greater certainty (Wood and Hedenquist, 2019). During exploration, significant investment is required to enable characterisation of the deposit and assessment of its economic, environmental and social viability to become an operational mine. The exploration stage is often very lengthy, potentially taking more than 10 years to complete, and highly risky.

Figure 3 Graphite schist, Razafy North graphite deposit, Madagascar (© Blackearth Minerals).

[1] A resource is a concentration of naturally occurring material in or on the Earth's crust in such form that economic extraction of a commodity is regarded as feasible, either currently or at some future time. It can be divided (with decreasing levels of certainty) into measured, indicated, and inferred.

[2] A reserve is that portion of an identified resource from which a usable mineral or energy commodity can be economically and legally extracted at the time of determination. It can be divided into proven and probable.

Stage 2: the mining stage encompasses all the work that is done at a mine site, typically including extraction and production of ore for processing. This stage also includes initial mineral processing (otherwise known as beneficiation) into graphite concentrate which involves crushing, screening, grinding, froth flotation (Figure 4), dewatering and drying at the mine site to upgrade the carbon content and remove impurities. Recovery is generally in the order of 90 to 98%, and the ore is upgraded to a concentrate which grades 90 to 97% carbon (Leading Edge Materials, 2021). The 'sizing' of graphite can also be completed during the initial processing. The natural flake graphite concentrate is sorted into different sizes by screening at different mesh sizes. Flake size is less relevant for high purity battery grade applications as the graphite is micronized to less than 30 microns prior to shaping and purification (Leading Edge Materials, 2021). Graphite can also be sold as bulk concentrate.

Stage 3: the processing stage. The processing of graphite concentrate includes the production of spherical graphite. Spherical graphite is produced by the physical and chemical processing of graphite. Flakes of natural graphite are turned into spherical shapes ranging in size from 10 to 40 microns. After spheroidisation, the spheres are treated with a range of acids to purify the graphite to 99.95% C, in a process known as purification, to produce HPSG. There are a range of purification processes which are mainly undertaken in China and require a large quantity of chemicals that can have a negative environmental impact. This process increases the surface area and conductivity of the graphite. All HPSG is currently produced in China. A further processing stage where the HPSG is coated in a single layer of carbon is the final stage of graphite processing (Leading Edge Materials, 2021).The coating process occurs mainly in China, Japan, Korea and Taiwan (Leading Edge Materials, 2021).

Figure 4 Froth flotation of graphite, Graphmada, Madagascar (© Bass Metals).

Stage 4: the manufacturing stage includes the production of anodes for LIBs.

Stage 5: the use stage comprises the incorporation of the battery into a consumer product, and its use.

Stage 6: the end-of-life stage comprises the scrapping, reuse or recycling of the graphite anode from the lithium-ion battery after its primary use has ended. The recycling of graphite from end-of-life LIBs is not currently well developed. Given the energy intensive nature and high cost of the production of primary graphite, it should be considered due to the rapidly increasing demand for graphite. It may also be possible to re-purpose the recovered material for positive electrodes in next-generation aluminium-ion-batteries (Pham et al., 2020).

In this report, we review the situation in key countries in Africa, and assess the potential for those countries to progress along the graphite supply chain. Several African countries are engaging in exploration (Stage 1 of the supply chain), while Mozambique, Madagascar, Tanzania and Namibia have successfully attained Stage 2. The intermediate stages of the supply chain remain largely aspirational, although South Africa has some engagement in Stage 4. Stages 5 and 6 take place in many African countries, with import of products containing lithium-ion batteries and subsequent recycling or waste management. The major gap is at Stage 3, the processing stage. Currently all of the production of HPSG occurs in China, with coating occurring in China, Japan and Korea.

Major countries in Africa's graphite supply chain

This section provides a brief overview of the activities in the graphite supply chain in each of the key countries. Exploration, extraction and processing are the dominant stages, but where information is available on how a country is engaging in other stages, this is also reviewed. Details of exploration projects and mines, where available, are provided in Appendix 1 and the locations are shown in Figure 5.

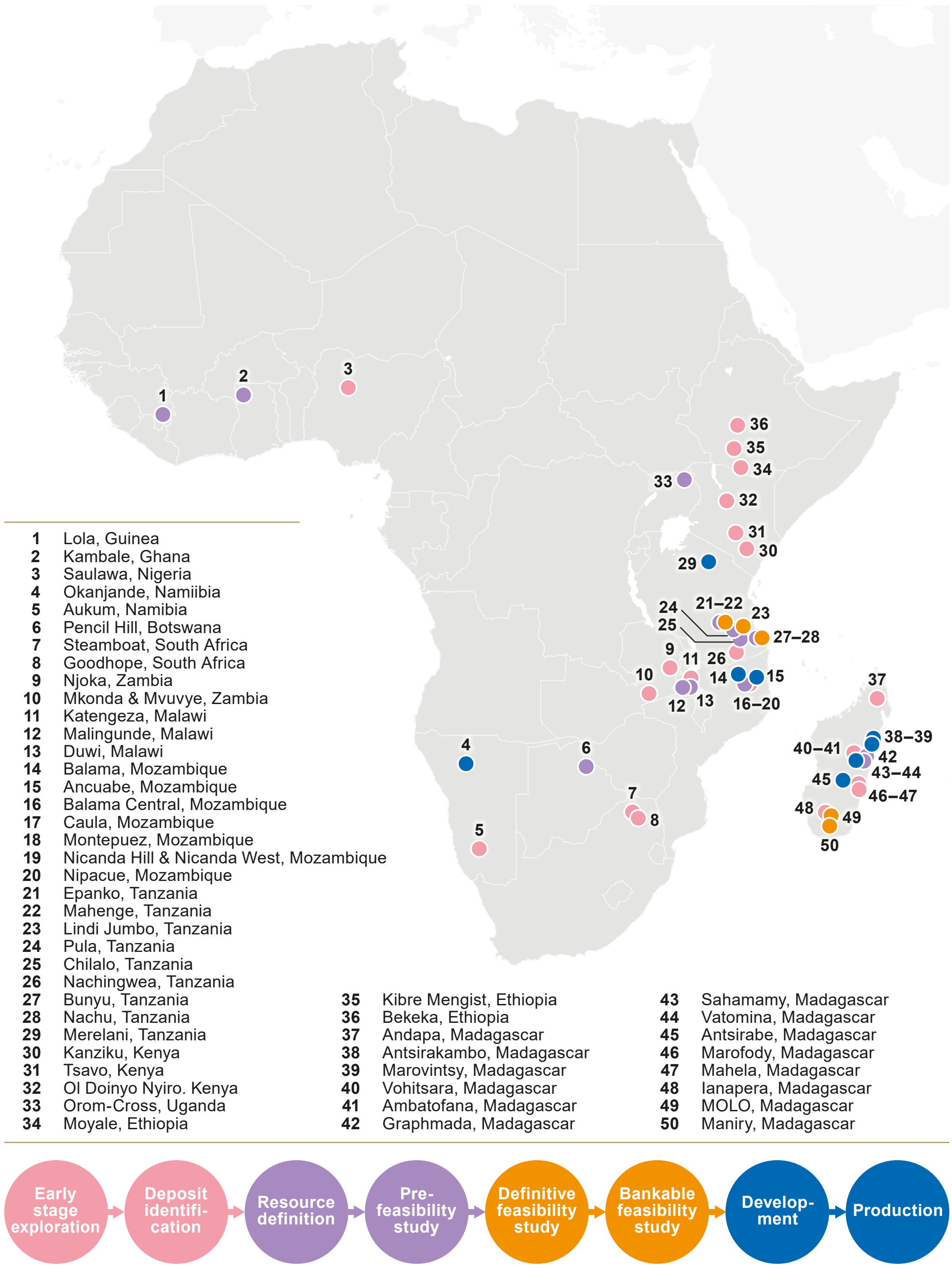

Figure 5 Map of Africa showing the main graphite resource localities.

Mozambique

In Mozambique, flake graphite occurs in the Proterozoic metasedimentary rocks (gneiss and schist) of the Mozambique Belt in the northern part of the country. Graphite production in Mozambique has increased dramatically in the last few years from 802 tonnes in 2017 to 113 803 tonnes in 2019 (Brown et al., 2021). Currently there are two known graphite producers operating in Mozambique.

Syrah Resources works the **Balama** graphite deposit in the Cabo Delgado province with a flake graphite production capacity of 350 000 tonnes per year. This is claimed to be the largest natural graphite resource in the world. The JORC-compliant reserve at Balama is 107.54 Mt at 15.73% graphite, while the JORC-compliant total resource estimate is 1.42 billion tonnes at 10% graphite, which gives the mine a 50 year life span (Syrah Resources, 2019).

Graphit Kropfmühl, a subsidiary of AMG Graphite, operates the **Ancuabe** graphite mine in the Cabo Delgado province with a flake graphite production capacity of 9,000 tonnes per year. The JORC-compliant measured resource estimate is 0.59 Mt at 11.17% graphite and the JORC-compliant indicated resource is 0.78 Mt at 8% graphite which gives a current mine life of 9 years (AMG Graphite, 2020).

There are currently eight ongoing graphite exploration projects in Mozambique including Ancuabe (Triton), Balama Central (Battery Minerals), Caula (New Energy), Cobra Plains (Triton), Montepuez (Battery Minerals), Nicanda Hill & Nicanda West (Triton) and Nipacue (Graphit Kropfmühl). Some of these deposits host compliant mineral resources, with more details listed in Appendix 1.

Madagascar

In Madagascar, flake graphite occurs in the Precambrian metasedimentary 'basement' (schist, gneiss, granitic and basic igneous rocks) that forms a broad north-south oriented belt underlying the eastern two-thirds of the country. Graphite production in Madagascar has increased significantly over the last few years from 12 852 tonnes in 2017 to 53 400 in 2019 (Brown et al., 2021). There are four known graphite producers operating in Madagascar.

Etablissements Gallois works the **Antsirakambo** and **Marovintsy** deposits with graphite production capacity currently being increased to 140 000 tonnes per year of flake graphite (Figure 6). The non-compliant graphite reserve estimate is 240 Mt at 10% graphite. Currently Gallois graphite products are sold to Europe, USA, UK, China, Russia, Japan, South Korea, India, Turkey, Brazil and Mexico amongst other countries (Etablissements Gallois S.A., 2021).

Bass Metals manages the **Graphmada** operation which is supplied by the Loharano and Mahefedok flake graphite deposits. Current production capacity is 6,000 tonnes of flake graphite per year. The JORC-compliant total graphite resource estimate at Graphmada is 20.2 Mt at 4% graphite (Bass Metals LTD., 2021).

Tirupati Graphite operates the **Sahamamy Sahasoa** mine which has a current production capacity of 3,000 tonnes per year of flake graphite and has plans to increase capacity to 21 000 tonnes per year. The maiden JORC-compliant resource estimates indicated resources of 1.4 Mt at 4.1% graphite and inferred resources of 5.7 Mt at 4.2% graphite (Tirupati Graphite, 2021a). Tirupati Graphite are developing a graphite mine at Vatomina with a production capacity of 60 000 tonnes per year of flake graphite (Tirupati Graphite, 2021b).

A fourth producer is a Chinese-owned graphite mine at Antsirabe with no further details available.

There are currently nine graphite exploration projects in Madagascar including Ambatofana, Andapa & Mahela (Bass Metals), Ianapera & Maniry (Blackearth Minerals), Molo (Next Source Materials), Vatomina (Tirupati Graphite) and Vohitsara & Marofody (DNI Metals). Some of these deposits host compliant mineral resources, with more details listed in Appendix 1.

Figure 6 Etablissements Gallois mine site, Madagascar (© Etablissements Gallois).

Namibia

In Namibia, graphite occurs in Neoproterozoic metasedimentary rocks (mostly schist and marble).

The **Okanjande** graphite mine is located 20 km south west of Otjiwarongo in central-north Namibia. The graphite occurs as disseminated flakes and small lenticular bodies in gneiss and schist. The operation currently produces 20 000 tpa of flake graphite and will be increasing production capacity to 30 000 tpa. The Weathered Ore Zone has NI 43–101 measured resource estimate of 3.3 million tons at 5.5% graphite and an indicated resource estimate of 0.714 Mt at 5.11% graphite. The Fresh Ore Zone has a NI 43–101 measured resource estimate of 9.56 Mt at 6.25% graphite and an indicated resource estimate of 4.874 Mt at 5.56% graphite (Gecko Namibia, 2021).

The **Aukam** vein graphite deposit is located near Bethanien in southern Namibia and was worked on a small-scale between 1940 and 1974. Graphite occurs as massive lenses, pockets and veins and more rarely as minor disseminated patches hosted by the hydrothermally altered granite of the Namaqualand Metamorphic Complex (Moss, 2016). No resource estimate has been publicly published for this deposit. Future production will be from waste piles from historic graphite production in addition to new underground workings. Current production capacity is 650 tpa with construction underway of a plant with a capacity to produce 20 000 tpa of graphite. The company has two pre-production purchase agreements for its high purity, vein graphite (Gratomic, 2021).

Tanzania

In Tanzania, flake graphite occurs in the Proterozoic metasedimentary rocks (gneiss and schist) mostly in the east of the country. There is a small amount of graphite production in Tanzania by a Chinese-owned company operating in Merelani; this area is also well known for gemstone mining, particularly Tanzanite.

There are currently ten ongoing graphite exploration projects in Tanzania including Bunyu (Volt Resources), Chilalo (Marvel Gold; see back cover image), Epanko (Figure 7),Tanga & Merelani-Arusha (EcoGraf Resources), Lindi Jumbo (Walkabout Resources; see front cover image), Mahenge Liandu (Armadale Capital), Nachingwea (Syrah Resources), Nachu (Magnis Energy Technologies) and Pula (Pula Group). Some of these deposits host compliant mineral resources, the full details of which are listed in Appendix 1.

Figure 7 Drill core, Epanko graphite deposit, Tanzania (© EcoGraf).

Other countries

In Botswana, graphite occurs in Precambrian metasedimentary rocks, typically marble and gneiss (Tassell, 2019). The Tonota Resources graphite deposit (**'Pencil Hill'**) occurs 30 km south of Francistown with a JORC-compliant inferred resource estimate of 6.9 Mt at 8.82% graphite.

In Cameroon, occurrences of graphite have been identified in Bétaré-Oya in East Province, Yingui north-east of Douala and Mayo Boula in the far north (Tita and Kaya, 2020).

In Egypt, graphite occurs in Wadi Law and Wadi Sikait in the south eastern desert, where it is associated with actinolite-bearing schists in the melange matrix of the ophiolite sequence (Bishady, 2017; Mahmoud, 2013).

In Ethiopia, flake graphite occurrences are located in Kibre Mengist and Gara Gedesa in the **Moyale** area in the southern part of the country. The main graphite-bearing rock types are amphibole schist, quartz-feldspar-mica schist, granodiorite, quartzite and graphite schist. The **Moyale** graphite deposit has a non-compliant resource of 0.46 Mt at 8.98% graphite, **Kibre Mengist** graphite deposit has a non-compliant resource estimate of 11 Mt at 9.6% graphite and **Bekeka** graphite deposit has a non-compliant resource of 150 Mt at 7.1% graphite (Geological Survey of Ethiopia, 2019; Ghebre, 2019).

In Ghana, flake graphite occurs in schist at the **Kambale** deposit 5-8km west of Wa (Figure 8), in the Palaeoproterozoic Wa-Lawra Birimian greenstone belt of north-west Ghana (Sunkari and Zango, 2018). Exploration by Castle Minerals yielded a JORC-compliant resource estimate of 14.4 Mt at 7.2% graphite (Castle Minerals, 2021).

Figure 8 Exploration at Kambale graphite deposit, Ghana (© Castle Minerals).

In Guinea, flake graphite occurs in the **Lola** deposit in south-east Guinea. Flake graphite occurs in a 20 to 50 metre thick layer of saprolitic weathered ore overlying graphite-bearing gneiss. The CIM-compliant resource estimate (measured and indicated) is 19.14 Mt at 4.38% graphite and an inferred resource of 2.82 Mt at 5.07%, using a cut of grade of 1.64% C. Current plans are to establish a graphite production facility with a capacity for 50 000 tpa of flake graphite (SRG Mining, 2020).

In Kenya, there are 19 known flake graphite occurrences in the Neoproterozoic metasedimentary rocks (kyanite-schist, graphitic limestone and feldspathic gneiss) of the Mozambique Belt in the central and western parts of the country. A small amount of graphite production took place from 1940 to 1960. Past exploration has indicated that the graphite potential of the deposits at **Kanziku** (up to 12% graphite), Tsavo (non-compliant resource of 0.5 Mt) and **Ol Doinyo Nyiro** (non-compliant 1.2 million tonne resource at 13% graphite) may warrant further investigation (Bu Bois, 1969; Robinson Jr et al., 2017).

In Malawi, there are 14 known flake graphite occurrences in the Archaean and Proterozoic basement rocks (gneiss, granulite and schist) in the centre of the country. Recent exploration by Sovereign Metals Ltd focused on the graphite deposits in the Lilongwe district. The **Malingunde** graphite deposit hosts a JORC-compliant reserve of 9.5 Mt at 9.5% graphite and a resource of 65 Mt at 7.1% graphite (Sovereign Metals Limited, 2018). The **Duwi** graphite deposit has a JORC-compliant resource estimate of 85.9 Mt at 7.1% graphite (Sovereign Metals Limited, 2015). The **Katengeza** deposit in Salima district has a non-compliant resource estimate of 2.7 Mt at 5.8% graphite (British Geological Survey, 2009).

In Morocco, graphite-sulphide deposits occur in ultramafic rocks in the Beni Bousera massif which is in the westernmost part of the Mediterranean Alpine belt (Crespo et al., 2006).

In Nigeria, graphite occurs in the Upper Proterozoic Birnin Gwari schist belt in Kaduna State. Graphite vein mineralisation occurs associated with quartz-rich veins and pegmatites in semi-pelites and quartz schist. Occurrences are known in the hills of Farin Rua, Lambada, Saulawa, Gwobirawa, Manda Kakina, Kwaskwasa and Sofon Kuyelo. The **Saulawa** graphite deposit consists of massive flakes with a total graphite content ranging from 0.1 to 3.4% with an estimated non-compliant resource of 0.77 Mt (Ministry of Mines and Steel Development, 2020).

In Somalia, a minor occurrence of graphite is reported in quartzose gneiss in the Ala Ule area in Baroma District associated with the Hamar Beryllium occurrence (Pallister, 1959).

In South Africa, graphite occurs in Archaean metasedimentary rocks in five out of the nine provinces in the country. The **Steamboat** graphite deposit in the Blouberg District, Limpopo Province is hosted in the Palaeoproterozoic graphitic gneiss of the Gumbu Group, Beit Bridge Complex. The non-compliant resource estimate is 3.5 Mt at 8.8% graphite (Buick et al., 2003; Industrial Minerals, 2010; Minrom, 2018). Other significant occurrences of graphite include the **Goodhope** deposit in Limpopo Province (Khoza, 2011).

In Sudan, graphite schist and gneisses occur in the Precambrian basement in southern Sudan, and sericite-graphite schists in central Sudan (Yassin, 1984).

In Swaziland (Eswatini), graphite schist occurs near Hlatikulu, Shiselweni district in the south of the country (Swaziland Geological Survey Department, 1951).

In Uganda, there are flake graphite occurrences in the Paleoproterozoic and Neoproterozoic metasedimentary rocks (gneiss, quartzite and schist) in the west and north of the country. The **Orom-Cross** graphite deposit in Orom District, Northern Uganda has a JORC-compliant resource estimate of 16.35 Mt at 6.01% graphite (Blencowe Resources, 2021).

In Zambia, there are flake graphite occurrences in the Proterozoic metasedimentary rocks (gneiss and schist) mostly in the central and eastern parts of the country. The graphite-bearing gneiss deposits at **Njoka** (10–13% flake graphite), **Mkonda** (6–7% flake graphite) and **Mvuvye** (6–12% flake graphite) in Eastern Province may warrant further investigation (Drysdall, 1960; Mitchell, 1992a).

In Zimbabwe, there are 21 known flake graphite occurrences in the Proterozoic metasedimentary rocks (gneiss, phyllite and schist) in the northern and western parts of the country. Zimbabwe was a significant producer of flake graphite in the past. **Lynx** graphite mine in Mashonaland started production in 1965, reached peak production of nearly 20 000 tonnes per year in 1983 and ceased production in 2017 (Brown et al., 2021).

Summary of Africa's participation in the graphite supply chain

Across the continent of Africa, and particularly eastern Africa, significant graphite resources have been identified many of which have delineated reserves and resources (Appendix 1). Definitive, and in some cases, Bankable Feasibility Studies exist for multiple projects in Tanzania, Madagascar and Mozambique, with many more projects in the exploration pipeline. Graphite exploration programmes are ongoing in Botswana, Ghana, Guinea, Madagascar, Malawi, Mozambique, Namibia, South Africa, Tanzania and Uganda. Past exploration has taken place in Ethiopia, Kenya, Zambia and Zimbabwe. It is anticipated that, with the significant exploration that has been ongoing on the continent in recent years, the production of graphite will increase.

Graphite extraction is ongoing in Madagascar, Mozambique, Namibia and Tanzania. Flake graphite production capacity in Africa was approximately 455,000 tonnes in 2019 (Table 1). Graphite production capacity will more than treble to 1.55 Mt per year if all of the planned projects in development come to fruition.

Table 1 Current and potential future production of graphite in Africa.

Deposit	Operation	Current production capacity (tonnes, 2019)	Potential future production capacity (tonnes per year)	References
Guinea	Lola	n/a	50 400	SRG Mining, 2020
Madagascar	Etablissements Gallois	60 000	140 000	Etablissements Gallois, 2021
	Graphmada	6000	20 000	Bass Metals, 2018
	Sahamamy	3000	21 000	Tirupati Graphite, 2021a
	Vatomina	n/a	60 000	Tirupati Graphite, 2021b
Mozambique	Ancuabe (AMG)	9000	9000	AMG Graphite, 2020
	Ancuabe (Triton)	n/a	60 000	Triton Minerals, 2020
	Balama	350 000	350 000	Syrah Resources, 2021
	Balama Central	n/a	110 000	Battery Minerals, 2021a
	Caula	n/a	120 000	New Energy Minerals, 2021b
	Montepuez	n/a	100 000	Battery Minerals, 2021b
Namibia	Aukam	650	20 000	Gratomic, 2021
	Okanjande	20 000	30 000	Gecko Namibia, 2021
Tanzania	Bunyu	n/a	170 000	Volt Resources, 2021
	Lindi Jumbo	n/a	40 000	Walkabout Resources, 2018
	Merelani	6000	6000	*Pers. Comm., 2020*
	Nachu	n/a	240 000	Magnis Energy Technologies, 2021
Total		**454 650**	**1 546 400**	

The more advanced processing in supply chain Stage 3, such as spheroidisation, is not currently carried out in Africa. As it currently stands graphite concentrate is shipped overseas, typically to China which is currently the only producer of HPSG in the world. Thus, the supply chain leaves Africa at the end of Stage 2. This concentration of production of HPSG in China is a significant bottleneck in the global graphite supply chain.

Graphite exports from Africa to China rose by 170% in 2019. Some of the graphite production from Balama will eventually be diverted to the Syrah Resources spherical graphite plant currently under construction in Vidalia, Louisiana, USA (Roskill, 2021). This will be the first major integrated producer of natural graphite Active Anode Material (AAM) outside of China for electric vehicle batteries. Natural graphite concentrate (-100 mesh fines material) will be transported from the Balama graphite operation to Vidalia. This will then be processed into a spherical shape, purified, coated and heat treated to produce a finished AAM.

Africa needs to invest in graphite processing (Stage 3) capacity to capitalise on the opportunities created by potential supply disruptions and on the impetus to break down the bottleneck formed by the concentration of HPSG production. Stage 4, the manufacturing stage, does not take place in Africa, and so the value-adding stages are outside the continent, leading to reduced income. African leaders are being encouraged to adopt battery production as a continent-wide development priority (The Africa Report, 2020). There is a growing Lithium-ion battery industry in South Africa which may potentially develop the capacity to process graphite into AAM.

Opportunities for Africa

Africa's primary contribution to the graphite supply chain is likely to come via mining of its extensive resources. As many companies develop graphite exploration and mining projects across Africa, offtake agreements are being signed, with more graphite concentrate being exported either as sized or bulk concentrate. Significant proportions of the concentrate are shipped to China for HPSG production. Global transportation of concentrate potentially represents a missed economic opportunity for the producing country, and is also likely to have significant environmental impacts. Many of the mines, and potential future operations currently outlined, are some of the largest deposits of graphite in the world. As such, the production of graphite in Africa as a whole, or even from individual countries, may be able to support the development of a HPSG plant. This would need to consider the potential environmental impact of the chemical reagents used in the purification stage. If Africa is to engage in Stage 3 of the graphite supply chain, there may be a need for regional cooperation to ensure that the supply chain is sustainable.

This section highlights some of the common factors influencing the successful development of mining operations that contribute to sustainable, economy-wide growth (Deloitte, 2015; OECD, 2021; United Nations Economic and Social Council, 2009; World Bank, 1992).

1. Good mineral deposits, geological information and mining companies

Good quality, detailed, accessible geological information for mineral resources is a key requirement for mineral-rich countries looking to attract investment, particularly Foreign Direct Investment (FDI), from good mining companies.

2. Good governance, legal framework and regulatory stability

Good governance of the mining industry is essential to attract investors and to ensure that mining supports positive impacts for communities. This is particularly true in conflict-affected and high-risk countries, for which clear guidance is available (OECD, 2016). A transparent, equitable and consistent legal context is needed which clearly spells out the rights and obligations of the investor and the government. In addition, effective support and monitoring by well-organised government institutions is required. This will give mining companies the confidence to invest in the exploration and development of resources. Understanding of graphite supply, demand and markets is essential for development of the graphite supply chain in Africa. Governments may decide to implement export control measures, such as export taxes, export licences or export bans, hoping that this will promote local downstream mineral processing industries. Care must be taken when implementing such policies. Recent changes to export regulations in Tanzania specify a minimum of 65% graphite for exports. It was initially hoped that the new regulations would mark a period of renewed stability in Tanzania with increased investment in new graphite mining projects. However, it appears to have had the opposite effect as the changes were poorly understood by the international market (Ramdass, 2021; Roskill, 2020).

3. Good infrastructure, mining services and supply chain

Mining investments often require the upgrade or establishment of infrastructure (roads, rail networks, ports, water supply and power generation). Investment in infrastructure is happening in Africa but has long lead times to completion and has not kept up with economic growth. In addition, mining services to support the mining industry and a good understanding of the supply chain are both needed. Graphite mineral processing is highly energy intensive, and so secure energy supplies are essential for industrial engagement in the graphite supply chain. Many African countries already have energy demand that is greater than available supply, leading to concerns over energy security (Alemzero et al., 2021).

4. Environmental regulations

Concerns about the environmental impacts around mine sites and processing plants require good environmental assessment to be a critical part of any new developments. The processing of graphite is energy intensive and uses potentially harmful chemical reagents. Use of renewable energy may be a means of reducing the greenhouse gas emissions associated with graphite production.

5. Equitable taxation and use of revenues

A competitive and well-structured fiscal regime and access to foreign exchange are important. How mining revenues are spent is also important, for example Botswana spends all receipts from diamond mining on health, education and infrastructure. FDI is an opportunity for governments to finance infrastructure development and sustainable economic growth to generate job creation, upstream involvement in exploration, and downstream involvement in extraction and processing.

6. Skills and human resources

A cadre of well-trained, highly skilled local staff will be essential for a graphite mining industry to develop in any African country.

Conclusions

Decarbonisation requires significantly increased supplies of battery raw materials such as graphite. If new sources of graphite are not rapidly brought on stream, demand is forecast to far outstrip supply by 2030.

Flake graphite occurs in many countries in Africa, mostly in Archaean to Neoproterozoic metamorphic rocks. There are significant resources of flake graphite, particularly in eastern Africa where there is much ongoing exploration and development of mining operations. There are 25 graphite projects either exploring or developing new sources of graphite spread across 10 countries including Botswana, Ghana, Guinea, Madagascar, Malawi, Mozambique, Namibia, South Africa, Tanzania and Uganda. Current production of graphite in Africa, 256 650 tonnes in 2019, mostly comes from Mozambique (63%) and Madagascar (27%), with smaller amounts from Namibia (8%) and Tanzania (2%). Development plans would potentially see a six-fold increase in flake graphite production to 1.5 Mt per year over the next 5 to 10 years.

There is no advanced graphite processing capacity in Africa for the production of spheroidal graphite or other precursor products for the manufacture of Active Anode Material (AAM) for use in batteries. Currently, graphite is exported to China for the manufacture of HPSG, AAM and anodes. Development of more advanced graphite processing and AAM manufacturing capacity in Africa would require a significant level of investment. There is a growing Lithium-ion battery industry in South Africa which may potentially develop the capacity to process graphite into AAM.

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Appendix 1 Graphite resources and reserves in Africa (compliant figures only).

Country	Deposit	Company	Code	Category	Classification	Tonnage (Million tonnes)	Grade (% Graphite)	Reference
Botswana	Pencil Hill	Tonota Resources	JORC	Resource	Inferred	69.9	8.82	Tassell, 2019
Ghana	Kambale	Castle Minerals	JORC	Resource	Inferred	14.5	7.2	Castle Minerals, 2021
Guinea	Lola	SRG Mining	CIM	Resource	Measured + Indicated	28.56	5.17	SRG Mining, 2020
Guinea	Lola	SRG Mining	CIM	Reserve	Proven + probable	42	4.17	SRG Mining, 2020
Madagascar	Graphmada	Bass Metals	JORC	Resource	Total (Measured + Indicated + Inferred)	20.2	4	Bass Metals, 2021
Madagascar	Maniry	Blackearth Minerals NL	JORC	Resource	Total (Indicated + Inferred)	20.2	4	Blackearth Minerals NL, 2021
Madagascar	Molo	Next Source Materials	NI 43-101	Resource	Total (Measured + Indicated + Inferred)	141.28	6.13	Next Source Materials, 2019
Madagascar	Sahamamy	Tirupati Graphite	JORC	Resource	Indicated	1.4	4.1	Tirupati Graphite, 2021a
Madagascar	Sahamamy	Tirupati Graphite	JORC	Resource	Inferred	5.7	4.2	Tirupati Graphite, 2021a
Madagascar	Vatomina	Tirupati Graphite	JORC	Resource	Indicated	3.2	4.3	Tirupati Graphite, 2021b
Madagascar	Vatomina	Tirupati Graphite	JORC	Resource	Inferred	15.2	4.7	Tirupati Graphite, 2021b
Madagascar	Vohitsara and Marofody	DNI Metals	NI 43-101	Resource	Inferred	4	5	DNI Metals, 2021

Appendix 1 *Continued.*

Country	Deposit	Company	Code	Category	Classification	Tonnage (Million tonnes)	Grade (% Graphite)	Reference
Malawi	Duwi	Sovereign Metals	JORC	Resource	Total (Indicated + Inferred)	85.9	7.1	Sovereign Metals, 2015
Malawi	Malingunde	Sovereign Metals	JORC	Resource	Total (Measured + Indicated + Inferred)	65	7.2	Sovereign Metals, 2018
Mozambique	Ancuabe (AMG)	Graphit Kropfmühl	JORC	Resource	Measured	0.59	11.17	AMG Graphite, 2020
Mozambique	Ancuabe (AMG)	Graphit Kropfmühl	JORC	Resource	Indicated	0.78	8	AMG Graphite, 2020
Mozambique	Ancuabe (Triton)	Triton Minerals	JORC	Reserve	Probable	24.9	6.2	Triton Minerals, 2017
Mozambique	Balama West & East	Syrah Resources	JORC	Reserve	Probable	107.54	15.73	Syrah Resources, 2021
Mozambique	Balama West & East	Syrah Resources	JORC	Resource	Total (Measured + Indicated + Inferred)	1422	10.00	Syrah Resources, 2021
Mozambique	Balama Central	Battery Minerals	JORC	Reserve	Probable	19.66	11.06	Battery Minerals, 2018
Mozambique	Caula	Auspicious Virtue Investment Holding	JORC	Resource	Measured	21.9	13.4	New Energy Minerals, 2021
Mozambique	Cobra Plains (Triton)	Triton Minerals	JORC	Resource	Inferred	103	5.5	Triton Minerals, 2020

Appendix 1 *Continued.*

Country	Deposit	Company	Code	Category	Classification		Tonnage (Million tonnes)	Grade (% Graphite)	Reference
Mozambique	Montepuez	Battery Minerals	JORC	Reserve	Probable		42.19	9.27	Battery Minerals, 2018
Mozambique	Nicanda Hill (Triton)	Triton Minerals	JORC	Resource	Total (Indicated + Inferred)		1430	11.1	Triton Minerals, 2020
Mozambique	Nicanda West (Triton)	Triton Minerals	JORC	Resource	Inferred		30	6.6	Triton Minerals, 2020
Mozambique	Nipacue	Graphit Kropfmühl	JORC	Resource	Total (Measured + Indicated)		14.36	5.88 to 7.02	AMG Graphite, 2020
Namibia	Okanjande	Gecko Namibia	NI 43-101	Resource	Measured	Weathered Ore Zone	3.266	5.539	Gecko Namibia, 2021
					Measured	Fresh Ore Zone	9.564	6.252	
Namibia	Okanjande	Gecko Namibia	NI 43-101	Resource	Indicated	Weathered Ore Zone	0.714	5.11	Gecko Namibia, 2021
					Indicated	Fresh Ore Zone	4.874	5.566	
Tanzania	Bunyu	Volt Resources	JORC	Resource	Total (indicated + inferred)		461	4.9	Volt Resources, 2021
Tanzania	Bunyu	Volt Resources	JORC	Reserves	Total (proved + probable)		127.4	4.36	Volt Resources, 2021
Tanzania	Chilalo	Marvel Gold	JORC	Resource	Total (indicated + inferred)		67.3	5.4	Marvel Gold, 2021
Tanzania	Chilalo	Marvel Gold	JORC	Reserve	Total (proved + probable)		9.2	9.9	Marvel Gold, 2021

Appendix 1 *Continued.*

Country	Deposit	Company	Code	Category	Classification	Tonnage (Million tonnes)	Grade (% Graphite)	Reference
Tanzania	Epanko	EcoGraf	JORC	Resource	Total (measured + Indicated + Inferred)	30.7	>8	EcoGraf, 2021
Tanzania	Lindi Jumbo	Walkabout Resources	JORC	Resource	Total (measured + Indicated + Inferred)	41.8	10.8	Walkabout Resources, 2018
Tanzania	Lindi Jumbo	Walkabout Resources	JORC	Reserve	Total (proved + probable)	5.5	17.9	Walkabout Resources, 2018
Tanzania	Mahenge Liandu	Armadale	JORC	Resource	Total (measured + Indicated + Inferred)	20.4	7.5	Armadale Capital, 2021
Tanzania	Merelani-Arusha	EcoGraf	JORC	Resource	Total (Indicated + Inferred)	17.7	6.5	EcoGraf, 2015
Tanzania	Nachu	Magnis Energy Technologies	JORC	Resource	Total	174	5.4	Magnis Energy Technologies, 2021
Tanzania	Nachu	Magnis Energy Technologies	JORC	Reserve	Total (proved + probable)	76	4.8	Magnis Energy Technologies, 2021
Tanzania	Pula	Pula Group	NI 43-101	Resource	Indicated	34.7	6.13	Pula Group, 2018
Tanzania	Pula	Pula Group	NI 43-101	Resource	Inferred	62.0	5.81	Pula Group, 2018
Uganda	Orom-Cross	Blencowe Resources	JORC	Resource	Total (indicated + inferred)	16.35	6.01	Blencowe Resources, 2021