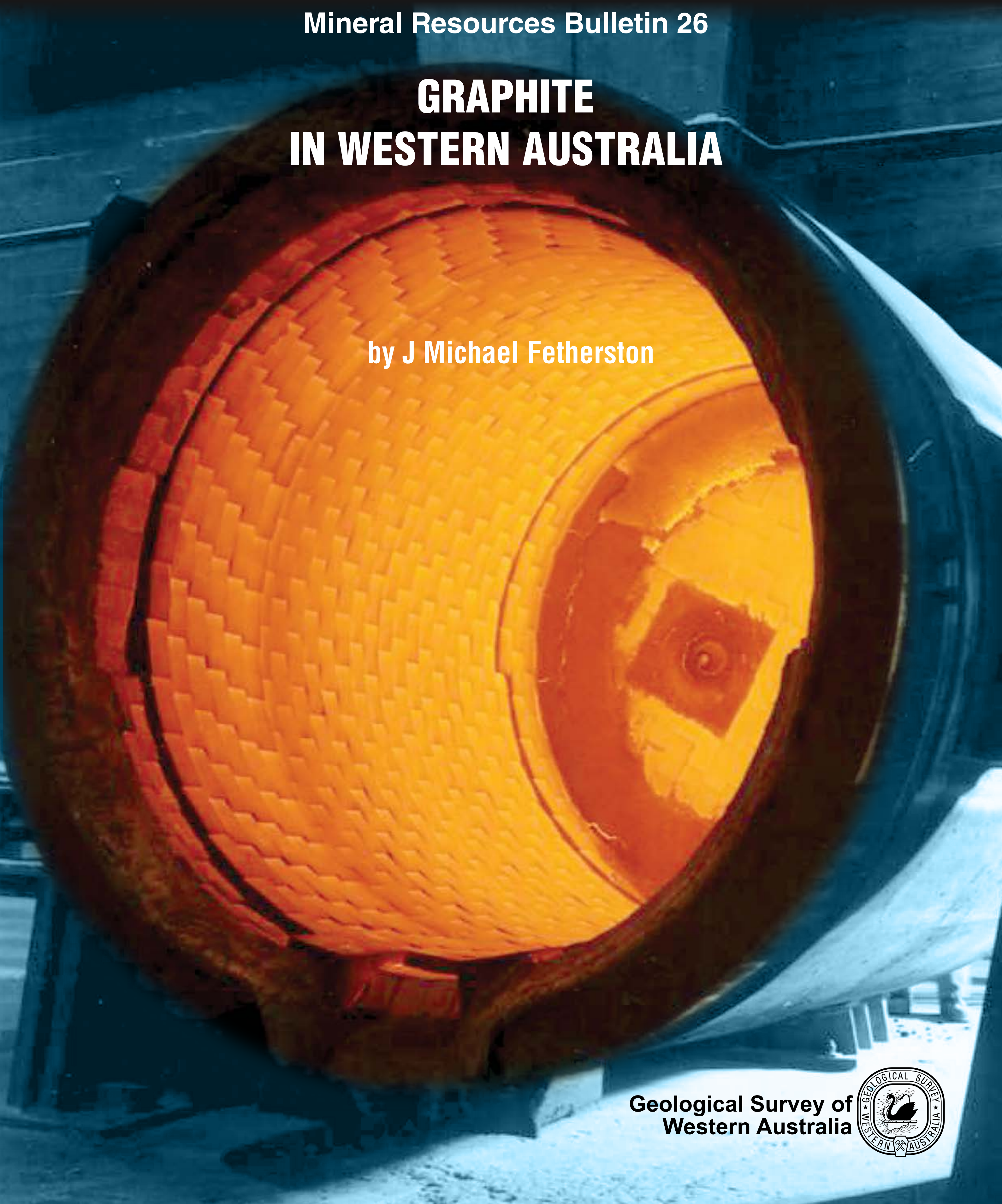
Department of
Mines and Petroleum

Mineral Resources Bulletin 26

# GRAPHITE IN WESTERN AUSTRALIA



by J Michael Fetherston

Geological Survey of
Western Australia

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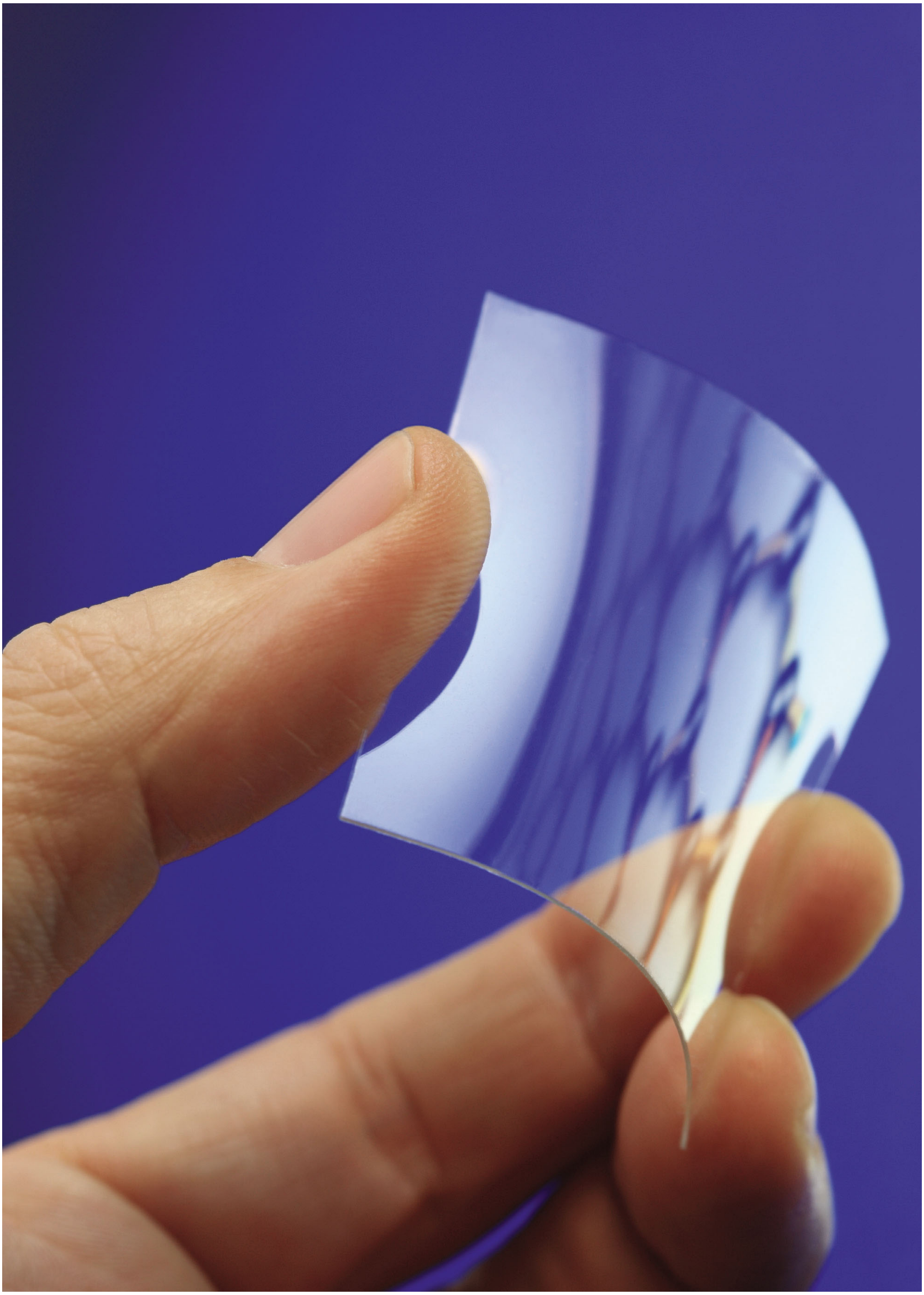

**FRONTISPIECE**

**Graphene, termed 'the world's next wonder material', comprises a series of one-atom-thick sheets of graphite. © gettyimages**

Government of **Western Australia**
Department of **Mines and Petroleum**

**MINERAL RESOURCES BULLETIN 26**

# GRAPHITE IN WESTERN AUSTRALIA

**by**
**J Michael Fetherston**

**Perth 2015**

**GEOLOGICAL SURVEY OF
WESTERN AUSTRALIA**

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**Front cover photograph:** High-temperature industrial furnace displaying internal refractory bricks rich in graphite providing structural strength, thermal shock resistance, high thermal conductivity, and chemical resistance up to 1540°C (courtesy Industrial Minerals)

**Back cover photograph:** Photomicrograph of flake graphite in a quartz-weathered feldspar matrix from the McIntosh graphite deposit, East Kimberley region; field of view 1.5 mm, plane-polarized light (courtesy Lamboo Resources)

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# Graphite in Western Australia

by

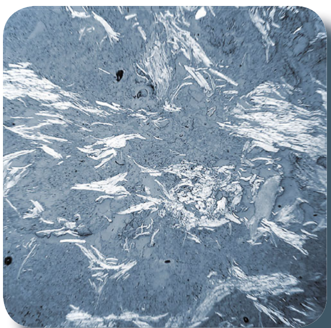
**J Michael Fetherston**

## Abstract

Western Australia has numerous recorded graphite prospects and occurrences. Almost all are found in graphitic schists or gneisses derived from the metamorphism of carbonaceous sedimentary rocks ranging from Archean to Mesoproterozoic age. Of these, only a few deposits have previously been mined, with total recorded production of only 222 ton mostly coming from the Munglinup deposit in the far south of the State with smaller amounts from the Donnelly River deposit in the southwest. Currently, two companies are well advanced in the exploration of two new high-grade, flake graphite deposits. In the Halls Creek area of the east Kimberley region, Lamboo Resources Ltd has identified five high-grade graphite targets at its McIntosh deposit. Target 1 is estimated to contain a JORC-compliant resource of 7.135 Mt over a 580 m strike length grading 4.73% total graphitic carbon (% TGC) for 337 700 t of contained graphite at a 2% TGC cutoff grade. It was recently announced that the company is to supply 50 000 tonnes per annum (tpa) flake graphite concentrate at 90% TGC to a Chinese client up to the end of 2018. At Yalbra, in the Gascoyne region in the central west of the State, Buxton Resources Ltd is exploring six closely spaced graphite-rich targets. It was recently announced that the Yalbra 1 prospect has a very high-grade, JORC-compliant resource over a 600 m strike length of 4.022 Mt grading 16.17% TGC using a 4% TGC cutoff grade. Also, the Munglinup deposit in the south has a JORC-compliant estimated resource of 1.47 Mt at 18.2% total (fixed) carbon (% TC) over a strike length of 555 m.

In recent years, higher prices on world graphite markets have resulted from increased demand for high-grade, large flake graphite especially for the refractories industry, the world's largest graphite consumer, and for new-found demand for high-tech graphite applications such as the lithium-ion battery industry supplying batteries in increasing numbers for electric cars. Accordingly, many countries including Australia have recommenced exploration to prove up new and existing deposits of high-grade flake graphite. Should this increased demand persist, Western Australia's potential graphite operations could establish the State as a producer and exporter of both high-grade flake and finer grade graphite concentrates into world markets.

**KEYWORDS**: Western Australia, applications, beneficiation, graphite, industrial minerals, mineral exploration, natural resources



## Object and scope

Mineral Resources Bulletin 26 Graphite in Western Australia has been written in response to a substantial resurgence in demand on world graphite markets in recent years, particularly for high-grade, coarse flake graphite. This resurgence can be attributed in part to the imposition in 2010 by China, the world's largest graphite producer, of a 20% export tax together with accompanying legislation that effectively restricted the country's graphite exports to 40% of total production. This significant reduction in supply was largely responsible for a spike in the price of high-grade flake graphite to more than US$2500/t, which persisted for more than 12 months.

Although prices returned in 2014 to around previous levels of up to US$1300/t for high-grade, flake graphite, indications are that prices are once again on an upward trend. This trend is partly due to further shortages in the Chinese export market and also to increasing competition for high-grade, coarse flake graphite between the refractories industry, the world's biggest graphite consumer, and the lithium-ion battery industry. Currently, this industry requires increasing quantities of high-grade graphite to supply demand from the electric car market. Also, many newly emerging high-tech industries now require the highest purity coarse flake graphite available.

In many countries, the anticipated shortage in supply of high-grade graphite on world markets has caused companies with existing graphite resources to enter into either exploration ventures to re-assess existing deposits, or further exploration to locate and prove up new commercial-grade resources. Currently, in Western Australia two companies are undertaking extensive exploration and research to prove up two graphite deposits, one in the east Kimberley region and the other in the Gascoyne region in the State's central western region. Both deposits are showing considerable potential as future high-grade, flake graphite producers.

This Bulletin is intended to assist future explorers in their search for new high-grade graphite deposits. The book sets out to document, in as much detail as possible, numerous previously recorded occurrences, prospects, and mining operations and new deposits currently under development in Western Australia.

## Sources of information

Information used in this Bulletin is from both published and unpublished sources, supplemented by data supplied by industry. Published information is mainly derived from Geological Survey of Western Australia records, reports, bulletins, annual reports, and geological maps. Other published sources include papers in geological journals, conference papers, and articles in industry reports and newspapers.

Unpublished information is obtained from open-file statutory reports submitted to the Department of Mines and Petroleum in Western Australia by mineral exploration companies and incorporated in the WAMEX online database. This information is supplemented by unpublished data made available by graphite exploration companies.

In this Bulletin, all graphite prospects and exploration sites in Western Australia are described within the broad tectonic units in which they are found (Fig. 1).

Locational information on almost all graphite sites described in this Bulletin is listed in Appendix 1. This information is also incorporated with other technical data in the Department of Mines and Petroleum's mineral resources database (MINEDEX), which is available online for public access. An index of all Western Australian graphite localities is also provided at the end of this Bulletin.

## Abbreviations

Two common abbreviations for the percentage of carbon in a graphitic rock appear in this Bulletin:

TGC total graphitic carbon (%)

TC total (fixed) carbon (%) – typically a higher value than TGC.

## Acknowledgements

The author gratefully acknowledges the significant contributions made by current graphite explorers in the State; Lamboo Resources Ltd for detailed information, photographs and specimens from the McIntosh graphite deposit in the east Kimberley region; and Buxton Resources Ltd for detailed information and photographs from the Yalbra graphite deposit in the Gascoyne region in the central west of the State.

Particular thanks are extended to Dr Craig Rugless, Technical Director of Lamboo Resources Ltd, and Mr Anthony Maslin, Managing Director of Buxton Resources Ltd, for their personal assistance and provision of company data for inclusion in this Bulletin.

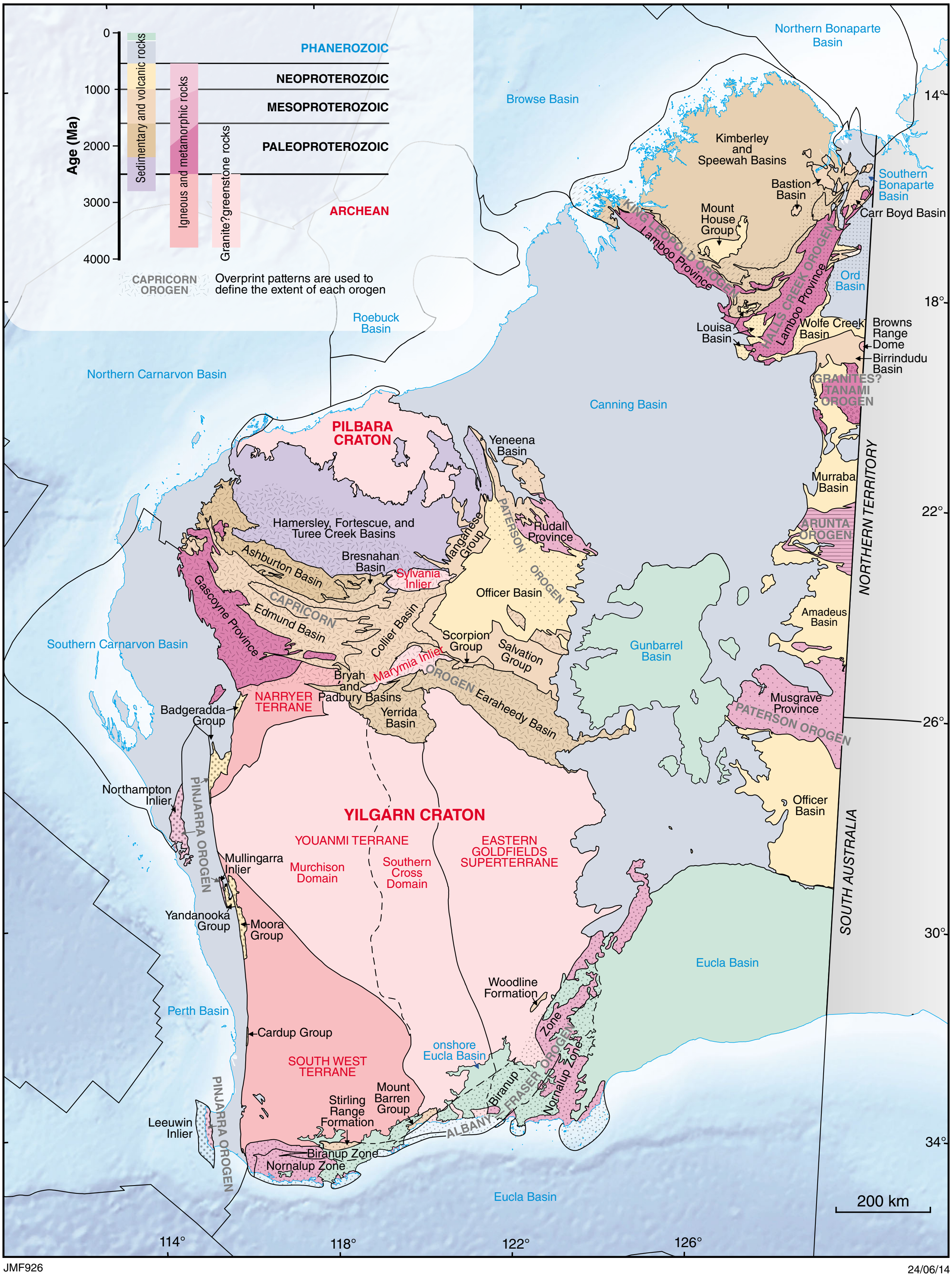
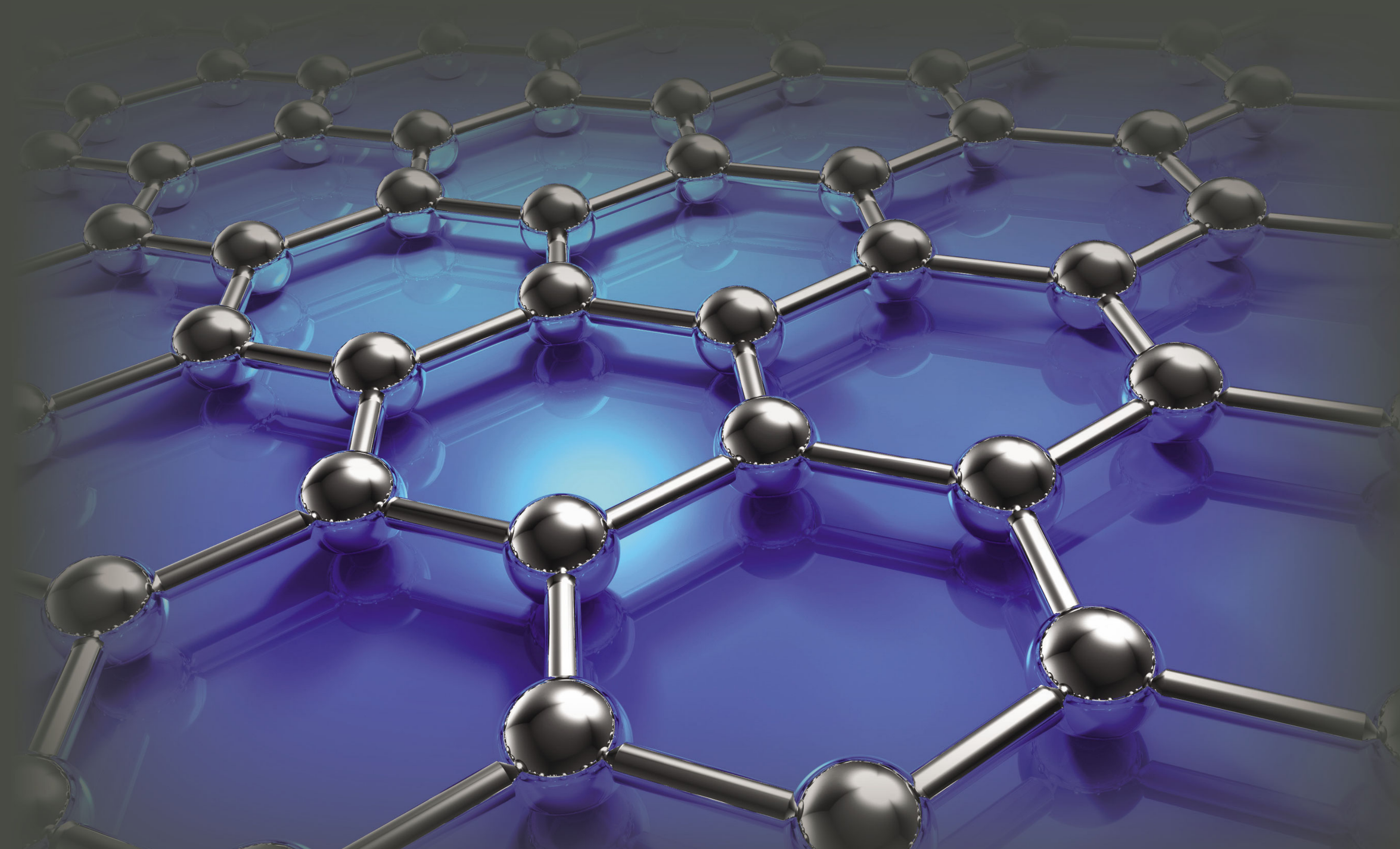



**Figure 1.** Main tectonic units of Western Australia (modified after Johnson, 2013)

# 1

# Specifications, applications, distribution, and markets



**Hexagonal structure of graphene, a single atomic layer of graphite ©Dreamstime images**

# Properties, processing, applications, and prices

## Properties

Graphite is a naturally occurring crystalline form of carbon that is dimorphous with diamond. It is a hexagonal mineral, black to steel grey in colour, and is opaque, lustrous, soft (hardness 1–2), and greasy to the touch. It may exist naturally as crystals, flakes, scales, or grains, or disseminated in veins, lenses, and pods. Graphite is an excellent conductor of electricity and heat, resists attack from most acids, and has extremely good refractory properties.

## Classification

### Natural graphite

Natural graphite has three main commercial forms: amorphous, lump or vein type, and crystalline flake (Fig. 2). These types are distinguished by physical characteristics related to different geological origins and occurrence.

#### Amorphous graphite

The term 'amorphous graphite' is a misnomer because the material has either a microcrystalline or cryptocrystalline structure discernible only under the light microscope and electron microscope, respectively. Amorphous graphite has a soft, black, earthy appearance and is defined by a crystal size finer than 40 µm (although some trade statistics define the upper limit at 70 µm). Amorphous graphite is typically formed by the thermal metamorphism of coal and may be hosted by quartzites, phyllites, metagreywackes, and metaconglomerates. Deposits with grades in excess of 80% carbon are commonly considered economically viable (Kibaran Resources, 2014). Amorphous graphite is mainly sourced from China, North and South Korea, Mexico, and Austria.

#### Lump or vein graphite

Graphite in fissure veins or fractures exists as massive, interlocking aggregates varying from coarse to microcrystalline platy or less commonly, acicular, crystals and is probably of hydrothermal origin. Veins typically vary from 1 cm to 1 m thick and the carbon content may be very high (up to 90–99%). Host rocks include gneiss, schist, quartzite, and marble. Although lump graphite is found in many places throughout the world, it is currently mined on a commercial basis only in Sri Lanka (Pistilli, 2012).

#### Flake graphite

Flake graphite (also known as crystalline flake graphite), originally derived from carbonaceous sedimentary rocks, is found in metamorphic rocks such as quartz–mica schist, feldspathic or micaceous quartzite, gneiss, and marble. Within these host rocks, flake graphite is present as discrete, flat, scaly, or platy crystals with edges that may vary from hexagonal to angular, rounded, or irregular. Carbon concentrations in these host rocks commonly vary from 5 to 40% (locally up to 90%) although 10 to 15% carbon is a more typical commercial grade for an orebody. Impurities commonly include quartz, feldspar, mica, garnet, and calcite, with minor amphibole, pyrrhotite, pyrite, and magnetite.

Although most graphite displays a flaky morphology at certain size ranges, crystalline flake graphite displays this property regardless of particle size.

Commercial flake graphite crystal size ranges include:

- coarse flake 150–850 µm
- medium flake 100–150 µm
- fine flake 75–100 µm
- powder <75 µm.


**Figure 2. Three main commercial forms of graphite (courtesy Lamboo Resources)**

Flake graphite orebodies are normally tabular in profile although they may also be lenticular or form as irregular bodies in fold hinge zones. Most economic deposits of flake graphite are of Archean to Paleoproterozoic age (Kibaran Resources, 2014).

## Synthetic graphite

Although synthetic graphite can be made from a number of carbonaceous raw materials, it is mostly made commercially from specified grades of petroleum coke and/or coal tar pitch. These materials are first calcined and then heated in an electric furnace at 2800°C to produce synthetic graphite suitable for electrodes, anodes, moulded shapes, and powders (Asbury Carbons, 2006). Synthetic graphite tends to have a lower density, higher porosity, and higher electrical resistance than does natural graphite. Because of its higher porosity, synthetic graphite is unsuitable for refractory applications.

# Processing

Processing graphite ore to a saleable product to suit customer requirements is a two-step operation involving concentration of the flake graphite by liberation from the host rock, followed by product beneficiation comprising further purification and product size classification. An example of the more common froth flotation process for purifying flake graphite is given in Figure 3.

## Milling and concentration

Initial processing of graphite varies with the state of weathering of the host rock, flake morphology, and the liberation size. In highly weathered graphitic-rich rock or graphite-bearing soil, the graphite ore is commonly free of the host rock and may be pre-concentrated but graphite contained within its host rock will require liberation. Roller mills and cone crushers liberate the graphite and concentrate it in different size fractions. During this process, granular contaminants such as quartz and feldspar are ground into fines while the graphite flake fraction slips through relatively unaffected. Care must be exercised not to overgrind the graphite as it may smear over other minerals present in the mixture.

During froth flotation, contaminants must be removed especially the mica, quartz, feldspar, and carbonate gangue. This separation may be achieved by adding reagents such as kerosene, which coat the graphite flakes, while adding caustic soda to the mixture to adjust the pH to 7.5 – 8.5 to improve selectivity. Later in the process, a second flotation further improves the sized graphite concentrates and removes any mica and other materials smeared with graphite during earlier processing (Mitchell, 1993).

## Beneficiation

Once the flake graphite has passed through initial processing the size fractions are checked by microscopic examination to establish if the correct graphite liberation size has been achieved and whether the graphite flakes have been completely freed from the host rock. If a substantial proportion of the graphite is still attached to host rock particles, then the larger size fractions may require regrinding. If regrinding is necessary, the next largest sieve-size graphite fraction will be selected as the new liberation size and so on down the size range until a satisfactory size is achieved. Sieve sizes range from 2 mm (largest diameter) downwards through 1 mm, 500 µm, 250 µm, and 125 µm. Graphite particles below this size tend not to concentrate effectively. The process of regrinding and microscopic examination is repeated until all graphite particles have achieved optimum liberation size (Mitchell, 1993).

# Applications

Graphite is known to have been in use since the Neolithic Age (4th millennium BCE) for the manufacture of ceramic paint in pottery decoration by the Marita people in southeastern Europe. During the 1500s a very large graphite deposit was found at Grey Knotts in the Borrowdale area in Cumbria, northwest England. Originally used for marking sheep, the Elizabethans soon discovered graphite was an excellent refractory material to line moulds for the manufacture of rounder cannonballs. These improved cannonballs could be fired further and were adopted by the English navy.

## Conventional applications

Graphite has many applications that have been developed over the last several hundred years and many of these are still in use today. The most common current applications are given in Figure 4. These and other these applications are described below.

### Graphite pencils

During the 1500s in England, the first pencils were made from square sticks of natural graphite wrapped in string or sheepskin. Around 1560, a design for the first wood-enclosed carpentry pencil using a hollowed out stick of juniper wood was made by two Italians, Simonio and Lyndianna Bernacotti. Soon after a superior design was invented using two carved wooden halves in which a graphite stick was inserted and the two halves joined. In 1761, Kaspar Faber discovered a way of grinding graphite so that it did not splinter during the production of ground leads, which were inserted in wooden sticks. This is essentially the same method used in pencil production today, albeit by a highly automated process.

It is currently estimated that more than 14 billion pencils are manufactured worldwide each year. Despite the large volume produced, the quantity of graphite required is smaller than for some current high-end applications. Thus, pencils are included with ‘Other’ in Figure 4.

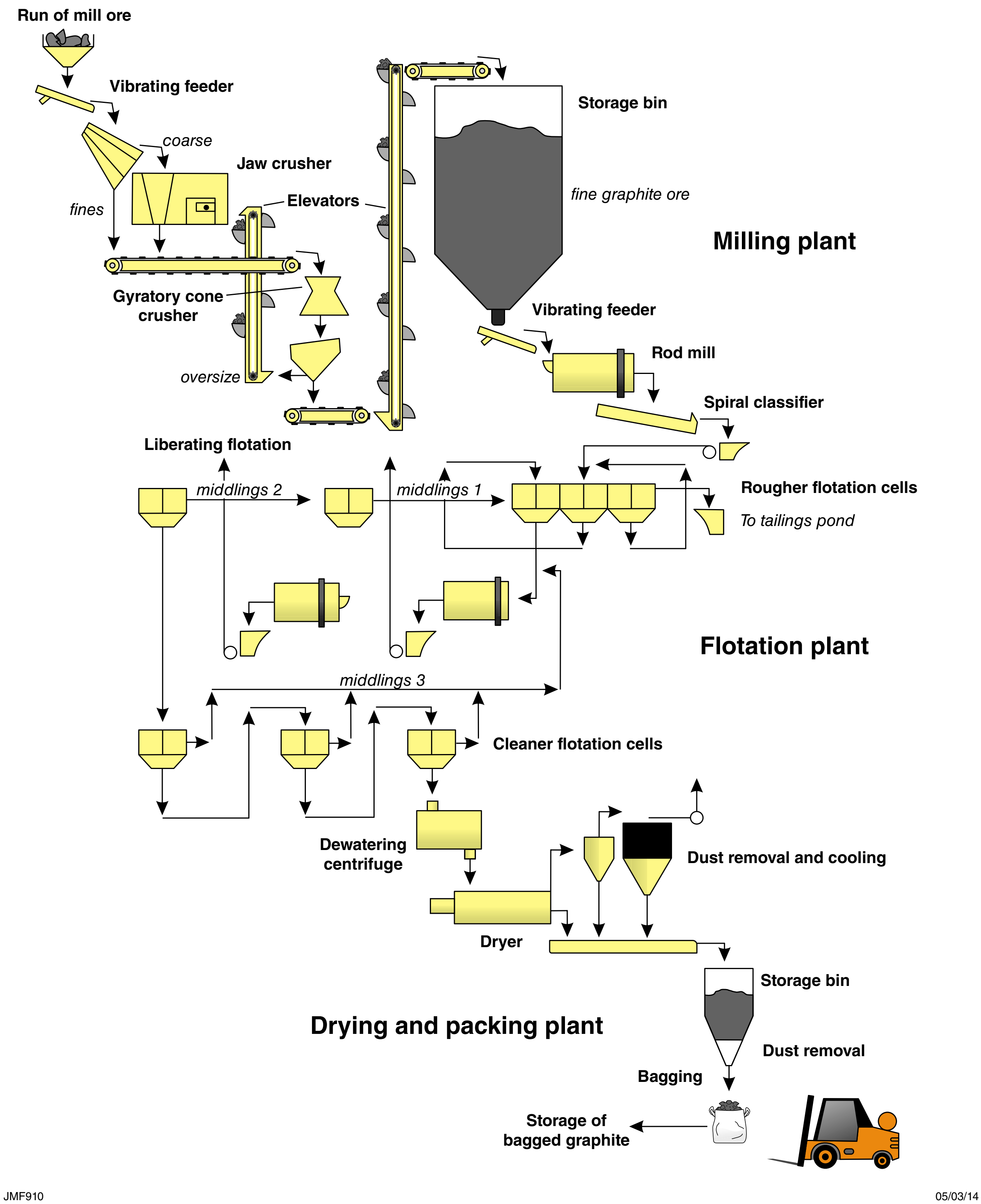



**Figure 3. Graphite concentration and beneficiation by froth flotation (modified after Kibaran Resources, 2014)**

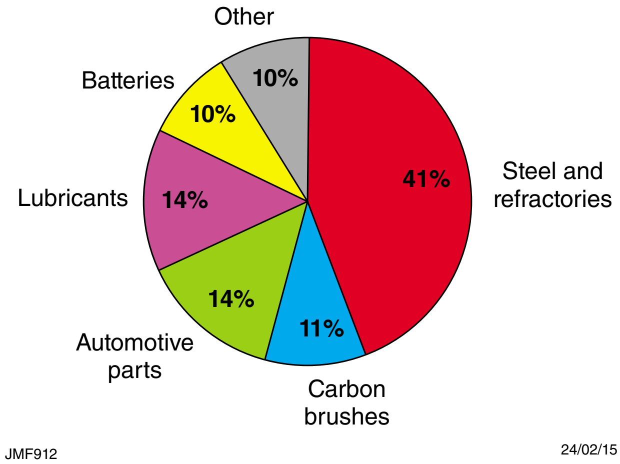



**Figure 4.** **Relative distribution of the most common applications for graphite (courtesy Lamboo Resources)**

## Refractories and the steel industry

Graphite's high temperature stability and chemical inertness make it an excellent refractory material. This application is by far the largest for graphite at 41% of the world market. The manufacture of modern graphite crucibles was well advanced before the 20th century with the advent of cast vessels designed to contain molten metal. Refractory products originally used very large flake graphite although modern technology allows much more flexibility in the size of graphite flake required, so amorphous graphite is no longer restricted to low-end refractory applications.

Graphite is also used in the manufacture of carbon–magnesite refractory bricks known as 'mag–carbon', which are used to form part of the lining of furnaces for the production of molten steel (see illustration on cover). These bricks are suitable for this application due to their structural strength, thermal shock resistance, high thermal conductivity, and chemical resistance at the melting point of steel between 1400 and 1540°C. Also in the steelmaking process, graphite flake is mixed with alumina and zirconia and then pressed into components such as stopper rods, subentry nozzles, and ladle shrouds to regulate the flow of molten steel and protect it against oxidation.

Graphite electrodes are used in many electrical metallurgical furnaces such as the electric arc furnaces used for processing molten metals, including special steels.

## Coatings and lubricants

In the foundry industry, a water-based paint consisting of amorphous or fine flake graphite is painted on the inside of a mould. When dry, the fine graphite coating makes it easy to separate the cooled cast metal from the mould wall.

Speciality graphite lubricants designed for high-temperature applications are used as a forging die lubricant, an antiseize agent, and a high-temperature gear lubricant especially for mining machinery. At low temperatures graphite is used as a dry powder for lubricating locks. In other applications it is suspended in a liquid as colloidal graphite.

## Brake linings and clutches

Natural amorphous and fine flake graphite are used in thermal and high-friction applications such as vehicle brake linings, clutches, and brake shoes in heavier applications. Graphite is largely used as a substitute for asbestos, which is no longer used in this industry.

## Chemical industry

In the chemical industry there are many high-temperature applications for graphite. For example, graphite is used in the manufacture of calcium carbide, and phosphorus in electric arc furnaces. Other applications include graphite anodes in electrolytic aqueous processes such as the production of chlorine and fluorine gases.

## Mechanical applications

Graphite has a wide range of mechanical applications, especially in the manufacture of piston rings, thrust and journal bearings, and vanes. It is also used in carbon-based seals in jet engine shafts and fuel pumps.

## Electric motor brushes

Graphite has been used for many years as carbon brushes in electric motors. This application requires high-grade graphite to ensure long life and satisfactory performance.

## Batteries

Conventional batteries have been in use for many years providing power to numerous portable electric appliances. In batteries such as the original zinc type, and more recently in rechargeable alkaline varieties, graphite rods used as positive electrodes provide high electrical conductivity and good corrosion stability within the cell. In primary alkaline batteries, graphite is used as a conductive additive, lubricant, and processing aid within the cathode to improve the cells' electrical conductivity (Superior Graphite, 2012).

# Contemporary high-end applications

Low-purity flake graphite and amorphous grades are typically unsuitable for use in new technologies and world demand for graphite is shifting to high-purity crystal flake for use in contemporary higher end applications. Many of these applications are described below and some are displayed on the cover and frontispiece of this Bulletin.

## Pebble-bed nuclear reactors

Pebble-bed nuclear energy generators are small, modular reactors that are becoming important to the energy sector. Instead of uranium-enriched rods, pebble-bed reactors use uranium fuel embedded in golf ball-sized graphite-coated pebbles that act as moderators. These pebbles are supplied in a controlled flow to the reactor core where thousands of pebbles are amassed for the generation of heat. Spent fuel pebbles are tapped off at the base of the reactor. A 100 GW pebble-bed reactor requires 300 t of graphite for start up, and a further 60–100 tonnes per annum (tpa) of graphite for continual operation (Pistilli, 2012). An example of a graphite-coated fuel pebble is shown in Figure 5.

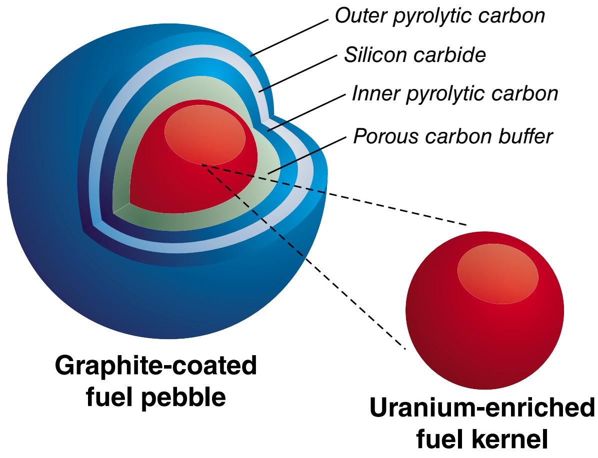



**Figure 5.** Example of a graphite-coated nuclear fuel pebble. Pebble is approximately 3–4 cm in diameter (modified after World Nuclear News, 2009)

## Lithium-ion batteries

In recent years, lithium-ion batteries have become increasingly popular for long-life, rechargeable batteries used in devices from mobile phones, computers, and cameras to electric cars. Lithium-ion batteries feature a very high energy density enabling them to store large quantities of electricity. These batteries require 10–20 times more graphite (in the anode) than lithium carbonate. An average hybrid electric car uses more than 10 kg of graphite in its battery and a fully electric car uses up to 70 kg. A conventional electric car is shown in Figure 6.


**Figure 6.** Conventional electric car at a recharging station in a European street (image courtesy Wikipedia)

## Fuel cells

Fuel cells are energy conversion devices that convert fuel such as hydrogen into electrical energy. Within the fuel cell, the proton exchange membrane requires large quantities of graphite. Fuel cells of all sizes are currently making their way into the electronics and utilities sectors where, for example, they may provide emergency power at institutions such as hospitals.

## Vanadium redox flow batteries

As with fuel cells, vanadium redox flow battery technology can be used for the long-term storage of large quantities of energy. These batteries, still in the developmental stage, are electrochemical storage devices that store energy in two electrolyte solutions containing vanadium in different valence states. The system's capacity is determined by the size of the electrolyte tanks and the system power is determined by the size of the cell stacks.

Studies are continuing to determine the optimum design of graphite electrodes and graphite felts used in vanadium redox flow batteries that will achieve the most efficient electron flow. Natural graphite, graphite composite materials, graphene-like materials, and graphite nanotubes have been used in tests. Since 2011, technological developments have allowed for the construction of redox flow battery plants in China, ranging from 2 to 5 MW capacity (Noack and Tübke, 2010; Xie, 2011).

## Aerospace industry

Graphite and its derivatives have found current and future applications in the aerospace industry because they have exceptionally high thermal stability properties. Lightweight graphitic substances have found uses in rockets and aerospace re-entry vehicles due to their very high thermal shock resistance. Graphite applications have also been found in jet engine cases, blast tubes, rocket nozzles and nose cones, edge components, and thermal insulators.

## Graphite foil

In the manufacture of graphite foil, graphite is first oxidized with a fuming sulfuric – nitric acid mix and is then hydrolyzed, washed, and dried. This material is then heated and pressed to form graphite foil, which is impervious to gases and liquids, and is fireproof. It is manufactured into various shapes, and flat products like adhesive-backed tape, ribbons, rolls, sheets, and laminates are used for high-temperature gaskets, seals, heat shields, and valve packing, and in cryogenic applications (Fig. 7).

## Graphite nanocomposites

Graphite-based carbon-fibre nanocomposite materials have applications in the automotive, marine, aerospace, and sporting goods industries. Intercalated or exfoliated graphite nanoflakes are used in the manufacture of reinforced polymers with superior mechanical, thermal, and electrical properties. Products manufactured from these nanocomposites include fishing rods, golf club shafts, bicycle frames, sports car body panels, and the fuselage of the Boeing 787 Dreamliner aircraft.

## Graphene

Termed 'the world's next wonder material', graphene is an allotrope of carbon, and is essentially a one-atom-thick sheet of graphite. First isolated into individual sheets in 2004, graphene exhibits remarkable properties not seen in crystalline graphite. Properties include very fast electron transport, the highest mechanical strength and greatest thermal conductivity yet measured, and room-temperature quantum Hall effect. The quantum Hall effect is a quantum-mechanical phenomenon that has recently become observable in very high magnetic fields at room temperature. In this environment, single atomic sheets of graphene display frictionless current flow and electrical resistances as accurate as a billionths of an ohm (ScienceDaily, 2007).

In practical terms, graphene is around 200 times stronger than steel, more conductive than copper, 50–100 times more efficient than conventional solar panels, 50–100 times faster than today's semiconductors, and has the potential to make aircraft 70% lighter and charge batteries 10 times faster and store 10 times more power. It could also be used in the manufacture of supercapacitors for the electronics industry. Graphene applications are discussed in more detail in Gladstone (2012).

An example of a series of one-atom-thick sheets of graphene is pictured in the frontispiece of this Bulletin.

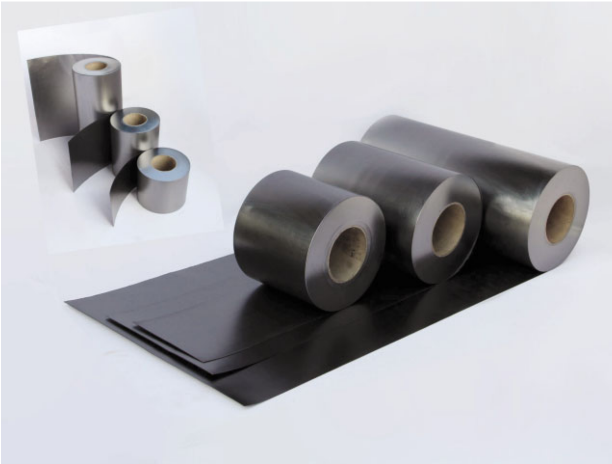


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**Figure 7. Rolls of flexible graphite foil commonly used for high-temperature gaskets and seals (courtesy Lamboo Resources)**

# Current price trends

From 2007 until mid-2010, graphite prices experienced an overall gradual increase reaching about US$1500/t for highest grade (94–97% TGC) coarse flake graphite. Around that time, China, the world's biggest graphite producer with 89% amorphous and 66% flake graphite grades, imposed export quotas on graphite producers of 20% export tax and enforced legislation that effectively limited graphite exports to only 40% of total production. This significant reduction in supply to world graphite markets coupled with increased demand for high-grade, flake graphite for the refractory industry, and new high-tech graphite markets such as lithium-ion batteries and pebble-bed nuclear reactors, caused an upsurge in prices for high-grade flake graphite that exceeded US$2500/t by mid-2011. Since that time supply and demand has changed to bring highest grade prices down to bottom out at a little more than US$1300/t by late 2013 (Fig. 8). In the first quarter of 2014, international prices quoted by Industrial Minerals magazine for commercial graphite grades were as shown in Table 1.

In late 2013, the Chinese Government closed 55 mine operators and producers in the Pingdu region in Shandong Province on environmental grounds. Pingdu is China's second-largest graphite producing region (after Heilongjiang Province) with an annual capacity of 100 000 t. These regulations have effectively put 20% of China's graphite production on hold. Although this situation may be temporary, prices have remained relatively static although it is expected that high-grade prices may reach US$1400–1500/t in the short term and may increase further to US$1600–1800/t in future. Price increases may be supported by increased competition between refractory and battery manufacturers for supplies of the same grade of large flake graphite >80 mesh (>177 μm) particle size and higher purities between 95 and 98% carbon (The Mining Report, 2014). This situation, coupled with expected increases in demand for other high-grade graphite applications from newly emerging, high-tech graphite industries will require substantial increases in supply, which is expected to reach at least 2 M tpa by 2020.

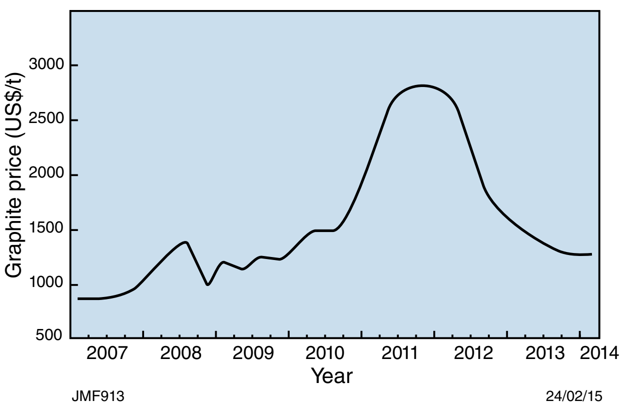



**Figure 8. International price trend for coarse flake graphite (94–97% TGC) for 2007–14 (modified after Moores, 2012)**

**Table 1. International graphite prices for first quarter 2014**

| *Graphite grade (% TGC)[a]* | *Price (US$/t)* |
|---|---|
| Amorphous powder (Chinese, delivered in Europe) | 500–550 |
| Synthetic fine graphite (CIF[b] Asia) | |
| 97–98% | 950–1450 |
| 98–99% | 1000–1500 |
| Crystalline graphite (FCL,[c] CIF[b] at main European port) | |
| Fine: 90%, –100 mesh (<149 μm) | 750–850 |
| Fine: 94–97%, –100 mesh (<149 μm) | 850–950 |
| Medium: 85–87%, +100–80 mesh (>149 μm to <177 μm) | 700–800 |
| Medium: 94–97%, +100–80 mesh (>149 μm to <177 μm) | 1050–1150 |
| Medium flake: 90%, +100–80 mesh (>149 μm–<177 μm) | 900–1000 |
| Large flake: 90%, +80 mesh (>177 μm) | 1100–1150 |
| Large flake: 94–97%, +80 mesh (>177 μm) | 1250–1300 |

**SOURCE**: Industrial Minerals (2014)
**NOTES**: (a) Percent total graphitic carbon
(b) Cost, insurance, and freight
(c) Full container load

## Graphite deposits

Harben and Kuzvart (1996) subdivided graphite deposits into five main types, essentially related to the degree of graphitization of original carbonaceous sedimentary rocks or of carbon derived from deep-seated, mantle rocks. The formation of graphite is dependent on temperature (typically between 400 and 650°C or higher) together with pressure to a lesser extent, caused by metasomatic or metamorphic processes, commonly followed by weathering and concentration.

### Magmatic deposits

These deposits are comparatively rare and are associated with intrusive rocks such as nepheline syenite and microcline granites at temperatures <650°C. Graphite ore in these deposits, formed from mantle-derived carbon, tends to be high quality. The Botogol deposit in the Eastern Sayan Mountains in the Russian Federation is an example of this type.

### Contact metasomatic deposits

Contact metasomatic or skarn deposits develop at the contact of carbonate rocks with plutonic magmas such as pegmatite and aplite. Crystallization of coarse flake graphite bodies within Ca–Mg skarns may result. Examples of this type are found in stocks and veins in the Grenville rocks of the Ontario – Quebec – New York region of Canada and the USA.

### Vein deposits

Vein deposits result when hydrothermal solutions rich in volatiles such as $CO_2$, associated with pegmatites, form veins and lenses ranging from a few millimetres to 5 m in thickness. The graphite-rich veins display sharp contact with the wallrocks. The contained coarse flake, or in places euhedral, graphite may reach 80–98% purity and is commonly accompanied by biotite, orthoclase feldspar, quartz, apatite, and other minerals. The graphite is thought to have formed during early crystallization of the pegmatite at temperatures between 600 and 650°C. Large, commercial vein graphite deposits are present in central and southwest Sri Lanka.

### Metamorphic deposits

Metamorphic graphite deposits are formed by either contact or regional metamorphism of carbonaceous sedimentary rocks containing coal, bituminous material, or other carbon-rich substances.

#### Contact metamorphosed deposits

These deposits form by comparatively low-temperature thermal metamorphism in which carbonaceous sedimentary rocks commonly containing coal have been contact metamorphosed by local intrusive rocks such as granite and felsic intrusive rocks. In this situation, carbon present in coal seams may be recrystallized into beds and veins grading from anthracite to coke and graphite depending on distance from the intrusive body. Graphite formed in this manner is commonly low-grade, extremely fine-grained material known as ‘amorphous graphite’. Deposits of this type are found at a number of sites in the coal basins of central Queensland and northern New South Wales.

A few examples of graphite deposits formed by high-temperature contact metamorphic processes are present in Mexico and the Russian Federation.

#### Regionally metamorphosed deposits

Graphite deposits of this type are almost exclusively the result of high-grade regional metamorphic processes. Such deposits may be formed by metamorphism of carbonaceous shale, limestone, and sandstone, which may contain from 2 to 60% carbon and have been altered by pressure and high temperatures of at least 650°C to form graphitic phyllites, mica schists, gneisses, marbles, and quartzites. This process commonly results in the formation of beds, veins, and lenses containing graphite ranging from low-grade, amorphous material to deposits of high-grade, large diameter flake graphite. Most of the world’s flake graphite production comes from deposits of this type. In Western Australia, almost all graphite deposits, prospects, and occurrences of Archean and Proterozoic age have been formed by this method.

### Residual deposits

These deposits form by the weathering of high-grade graphitic schists and gneisses by chemical leaching, resulting in the formation of weathering profiles rich in graphite flakes or grains. In Western Australia, residual deposits form as in situ clays and weathered, kaolinized schists. Commercial graphite deposits of this type are present in Madagascar.

## Global distribution and production of graphite

Graphite deposits are widely distributed throughout the world, although China is by far the largest producer with

89% of the world's amorphous grade and 66% of flake graphite in 2012 (Fig. 9). In that year, the United States Geological Survey (USGS) estimated that total world graphite production was 1070 kt with China producing 800 kt. Other large producers were India (160 kt), Brazil (110 kt), North Korea (30 kt), and Canada (25 kt) (USGS, 2014).

Globally, graphite in its three commercial forms is divided into amorphous graphite with 50% of total production, flake graphite with 49%, and lump or vein type with 1% (only from Sri Lanka). High-quality, flake graphite with a purity range of 85–95% TC is produced in decreasing order of volume by China, Brazil, India, North Korea, Canada, Norway, Zimbabwe, Ukraine, Czech Republic, Uzbekistan, Russia, and Madagascar. Lower quality amorphous grade with a purity range of 70–85% TC is produced in China, Mexico, Austria, North Korea, Russia, and Turkey (Moores, 2012).

# Graphite in Australia

## Eastern Australia

In the eastern Australian states, graphite occurrences and prospects have been reported from South Australia, New South Wales, and Queensland. The most significant prospects are in the eastern Eyre Peninsula in South Australia.

### *South Australia*

In South Australia graphite prospects exist in the Eyre Peninsula along a 200 km-long, north-northeast-trending zone extending both north and south of Port Lincoln. In this region, graphite was formed by high-grade metamorphism of carbonaceous sedimentary rocks from the Paleoproterozoic lower Middleback Subgroup.

The Uley graphite deposit, about 15 km southwest of Port Lincoln, was discovered in 1910 and was mined until 1950 and again from 1982 until 1993, producing 1025 t of flake graphite during the latter period. Since December 2014, the 14 000 tpa Phase I plant has been reprocessing raw material from existing stockpiles of graphite fines. In 2015, the mine, with a JORC-compliant resource of 6.4 Mt at 7.1% TGC, has been undergoing economic feasibility studies for future operational expansion: Uley Graphite Phase II (expanded production), and Phase III (advanced product handling and manufacturing) (McDiarmid, 2014a; Valence Industries, 2015).

Another Eyre Peninsula deposit, about 120 km west-southwest of Whyalla, is the Campoona graphite deposit owned by Archer Exploration Ltd, with total JORC resources of 2.527 Mt at 12.3% TGC (5% lower cutoff grade) of highly crystalline, ultrafine graphite (Archer Exploration, 2012). Other graphite prospects owned by Archer Exploration in this area include the Sugarloaf deposit, which yielded graphitic ore intervals of 13% and 14.37% TC over 20 and 31 m, respectively, from two drillholes in 2011, and the Cleve West exploration area.

In other areas of the eastern Eyre Peninsula, Lincoln Minerals Ltd is currently investigating a number of high-grade graphite resources on exploration licences including:

- Kookaburra Gully deposit, about 35 km north of Port Lincoln, is at the northeast end of a 4.5 km-long electromagnetic (EM) anomaly that may indicate the presence of a large graphite exploration target. Drilling in early 2013 confirmed a total indicated and inferred resource of 2.25 Mt at 15% TGC with 338 000 t of contained high-grade graphite (Lincoln Minerals, 2013).
- Koppio graphite mine, about 30 km north of Port Lincoln, previously operated intermittently between the early 1900s and 1946 producing high-grade, coarse flake graphite up to 32% TGC. In 2014 Lincoln Resources completed a drilling program near the mine. The highest graphite assay recorded from this program was 42.8% TGC from a one-metre graphite intersection. Investigations are continuing (Lincoln Minerals, 2014).
- Gum Flat graphite has recently seen sampling and re-evaluation of previous drill cuttings in which significant graphite intervals were identified. In one hole, 10 km north of the Uley graphite mine, a 13 m graphite interval at 12% TC from 57 m was confirmed (Lincoln Minerals, 2012a).
- Cockabidnie graphite–nickel prospect is on the Campoona syncline, adjacent to Archer Exploration's Campoona graphite prospect. The prospect was flown by a 400 m line-spaced EM survey in 2012. The interpretation and modelling of the EM data to detect possible graphite anomalies are awaiting completion (Lincoln Minerals, 2012b).

### *New South Wales*

In New South Wales there are 14 recorded graphite occurrences, mostly amorphous grade and mainly from the New England area at Undercliff Falls, north of Tenterfield, and Walcha, south of Armidale. Less than 3000 ton of graphite has been mined in the State, mostly from the Plumbago deposit in the Undercliff Falls area where nine separate graphite sites have been recorded. These deposits appear to have been derived from the metamorphism of Permian carbonaceous sedimentary rocks (Whitehouse, 2007).

### *Queensland*

Queensland graphite deposits are also mostly amorphous grade; crystalline and flake graphite deposits in commercial quantities are unknown in the State. Amorphous graphite derived from metamorphosed Permian coal seams is at Jacks Creek near Collinsville, and Cape Upstart in the Bowen area. The Jacks Creek deposit produced about 1955 t of graphite on an intermittent basis from 1935 to 1956. In the Gympie district a suite of metamorphosed Jurassic coal seams is at Mount Bauple. At this site, bituminous coal seams have been intruded by felsic igneous intrusive rocks to form metamorphosed carbonaceous rocks varying from lustrous anthracite to dull, earthy graphite in seams up to 1.2 m thick. This deposit produced 150 ton of graphite during 1905–08.

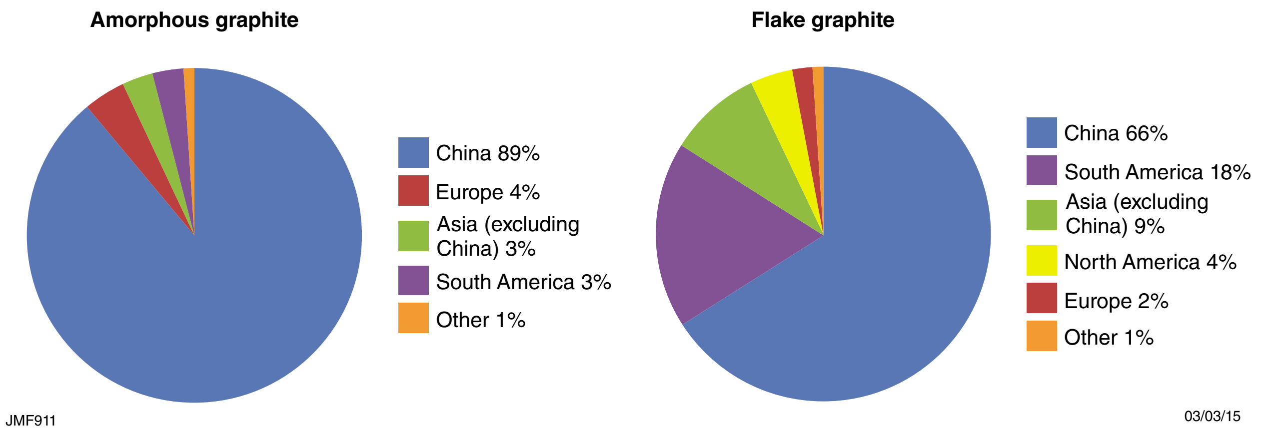



**Figure 9. Estimated world natural graphite production in 2012 (modified after Industrial Minerals, 2014)**

An amorphous graphite prospect at Homebush near the central Queensland coast comprises two graphite seams, each 0.5 m thick, in association with shale, quartzite, and intrusive igneous rocks. Graphite prospects have also been recorded in schists and slates in the Cloncurry, Mount Isa, Etheridge, Gympie, and Silverspur regions (Cribb, 1976).

## Western Australia

Western Australia has numerous graphite occurrences and prospects described in some detail later in this book. To date, almost all recorded sites in the State are found in graphitic schists or gneisses derived from the metamorphism of carbonaceous sedimentary rocks ranging from Archean to Mesoproterozoic age. In the Northampton district there are also relatively small graphite occurrences associated with Mesoproterozoic paragneisses and pegmatites. In general, Western Australian graphite ranges from high-grade, coarse to fine flake graphite, together with lower grade microcrystalline to amorphous varieties. During the 20th century, mining and concentration of graphite was a small industry with total recorded production of 222 t. Most of this material, amounting to 135 t, was produced at Munglinup in the far south of the State. Smaller amounts of graphite were also recovered from the Donnelly River mining area in the southwest of the State, and possibly from the Ajana district near Northampton. Graphite localities in the Western Australia are shown in Figure 10.

### *Current exploration*

Currently in Western Australia, two companies are in advanced stages of exploration on two graphite deposits: McIntosh in the Kimberley region, and Yalbra in the central west of the State.

In the Halls Creek area in the east Kimberley region, Lamboo Resources Ltd is well advanced on the McIntosh project area, which contains five high-grade, flake graphite targets. Recent drilling and core analysis from Target 1 have confirmed a JORC-compliant total indicated and inferred graphite resource over 580 m strike length of 7.135 Mt grading 4.73% TGC (4.95% TC) for 337 700 t of contained graphite at a 2% TGC cutoff grade. The graphitic orebody also remains open both along strike and at depth. The company is currently exploring other targets and running beneficiation trials relating to flake graphite production. Recently, Lamboo Resources entered into an MoU with a Chinese graphite processor to further this research and in June 2014 announced an offtake agreement to supply the company with 50 000 tpa flake graphite concentrate to the end of 2018.

At Yalbra, in the central west of the State, Buxton Resources Ltd has been conducting an extensive exploration program involving six relatively closely spaced, high-grade, graphitic-rich zones. The exploration has concentrated on a graphite resource previously identified by Carpentaria Exploration in 1974. In 2012–13, Buxton Resources combined the earlier drillhole data over Yalbra 1 and Yalbra 1a graphite targets with a versatile time domain electromagnetic (VTEM) survey followed by a reverse circulation drilling program over the same area. The program confirmed the presence of two major parallel, steeply dipping, high-grade graphite horizons extending along strike for over 600 m within the Yalbra 1 target area. In October 2014, the company announced an updated high-grade, inferred JORC-compliant resource estimate of 4.022 Mt at 16.17% TGC for a contained graphite content of 650 000 ton at a 4% TGC cutoff grade. There is also significant future potential to extend this resource both along strike and at depth. This exploration program is continuing.

## Overseas exploration

In the light of the spike in world graphite prices in 2011–12, overseas exploration is continuing apace. Many companies, including Australian companies, are attempting to evaluate and prove up both new and existing graphite deposits with a view to supplying the high-tech graphite market with suitable high-grade flake graphite. In Europe, exploration is continuing in Finland, Sweden, and Spain, and in Asia, in South Korea, Myanmar (Burma), and Sri Lanka. In Africa, exploration is underway, especially in Tanzania, Mozambique, Madagascar, Botswana, and Namibia. In the Americas, exploration is continuing in Canada (Quebec, Ontario, and British Columbia), USA (Alaska and Nevada), Mexico, and Brazil.

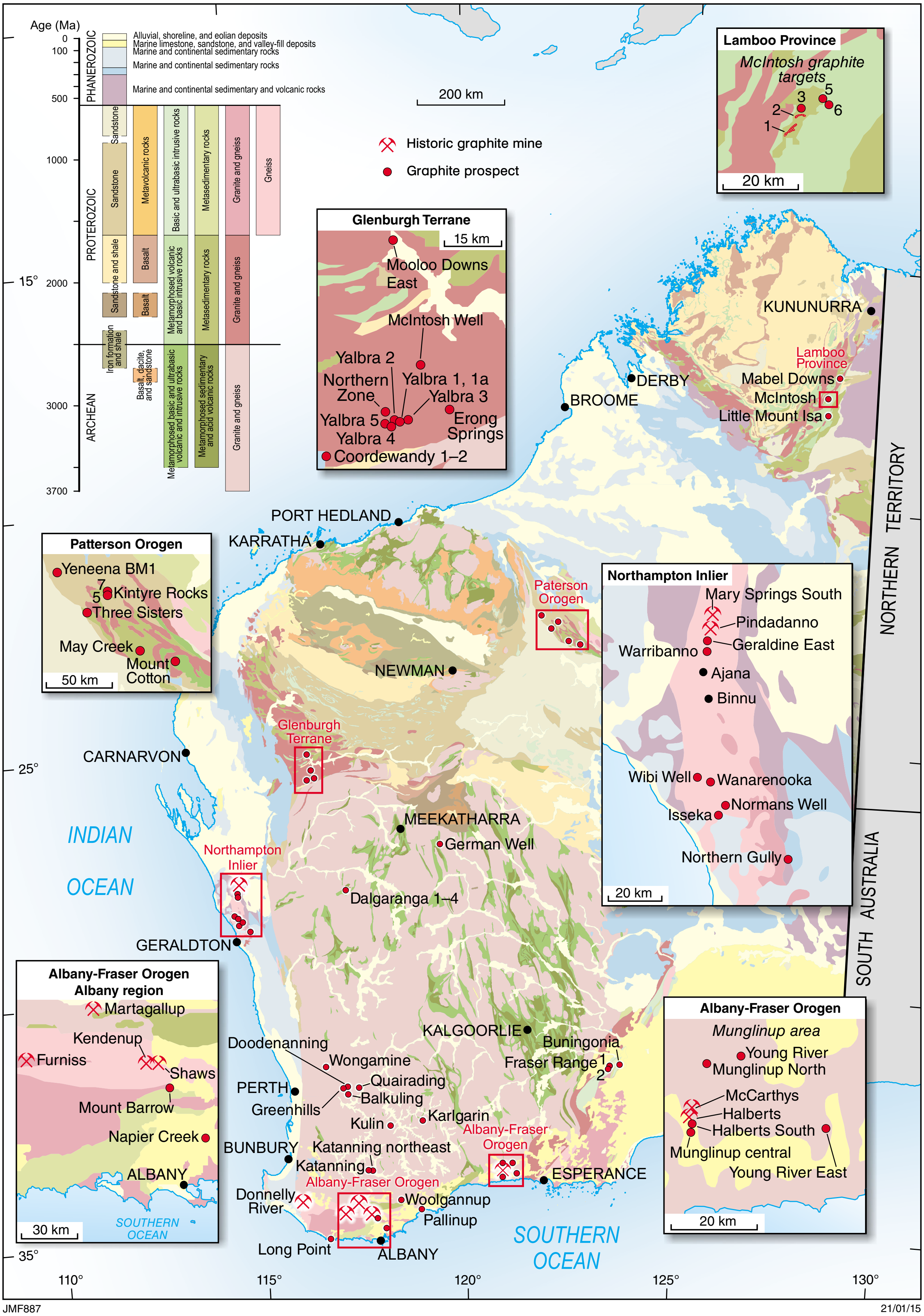



**Figure 10.** Graphite localities in Western Australia

# 2

# Graphite exploration and mining in Western Australia

**Prospecting for graphite targets in a graphitic gneiss zone, McIntosh area, East Kimberley region (courtesy Lamboo Resources)**

The Paleoproterozoic–Mesoproterozoic Albany–Fraser Orogen is a long, linear body extending around 800 km along the south coast of Western Australia before trending inland for about 550 km around the southern margin of the Archean Yilgarn Craton (Fig. 1). The orogen has been subdivided into two major, parallel, east–west trending zones. The older northern zone, known as the Biranup Zone, comprises high-grade quartzo-feldspathic gneiss, granite, and layered basic intrusions; the younger, southern zone, known as the Nornalup Zone, is composed of less intensely deformed high-grade orthogneiss and paragneiss, both intruded by sheets of granite (Myers, 1990a; Johnson, 2013; Spaggiari et al., 2014).

The Albany–Fraser Orogen contains numerous graphite occurrences that extend from Long Point, near Walpole in the far west, to Buningonia Spring in the Zanthus region in the northeast (Fig. 11). Throughout the Albany–Fraser Orogen, graphite is commonly present in kaolinitic or iron-rich material sourced from the weathering of metamorphic rocks ranging from metamorphosed shale, quartzite, and graphitic schist to recrystallized granitic rocks, pegmatites, and gneisses.

## Buningonia prospect

The Buningonia graphite prospect is about 45 km south-southeast of the settlement of Zanthus on the Trans-Australian railway in an area approximately 13 km south-southeast of Buningonia Spring (Fig. 11).

A kaolinized, iron-stained rock was found to contain 21.8% flake graphite in an area of gneiss and metasedimentary rocks within the Fraser Zone. The graphite was intergrown with mica and unevenly distributed in the host material in veins and nests. Two assays of graphite concentrates yielded >81% TC (Simpson, 1951).

## Fraser Range prospects

These graphite prospects are within the Fraser Zone (covering the Fraser Range) on former exploration licences E28/1127 and 1057 owned by Mr WS Yeaman. The tenements were about 120 km north-northwest of Balladonia (Fig. 11).

The exploration program was carried out in 2005 with the objective of identifying alluvial deposits of industrial-grade garnet and heavy minerals such as rutile, anatase, ilmenite, and zircon. During the survey, in situ hard-rock samples of coarse flake graphite were found in paragneissic rock at two main localities (Fraser Range 1 and 2), approximately 5 km apart, along the central, northeast-trending ridge within the tenements (Yeaman, 2005).

At Fraser Range 1, medium to coarse flake graphite was found within alternating bands of strongly lineated quartzite and goethite. At Fraser Range 2, sporadic graphite is present as single flakes within a leucocratic, graphite–garnet–K-feldspar–quartz gneiss. At this locality, graphite crystals, mostly less than 200 µm wide, exist preferentially with garnet crystals and also with iron oxides. At these sites, flake graphite crystals range from 150 to 200 µm wide and 30 to 40 µm thick and graphite content was visually estimated at 0–5% TGC.

## Furniss mine

The abandoned Furniss graphite mine is near Muirs Bridge on the Muirs Highway, about 105 km northwest of Albany and 10 km west-northwest of Rocky Gully. The mine's precise location is difficult to determine although it is probably about 2.5 km south of Muirs Bridge close to the Frankland River (Fig. 11).

Although the mine is in an area surrounded by recrystallized granitic rocks, no granitic bedrock is in evidence in the vicinity. Instead, the old workings have been excavated from a dense clay probably derived from weathered quartz–mica schist probably of sedimentary origin, possibly shale. In operation from 1909 to 1922, the mine workings comprised several shallow costeans and a shaft 4.6 m deep with several short drives extending from the base of the shaft. These were inspected by Blatchford (1922) who noted a narrow (70–150 mm thick), steeply dipping vein of graphite intersecting the shaft and crosscuts. Another lower grade vein was also present. Eight samples collected by Blatchford (1922) from veins at this site yielded variable carbon contents ranging from 7.62 to 50.49% TC. Blatchford (1922) also noted the similarity between the clayey host rock at this site and the Kendenup graphite mine in the Mount Barker area about 80 km east.

## Rocky Gully West

Between 2011 and 2013, Heron Resources Ltd carried out studies relating to graphite prospectivity in the area of former exploration licence E70/3878 in a 45 km-wide, east–west zone covering the town of Rocky Gully and the old Furniss graphite mine (Fig. 11).

The area under investigation is in an area of paragneiss and orthogneiss forming part of the Biranup Zone. Interpretation of aeromagnetic data covering the area indicated the probability of linear rock bands of medium to high magnetic intensity trending east-northeast. It is suggested that these bands, which trend towards

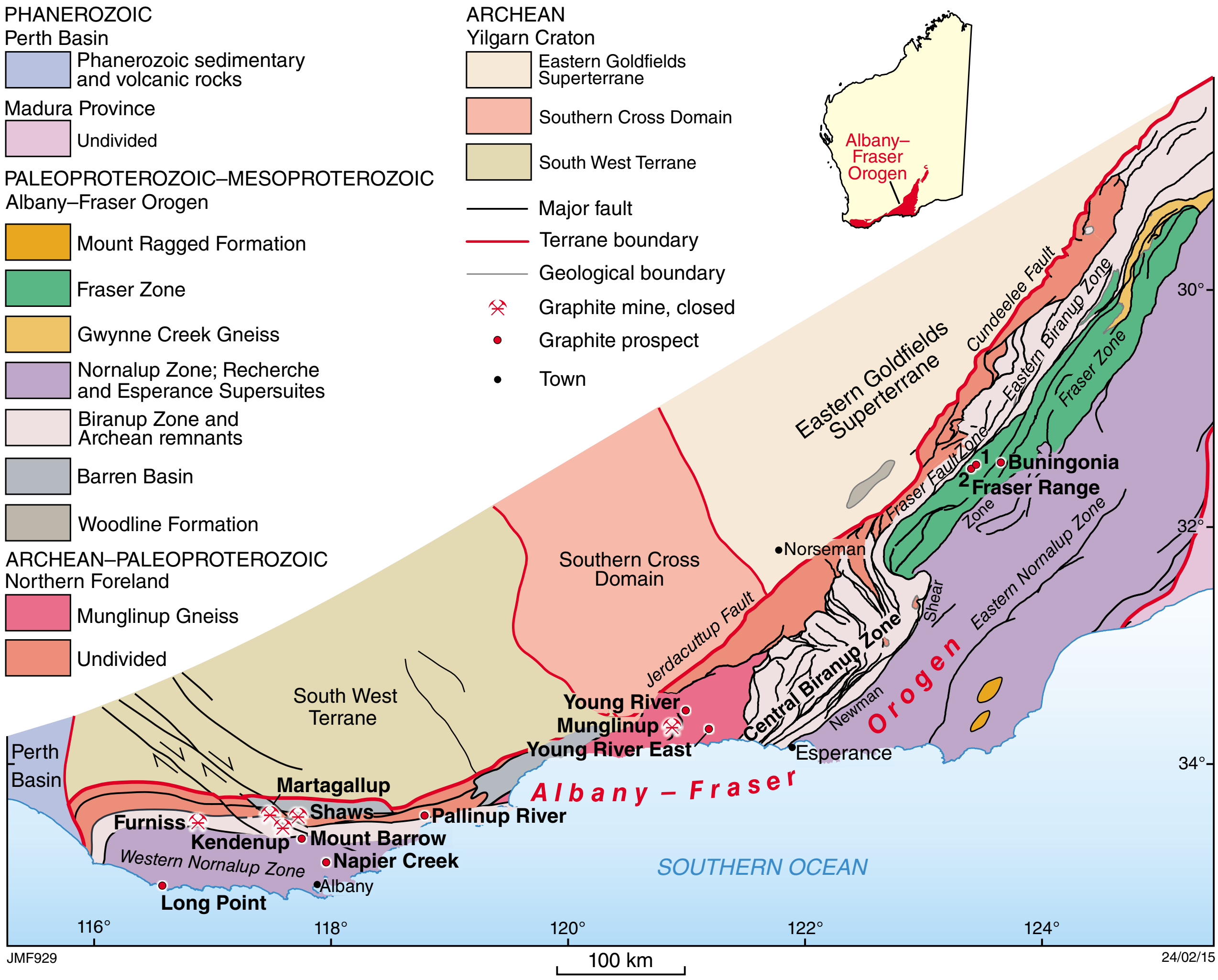



**Figure 11. Geological map of the Albany–Fraser Orogen (modified after Johnson, 2013)**

established graphite deposits east of the area, including the former Martagallup mine, may be prospective for concealed deposits of flake graphite (Patrick, 2013).

## Long Point occurrence

A graphitic schist was recorded by Simpson (1951) on the northwest side of Long Point, which abuts the Southern Ocean about 15 km west-southwest of Walpole (Fig. 11). Nornalup Zone rocks in this area comprise interlayered, granulite-facies ultramafic, mafic, and felsic rocks, and granitic gneiss.

## Mount Barker area

Despite a notable lack of surface outcrop, the four graphite localities in this area seem to be in an area of mostly quartzo-feldspathic gneiss of the Biranup Zone.

## Kendenup

### Kendenup mine

The Kendenup graphite mine is in a zone of quartz–mica schist on the south side of the Kalgan River on the former mineral claim MC70/279H, approximately 4 km south-southwest of Kendenup railway siding (Fig. 11).

Graphite deposits in the Kendenup area have been known since 1875 and attempts to mine them were made on at least three occasions before 1900 although all were abandoned after short periods due to the low grades of graphite recovered. In 1903, high-grade graphite zones were located by underground testing although the site remained undeveloped because of lack of sufficient funds (Townsend, 1994).

The Kendenup mine was eventually developed around 1916 over a west-northwest-trending graphitic lode estimated at about 7.6 m wide. At this site, a vertical shaft of 15 m depth was excavated in soft and extremely weathered schist, metamorphosed shale, and other sedimentary rocks. At a depth of 6 m, two horizontal drives were cut, with the short western drive extending about 6 m to the west, and the main drive for almost 18 m in an easterly direction where it encountered a hard band of crushed quartzite along the northern wall for 6 m (Fig. 12). It was noted that rich lenses, seams, and veins of scaly, crystalline graphite were present adjacent to the quartzite band although it was evident that the graphite grade diminished rapidly as the distance from the band increased. This observation was borne out in subsequent graphite analyses, which yielded 80.5% TGC against the quartzite band, decreasing within a few metres westward along the main drive to 46.2% TGC, and to 26.9% TGC about halfway along the drive. Along the western drive, a sample yielded only 12.1% TGC (Woodward and Blatchford, 1917) (Fig. 12).

Ellis (1944a) visited the mine site and found that because there had been no further development of the deposit, the original openings had fallen in and the shaft had been backfilled with rubbish.

## Shaws mine

Shaws graphite mine is also in the Kendenup area about 5 km southeast of the railway siding and about 6 km east of the Kendenup graphite mine (Fig. 11).

There are no rock outcrops in the immediate area of the mine; however, the area was assumed similar to the weathered metasedimentary rocks and schist present at the nearby Kendenup mine site. Woodward and Blatchford (1917) visited the mine site and found a vertical shaft, almost 8 m deep, still in existence. The shaft had been excavated through very weathered clay containing numerous ferruginous nodules. The walls contained graphite in minute specks and occasional small nodules. A sample taken from the bottom of the shaft contained 6.57% of fine graphite with a platy texture. Samples taken from bagged concentrates at the mine yielded 43.63 and 54.38% graphite.

## Martagallup mine

The Martagallup mine, in the Mount Barker area along with the former Kendenup and Shaws graphite mines, is sited on former mining leases PA70/11 owned by Messrs Herbert and Coombes, and PA70/357 on Location 973 about 10 km southwest of Tenterden and 2 km northwest of Lake Martagallup (Fig. 11). Over three years in the early 1920s, attempts were made to prove up this deposit for mining with the sinking of five shafts, each to a depth of 15 m, and several drives were extended from the shafts.

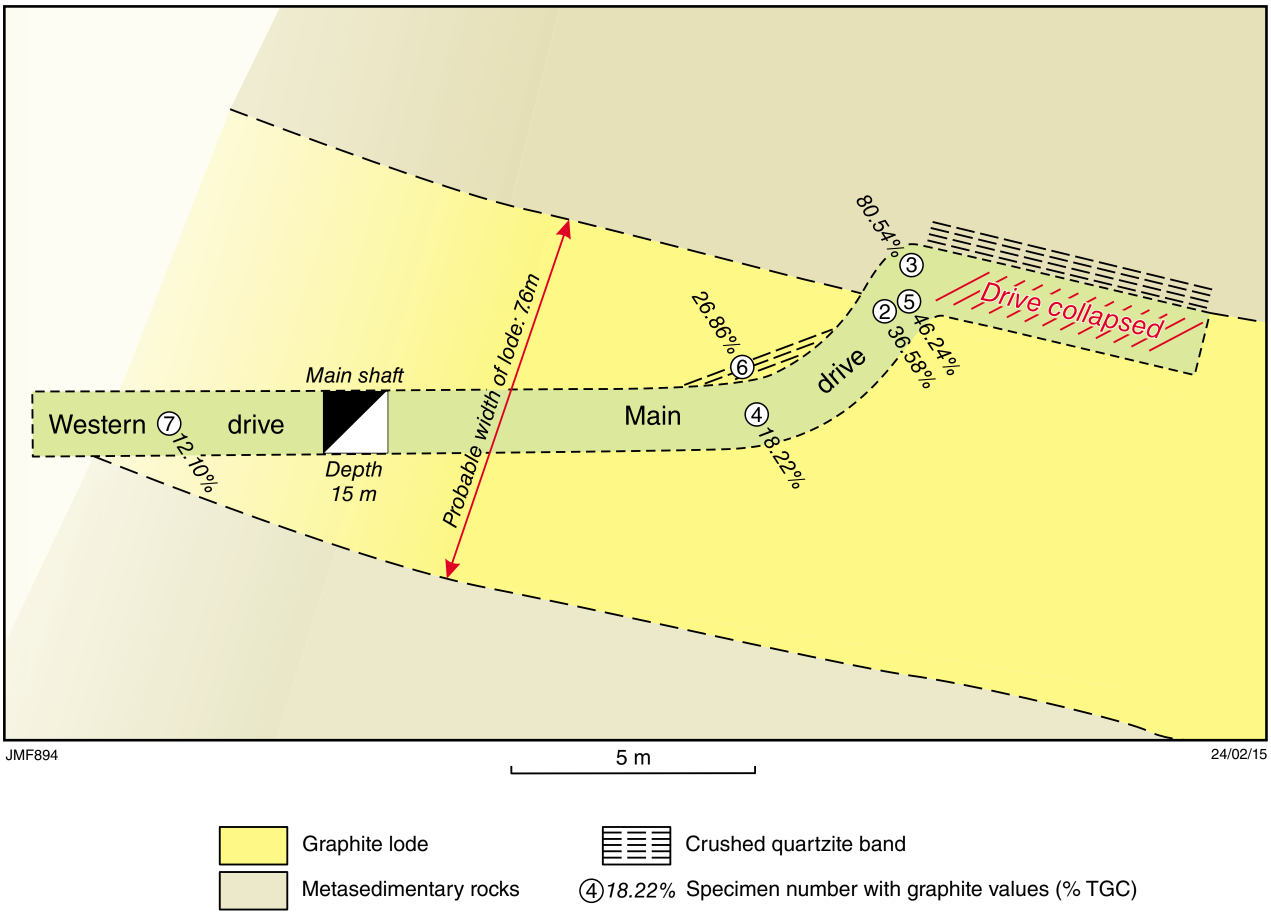



**Figure 12. Sketch map of the Kendenup mine (modified after Woodward and Blatchford, 1917)**

Wilson (1924) inspected the mine site and observed graphite in discontinuous lenses that varied between 0.15 and 0.6 m in width within flat, shallow, undulating beds of kaolin or clay. Seven assays obtained by Wilson (1924) ranged from trace amounts of carbon in one sample to a maximum of 10.94% TC.

Simpson (1951) reported that the site was composed of a surface layer of gossan with scattered graphite flakes that merged downwards into a completely kaolinized zone, probably derived from weathered micaceous schist or gneiss. Graphite veins ranging from 0.15 to 0.76 m in thickness were encountered throughout the mined area. In one area a band had formed a swelling of 2.4 m thickness, and in another, there were eight discrete graphite bands. Bands had variable dips ranging from 0 to 45°. Within these bands, graphite was interleaved with mica as very small lenses or separate scales ranging from 0.2 mm to seldom more than 0.6 mm. Simpson (1951) assayed 19 samples from the graphitic bands, which yielded graphitic contents ranging from 1.8 to 26.5% TGC and averaging 10.3% graphite.

## Mount Barrow occurrence

The Mount Barrow graphite exposure, 8 km east-northeast of Mount Barker on Locality 3792, was discovered in 1917 (Fig. 11). The graphite flakes were contained within gossan and kaolinized rock at the surface in an area of weathered rocks, possibly granitic garnet gneiss and some indeterminate rocks. The flakes were interleaved with mica and limonite. Analyses of two samples showed highly variable amounts of graphite of 1.1% and 23.9%, respectively (Simpson, 1951).

# Munglinup area

## Munglinup mining area

The Munglinup graphite mining area is between 2.5 and 6.0 km north of the town of Munglinup on the South Coast Highway about 75 km east-southeast of Ravensthorpe (Fig. 11).

### Historical mining activities

Graphite mining has been in operation, albeit somewhat discontinuously, at Munglinup over the last 100 years. Prior to 1917, five shafts had been established: McCarthys (No. 6), Stewarts (No. 1), Rabbit Burrow (No. 5), Herberts (No. 4), and No. 7 shaft. By 1945, another two shafts, Halberts Middle (No. 3) and Halberts South (No. 2), were in operation although by the early 1950s they had been renamed to Snake shaft and Daw shaft, respectively. No information relating to ore quality or tonnages extracted from these operations is available. The location of McCarthys shaft is shown on Figure 13. All other early operations were scattered about this site, no more than 175 m distant. These early mining operations are described in some detail in Blatchford (1917), Ellis (1945), Simpson (1951), and Sofoulis and Connolly (1957).

### Contemporary operations and production

The Munglinup area has produced the bulk of Western Australia’s recorded graphite production of 222 ton of ore, of which the Munglinup mines produced 135 ton intermittently between 1953 and 1956. Average ore grade was 19% graphite, which was valued at the time of production at $2714 (A$ of the day). In the 1950s the largest production of graphite came from the Drummond mineral claim (MC 451) of indeterminate location, and the operations of Halbert, both in the McCarthys Zone. In 1956, a pilot plant test operation confirmed that a high-grade graphite concentrate from Munglinup could be produced by a continuous, on-site processing plant (Carter, 1976).

From 1971 to 1988, three major exploration programs were conducted in the Munglinup mining area, covering areas surrounding the McCarthys and Halberts Main Zones and prospects including Halberts South, Harris, Blatchfords, and Whites, and the Munglinup magnesite prospect (Fig. 13). Exploration programs were carried out by Metals Exploration NL in 1971–72, Picon Explorations Pty Ltd in 1985–86, and Gwalia Minerals NL in 1988.

From 2010 to 2013, mining lease M74/245 and exploration licence E74/505, covering the Munglinup mining area, were owned by Graphite Australia Pty Ltd. Further south, on Munglinup Central area (contiguous exploration licence E74/518), Lithex Resources Ltd carried out exploration for graphite and base metals from 2012 to 2014 (Fig. 13).

### Geology of the Munglinup graphite deposits

The Munglinup area comprises Archean to Paleoproterozoic, metamorphosed granitic and other metamorphic rocks of the Albany–Fraser Orogen, typically hornblende (± garnet) gneiss and migmatite. Rocks in this area form part of the Munglinup Gneiss and have been ascribed to a metasedimentary rock origin. Within the gneissic rockmass, rocks containing the Munglinup graphite deposits consist of a succession of tightly folded metasedimentary rocks with a consistent dip of 30° to the southeast (Fig. 14). This succession, originally carbonaceous shales, comprises graphitic schists and gneisses together with jaspilite (also called ‘ironstone’), and clastic rocks that have been weathered to kaolinite, quartz, graphite, and goethite, with the graphitic horizons having been subjected to the most intense form of weathering in comparison to the wallrocks.

Sofoulis and Connolly (1957) considered the graphite to have been derived from the breakdown of the carbonate radical in dolomite. However, many other theories have been advanced relating to the origin of graphite from Proterozoic or Archean sedimentary rocks including the metamorphism of carbon-rich inclusions in rocks such as shale, limestone, sandstone, and bituminous or coal-like material (Harben and Kuzvart, 1996).

Along the margins of the graphitic schist and gneissic zones are numerous conformable and mainly narrow jaspilite zones that may extend to a depth of at least 45 m.

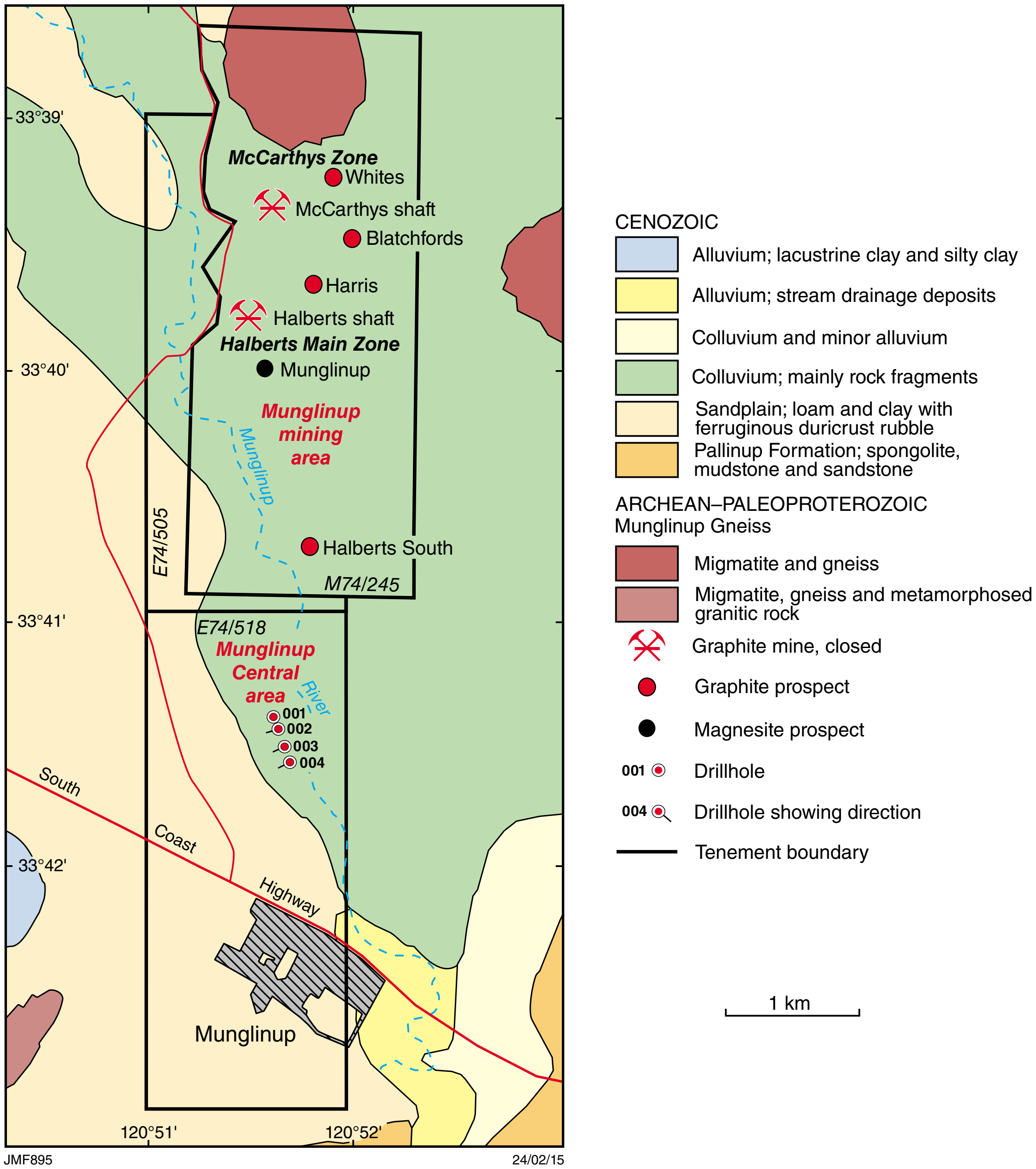



**Figure 13. Geological sketch map of the Munglinup mining and Munglinup Central areas (modified after Thom and Lipple, 1974; Lithex Resources, 2013b)**

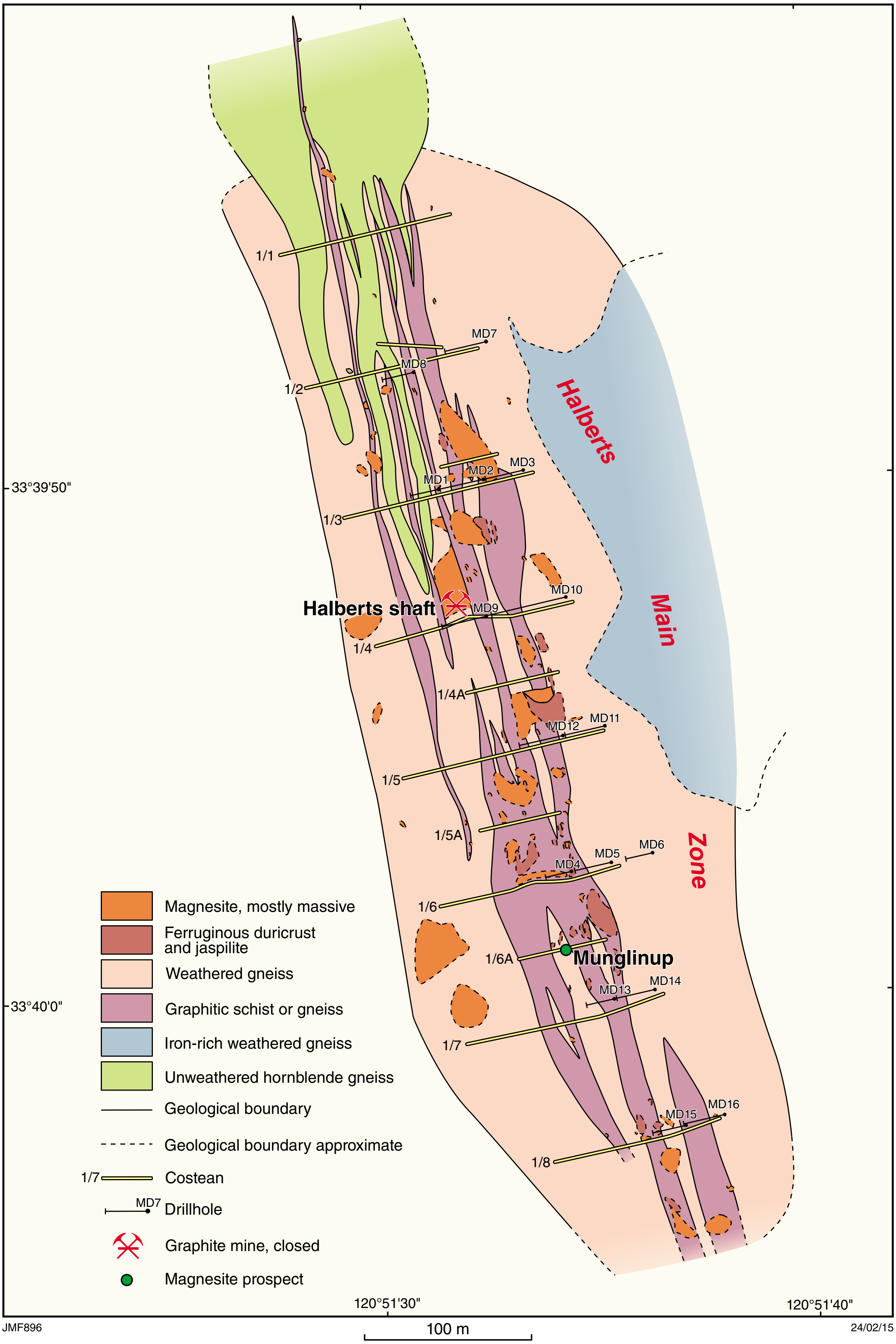



**Figure 14. Geological interpretation of the Halberts Main Zone area at Munglinup (modified after Bleakley, 1988)**

These jaspilites may contain coarse flake graphite crystals up to 1.5 mm in length and range from trace amounts to 15% graphite. Bleakley (1988) considered the presence of graphite in the jaspilite as either the result of former weathering events that conveyed graphite (together with iron-rich minerals) down fractures and faults, or part of the original sedimentary succession. On the surface, the jaspilite is mostly capped by massive ferruginous duricrust.

Massive or pisolitic secondary magnesite is also commonly associated with graphitic zones at Munglinup. Magnesite is more common close to the surface although may extend in places to a depth exceeding 30 m. Magnesite zones range from white, massive, pure magnesite to pisolitic magnesite that may contain up to 15% amorphous and fine flake graphite, and ultimately to weakly magnesitic graphitic schist and gneiss.

At Munglinup, graphitic horizons within zones of schist and gneiss are typically of variable thickness although have been found to a maximum of 14 m. The graphite varies in grain size both vertically and horizontally, ranging from microcrystalline (amorphous graphite) through fine to coarse-grained flakes up to 10 mm in length. Flakes tend to remain parallel to mineral lineation in schists and gneisses. Drillhole data suggest there may be a correlation between coarse graphite flakes and local heat sources possibly derived from pegmatites or narrow quartz veins. This increase in flake size was noted in the southernmost drillholes MD13 to MD16 (Fig. 14). Also, very coarse flake graphite exists in rare crosscutting veins near the McCarthys Zone and Halberts Main Zone prospecting areas (Fig. 13) (Bleakley, 1988).

## Mineral exploration and mining 1971–2013

Sofoulis and Connolly (1957) reported the most recent graphite mining activity at Munglinup in the early 1950s was the sinking of the Halberts shaft to a depth of 7 m with an east-facing crosscut of almost 4 m at the 5.5 m level. About the same time, a more detailed exploration phase through the installation of costeans, trenches, sample sites, and shallow auger holes was carried out in a north–south direction over a distance of 1.6 km adjacent to Halberts shaft (Fig. 14).

During this earlier exploration phase, concealed graphitic-rich zones could be detected from the surface soil type (unless covered by a thick soil mantle in excess of 1.2 m) where graphite-rich soil was of a dense black to dark-grey consistency. It was also shown that graphitic zones exposed at the surface were composite seams of variable width forming lenticular bodies up to 6 m in width and dipping between 30 and 60° in an easterly direction. This early work provided the basic information on the composition, structure, and potential ore quality for future major exploration programs that took place in 1971–72 by Metals Exploration NL, 1985–86 by Picon Explorations Pty Ltd, and 1988 by Gwalia Minerals NL.

### *Field program 1971–72*

In 1971, Mr R Lalor carried out an initial survey in the Halberts Main Zone area where 115 vertical auger holes, 6–15 m deep, were drilled at 15 m centres along 30 m-spaced lines. Because of this exploration work an option agreement was negotiated with Metals Exploration NL. The following year, Metals Exploration carried out detailed exploration in the McCarthys Zone surrounding the McCarthys shaft, and the Whites, Harris, and Blatchfords prospects (Fig. 13).

At the Whites prospect, a single line of 11 auger holes was drilled in an area of poor outcrop to determine the graphite potential of the area. Results were discouraging as graphite was not found because of a thick cover of magnesite.

Exploration at the Harris prospect included cutting of six costeans and drilling of 34 auger holes. Results were variable with at least 16 holes having no graphite intersections although 15 holes encountered moderate- to good-grade graphite ranging from 1 to 24 m in thickness. At the Blatchfords prospect, one costean was cut and seven auger holes drilled, with graphite intersections found in five holes ranging from 1 to 4 m. Drill log descriptions for the Harris and Blatchfords prospects are given in Morrison and Irons (1972).

The main focus of this survey was the area surrounding McCarthys shaft where one costean, and three 6 m-deep costean slots, were cut, followed by drilling, sampling, and metallurgical testing. An EM survey was run over the McCarthys and Halberts Main Zones resulting in weak anomalies over the McCarthys Zone. However, in the Halberts Main Zone, strong anomalies were obtained at 30 and 60 m line spacings, which correlated well with the high-grade graphite zone near costean 1/5A (Fig. 14).

At the conclusion of analysis and testing of graphitic ore from the McCarthys Zone, Metals Exploration concluded that the graphite resource was more variable and of lower grade than had been expected. A non-JORC resource, based on a limited amount of drilling, estimated 300 000 t of graphite ore grading 15% graphite (visual estimate) could be extracted from the McCarthys Zone to a depth of 30 m. Detailed information relating to exploration activities by Metals Exploration including drilling and metallurgical testing is given in Morrison and Irons (1972).

### *Field program 1985–86*

During this period, Picon Explorations Pty Ltd carried out detailed exploration around the Halberts Main Zone and Halberts South areas. Detailed surface mapping carried out in these areas was later combined with results from costean logging to produce detailed geological maps.

A series of costeans at 80 m intervals was cut across the south-southeasterly trending zones of graphitic schist and gneiss, together with a number of infill costeans at 40 m intervals for additional data recovery. Eleven costeans were cut in the Halberts Main Zone and eight at Halberts South (numbered costeans in Figs 14, 15). Detailed costean mapping was carried out and graphite-rich zones were sampled for graphitic carbon content.

As a result of this work, exploration was focused on the Halberts Main Zone where six diamond drillholes (MD1–MD3 along costean 1/3, and MD4–MD6 along

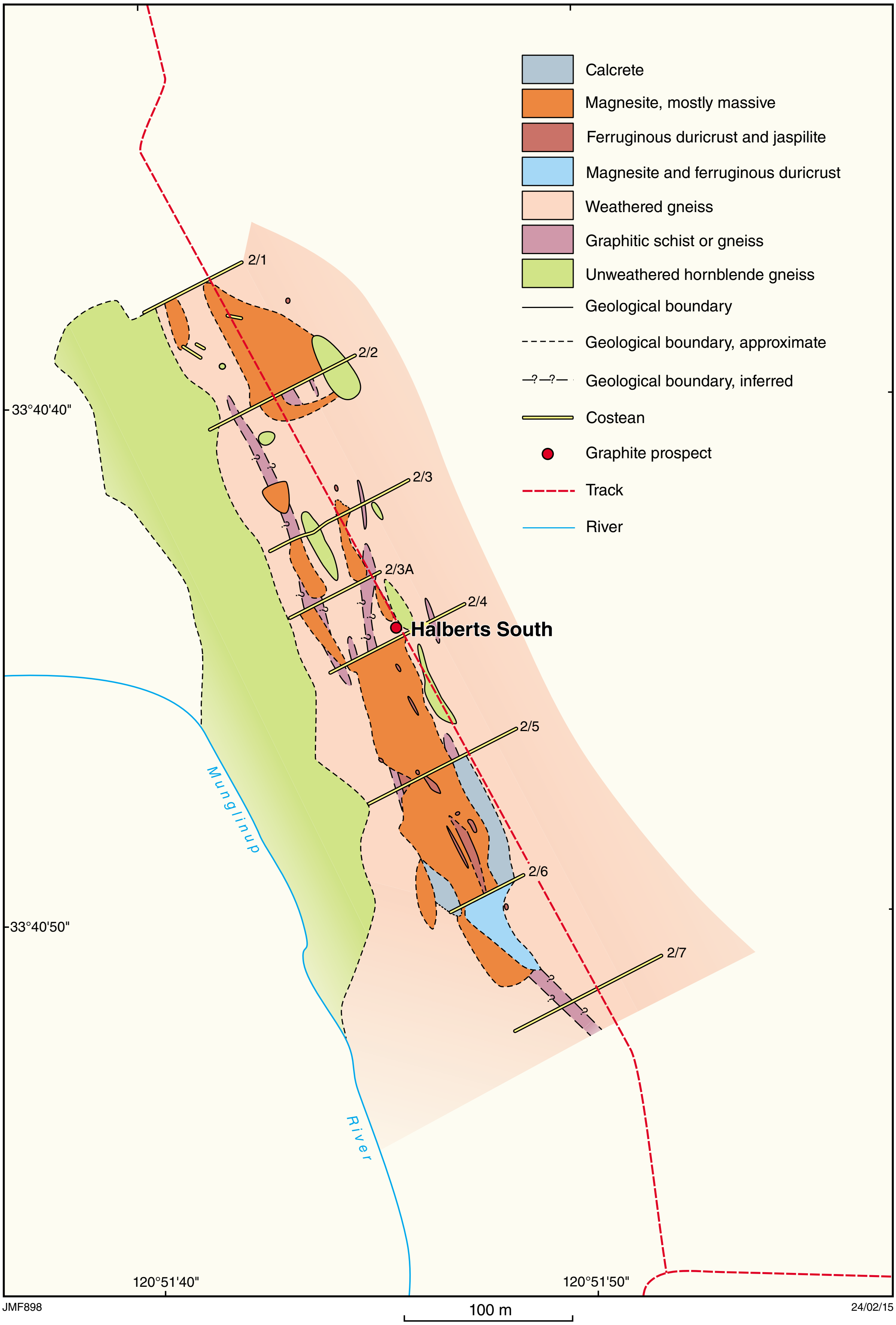



**Figure 15.** **Geological interpretation of the area around Halberts South prospect (modified after Picon Explorations, 1986)**

costean 1/6) were drilled to assess the downdip continuity of the graphite-rich zones and the depth of weathering. This drilling was followed up by a program of bulk sampling of graphitic zones from costeans and samples were subsequently submitted for metallurgical testing. Further details of the exploration program are given in Picon Explorations (1986).

### *Field program 1988*

The 1988 exploration program by Gwalia Minerals NL followed up on Picon Explorations's detailed work in the Halberts Main Zone. In this area Gwalia Minerals drilled another 10 diamond drillholes (MD7–MD16). These holes were also drilled along existing costeans in the same orientation and dip direction as for the previous holes MD1–MD6 (Fig. 14). Results from this program showed that thicknesses of graphitic bodies were quite variable ranging from a minimum of 0.47 m encountered in MD10, to a maximum thickness of 12.33 m in the southernmost drill traverse at MD16. Percent total fixed carbon (% TC) of graphitic bodies also varied considerably from a minimum of 5.0% in MD9 to a maximum of 34.2% in MD7. Average fixed carbon content was 15.45% from 42 analyses sourced from the 10 drillholes (Clifford, 2009).

Examples from this drilling program may be seen in two cross-sections parallel to costean 1/4, adjacent to the Halberts shaft, and costean 1/5, about 80 m to the south (Figs 14, 16). These cross-sections indicate the thickness and steeply dipping easterly trend of the tabular graphite bodies. Also shown are drillhole intersection thicknesses of graphitic bodies at depth and their respective graphite contents expressed as total fixed carbon content (% TC).

From data acquired from the drilling program and metallurgical testing in the Halberts Main Zone, Gwalia Minerals proposed a non-JORC-indicated graphite resource of 1.30 Mt at a fixed carbon content of 18.2% TC to a depth of 50 m. This resource was calculated from a total of 939 519 t graphite ore, 195 704 t of graphite-rich magnesite, and 165 911 t of graphite in jaspilitic ironstone. It was also noted that the graphitic mineralization was open to the north and also at depth (Bleakley, 1988). This resource estimate was subsequently upgraded to a JORC-compliant measured and indicated resource by Clifford (2009) to 1.47 Mt at a fixed carbon content of 18.2% TC over a strike length of 555 m to an average depth of 55 m. This resource calculation for Halberts Main Zone was based on an in situ ore density of 1.91 $t/m^3$ with a fixed carbon cutoff of 5% TC, and a minimum true thickness of 1.0 m for tabular graphite bodies.

### *Proposed program 2009–13*

In 2009, Graphite Australia Pty Ltd, owners of mining lease M74/245 and exploration licence E74/505, in conjunction with Adelaide Prospecting Pty Ltd, announced that on completion of marketing arrangements underway at that time, a new drilling program was to commence to prove up additional graphite reserves in the Munglinup mining area (Clifford, 2009). On successful completion of the exploration program it was expected that graphite mining could recommence. Despite these expectations, no new exploration appears to have taken place and Graphite Australia went into receivership in September 2013.

## Munglinup Central area

From mid-2012 to the first quarter of 2014, Lithex Resources Ltd explored for graphite and base metals on contiguous exploration licence E74/518 known as Munglinup Central area (Fig. 13). An initial rock-chip sampling survey yielded graphite ranging from 8.6 to 23.1% TGC from four surface samples of graphitic gneiss. The company then identified a strong EM anomaly, with conductors favourable as graphite-rich horizons, trending northwards towards the graphite-rich zones in the Munglinup mining area (Lithex Resources, 2013a). This was followed up in mid-2013 by a four-hole diamond drilling program on the eastern side of E74/518 (Fig. 13). This drilling program, totalling 467.7 m, yielded four significant graphite intersections in drillhole MCDD004 (inclined at 45° west-southwest). Graphite intercepts from MCDD004 are shown in Table 2.

**Table 2. Significant graphite intercepts from drillhole MCDD004, Munglinup Central drilling program**

| *Depth (m)* | *Graphite intercept (% TGC)* |
|---|---|
| 48.15 – 48.5 | 0.35 m @ 7.05% |
| 48.9 – 50.4 | 1.5 m @ 15.9% |
| 51.1 – 53.0 | 1.9 m @ 34.9% |
| 57.9 – 58.9 | 1.0 m @ 17.2% |

**SOURCE:** Lithex Resources (2013b)

## Munglinup North VTEM survey

In the first quarter of 2013, Lithex Resources carried out an airborne VTEM electromagnetic survey over exploration licences E74/517 and 531 covering an extensive area north of the Munglinup mining area (Fig. 17). The VTEM survey was designed to examine a probable north-trending extension of tightly folded metasedimentary rocks, comprising paragneiss and graphitic schist, present in the adjacent Munglinup mining area. The survey highlighted 17 high-priority electromagnetic conductors as prospective targets for graphite (graphite, and nickel and graphite targets, Fig. 17). The company subsequently assigned proposed drillhole sites at most of these anomalies for future exploration (Lithex Resources, 2013c).

Following the completion of the drilling program at Munglinup Central and the VTEM survey over Munglinup North, no further exploration appears to have taken place at these sites. In May 2014 Lithex Resources announced the sale of their Munglinup tenements (E74/517, 518, and 531) to Sol Jar Property Pty Ltd (Lithex Resources, 2014).

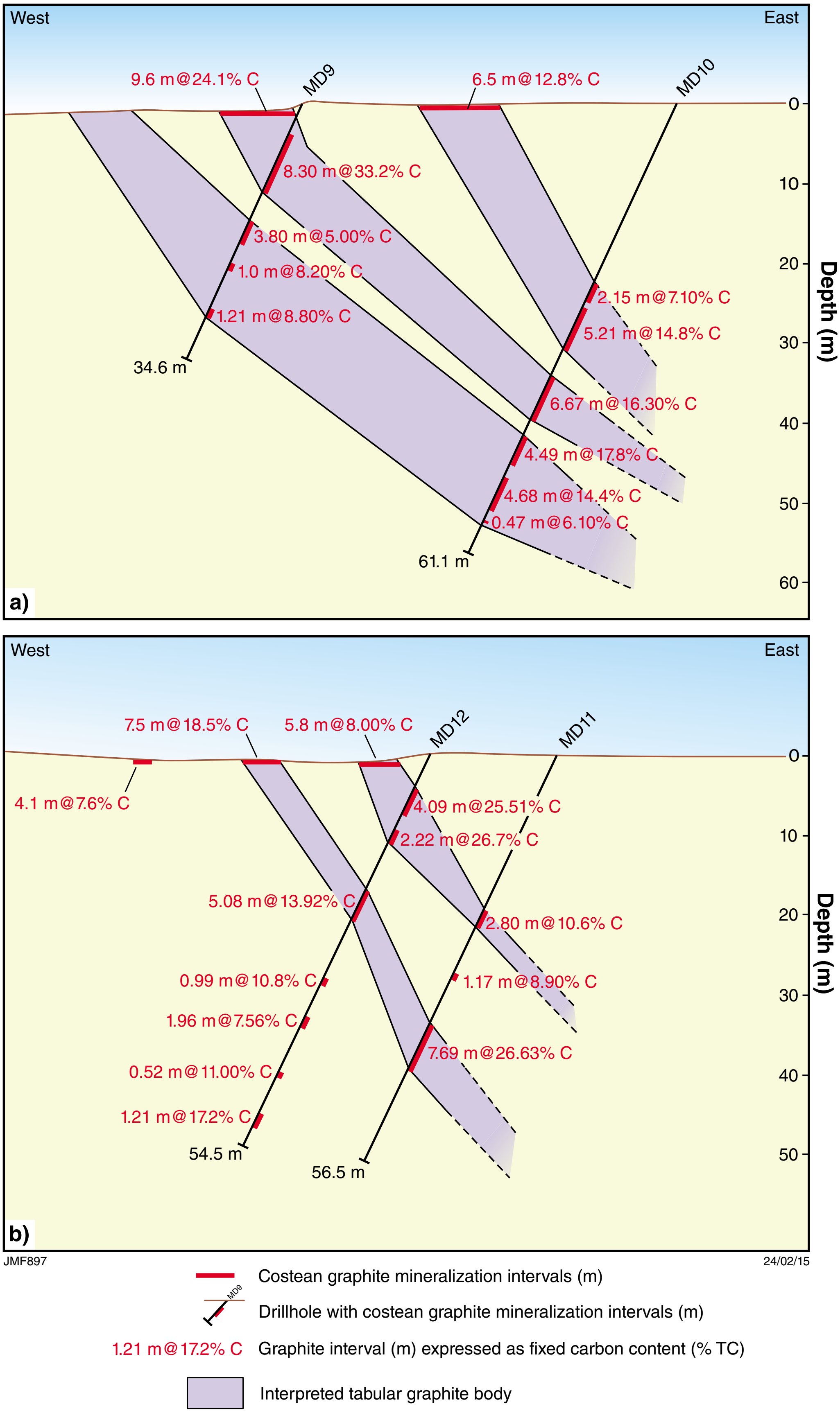



**Figure 16.** **Cross-sections through the Munglinup lode: a) cross-section adjacent to costean 1/4, near Halberts shaft; b) cross-section 80 m south, adjacent to costean 1/5 (modified after Clifford, 2009)**

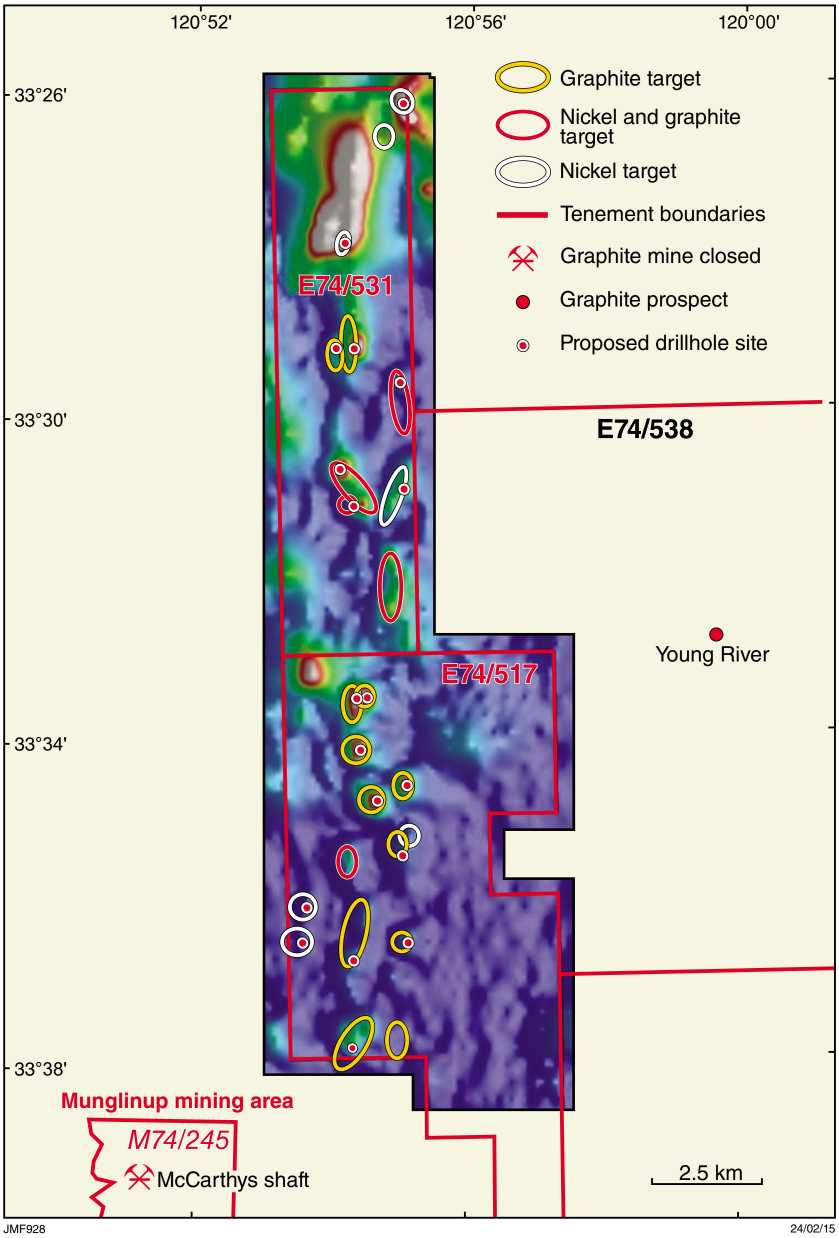



**Figure 17.** **Versatile time domain electromagnetic (VTEM) geophysical survey over Munglinup North exploration area. The survey area shows 17 high-priority electromagnetic conductors as potential graphite, and nickel and graphite, targets (modified after Lithex Resources, 2013c).**

# Young River area

## Young River prospect

The Young River graphite prospect is on the eastern side of the Young River, about 88 km east of Ravensthorpe, and about 18 km northeast of the major graphite deposit at Munglinup (Fig. 18).

Ellis (1944b) inspected the prospect and determined that graphite was present within a band of graphitic schist interbedded with biotite–hornblende gneiss probably derived from metamorphism of carbonaceous shale. Before the early 1940s, the graphitic schist band at this site had been opened by a broad costean to a depth of about 2 m. This excavation revealed a steeply dipping graphitic schist bed containing high-grade flake graphite, trending northwest with a thickness of approximately 2 m. The foliated graphitic schist was seen to outcrop over only 6 m although it could be traced to the southeast from surface float material for approximately 300 m. The host rock was thought similar in all respects to the host rock present at the major Munglinup deposit to the southwest and possibly containing a similar ore grade of around 20–25% fine flake graphite.

Currently, the graphite prospect falls within exploration licence E74/538 registered to Lithex Resources. To date, no exploration in this area has been reported by the company and in May 2014 it reportedly sold all of its exploration licences in the Munglinup – Young River area to Sol Jar Property (Lithex Resources, 2014).

## Young River East prospect

The precise location of the Young River East graphite prospect is uncertain. Simpson (1951) indicated that it was about 16 km north of Fanny Cove on the south coast, placing it approximately 65 km west-northwest of Esperance (Fig. 18).

Simpson (1951) stated that the graphite in this prospect was contained in a large outcrop of graphitic schist. A heavily ferruginized sample from Young River East contained 21.7% of flake graphite ranging from 0.2 to 1.0 mm in diameter. A test concentrate sample yielded 57% TGC.

# Napier Creek occurrence

Flake graphite was found on Napier Creek on former mining lease PA70/310, adjacent to the Stirling Bridge crossing, 23 km north-northeast of Albany (Fig. 11). At this site, the graphite mineralization was overlain by a hard cap of relatively thin, foliated gossan. Beneath this layer was a weathered, highly micaceous, kaolinized schist containing discrete flakes and thin graphitic bands distributed throughout the rock at a concentration of up to 5% of the rockmass. Two concentrates of this material gave average percentages for flake graphite lengths of >0.6 mm (8.2%), >0.25 mm (57.7%), and >0.2 mm (4.4%) (Simpson, 1951).

# Pallinup River prospect

A graphite prospect was first described by Gibb Maitland (1924) on the lower reaches of the Pallinup River, about 50 km west of the town of Bremer Bay (Fig. 11). In this area, graphite was found on the Pallinup River mainly on Location 431, about 6.5 km upstream from its confluence with the Southern Ocean at Wray Bay. In this area, graphite was found to extend over a distance of 1.6 km at several sites in east–west trending gneissic rocks on either side of the river. Gibb Maitland (1924) found that previous investigations had focused on a 0.6 – 0.9 m wide, near-vertical graphite vein extending over a strike length of about 60 m into which a shaft to a depth of up to 11.6 m had been sunk. Gibb Maitland (1925) reported that a graphite sample taken from the deposit showed 54.72% TC.

Simpson (1951) described the very fine-grained graphite as being wholly crystalline, soft, and intensely black. The graphite was commonly evenly intermixed within a white, greasy clay, and the host rock had the appearance of a ‘silky schist’. Analysis of 11 samples from the prospect showed the graphite content varied from 31 to 76% TGC of the whole rock with an average of 60%.

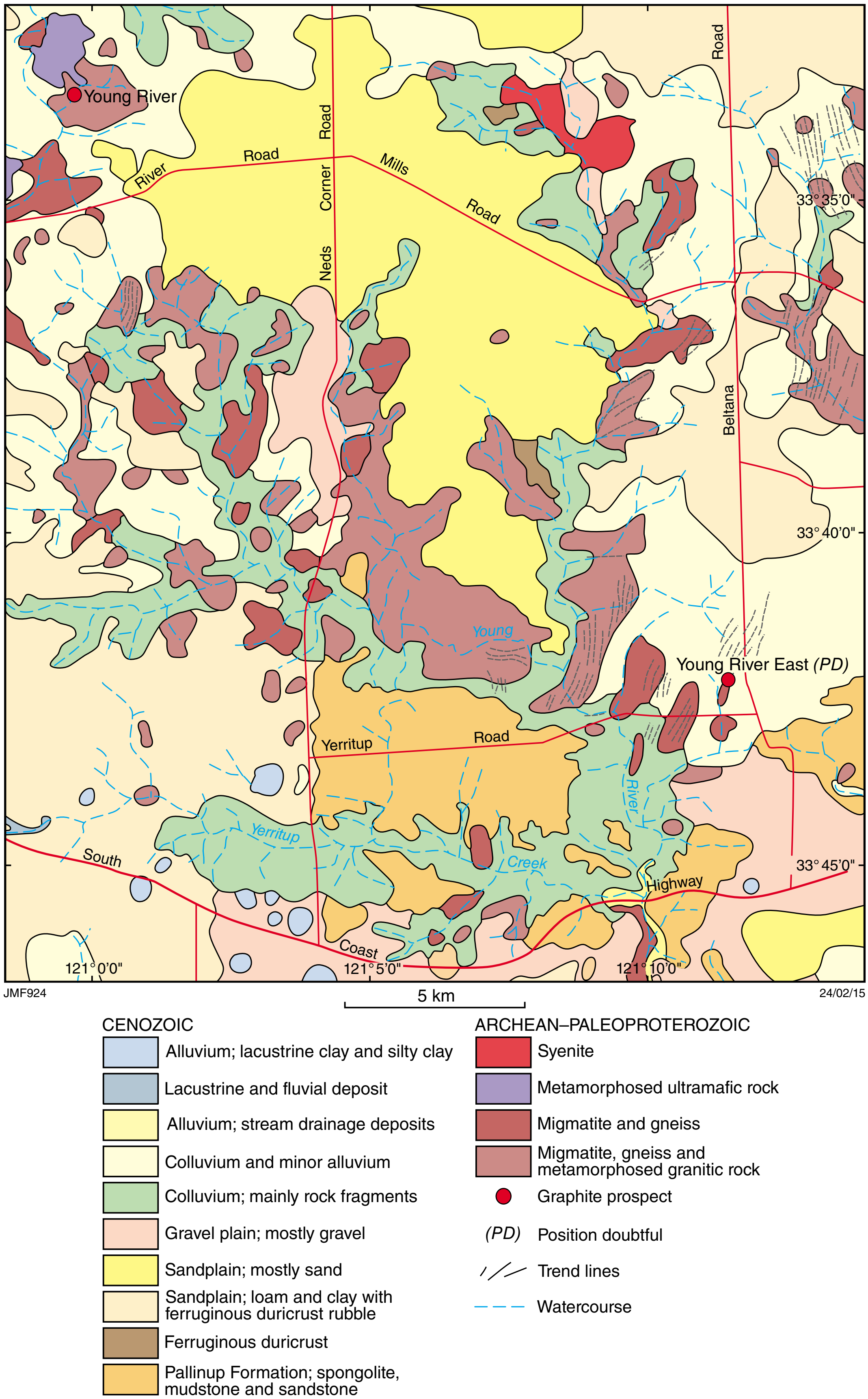



**Figure 18. Geological sketch map of the area surrounding the Young River prospects (modified after Thom and Lipple, 1974)**

## Glenburgh Terrane

The Archean to Paleoproterozoic Glenburgh Terrane forms the basement to the southern end of the Gascoyne Province in the Capricorn Orogen in the central west of the State (Fig. 1). The oldest exposed rocks in the terrane are reworked granitic gneisses, with dates ranging from about 2555 to 2430 Ma (Johnson, 2013). Younger Paleoproterozoic, medium- to high-grade metamorphic rocks, including the Moogie Metamorphics, contain graphitic metasedimentary rocks in places. These rocks are partly overlain by low-grade metasedimentary rocks (Aitken et al., 2014).

## Erong Springs occurrence

The Erong Springs graphite occurrence is on the Glenburgh pastoral lease, 140 km east-southeast of Gascoyne Junction and approximately 19 km west-northwest of Erong Springs Homestead (Fig. 19).

Johnson (1950) described a small lens of graphitic schist associated with jaspilite and mica schist at this site. The lens forms part of a small area of reworked Archean metamorphic rocks comprising fine-grained, banded gneiss and migmatite. The graphitic schist lens measured 2 m long by 0.6 m wide. A sample analysed from this site contained 5% TC.

Erong Springs graphite is also described by Simpson (1951) who refers to the site under Dalgety Downs graphite. Of four samples taken from this locality, two were described as hard, siliceous schists containing 4.9 – 9.8% graphite. The remaining two samples were identified as kaolinized slates with 12.2 and 16.9% graphite content. The graphite was distinctly flaky, with only a small proportion of flakes >0.2 mm. Five more samples examined later contained graphite ranging from 5.8 to 23.2% although they were excessively contaminated with mica and iron oxide.

## Mooloo Downs East occurrence

The Mooloo Downs East graphite occurrence was reported by Woodward (1891) at an unknown site on Mooloo Downs Station near the Gascoyne River although the occurrence remained unknown for the next 30 years. In the 1920s a graphite occurrence was located 'near the river 20 miles [32 km] east of Mooloo Downs homestead' Simpson (1951). The exact location of this site remains in doubt although it is suggested it may be in this area within an outcrop of pelitic schist about 30.5 km east of the homestead (Fig. 19).

According to Simpson (1951), the graphite was in a highly siliceous, graphitic rock that may now form part of newly named Paleoproterozoic Moogie Metamorphics (Occhipinti et al., 2011). Simpson also reported that the graphite was composed of very fine, scaly flakes with a silky lustre in places; a specimen collected in 1937 yielded 13.1% TGC.

## McIntosh Well prospect

The McIntosh Well graphite prospect is near McIntosh Well on former prospecting licence P09/55 about 23 km southeast of Dalgety Downs Homestead in an area of metamorphosed, Paleoproterozoic Nardoo Granite (Fig. 19).

Swan Resources Ltd examined the prospect in 1983. A 200 L bulk graphite ore sample obtained from the site was subjected to testwork (Swan Resources, 1983), as outlined below.

### Summary of testwork

#### *Size distribution*

A sample split into six size ranges from <0.106 to a maximum of 6.3 mm showed that graphite was relatively evenly distributed across all sizes ranging from 3.70 to 8.70% TC. From these figures a head grade of 5.90% TC was calculated.

#### *Flotation testing*

Three samples of different size ranges were subjected to flotation testwork:

1. Ore <2.0 mm diameter yielded 21.2% TC present in concentrate, and 39.5% carbon was recovered by flotation.
2. Ore <1.0 mm diameter yielded 46.9% TC present in concentrate, and 41.8% carbon was recovered by flotation.
3. Ore <0.5 to >0.3 mm diameter was subjected to heavy liquid separation, which yielded 44.7% TC present in concentrate.

#### *Chemical analysis*

Chemical analysis of a concentrate sample gave the results: total carbon 46.9%, $SiO_2$ 34.0%, $Fe_2O_3$ 7.6%, $Al_2O_3$ 4.1%, MgO 1.5%, $K_2O$ 1.4%, $TiO_2$ 0.4%, and CaO<0.01%.

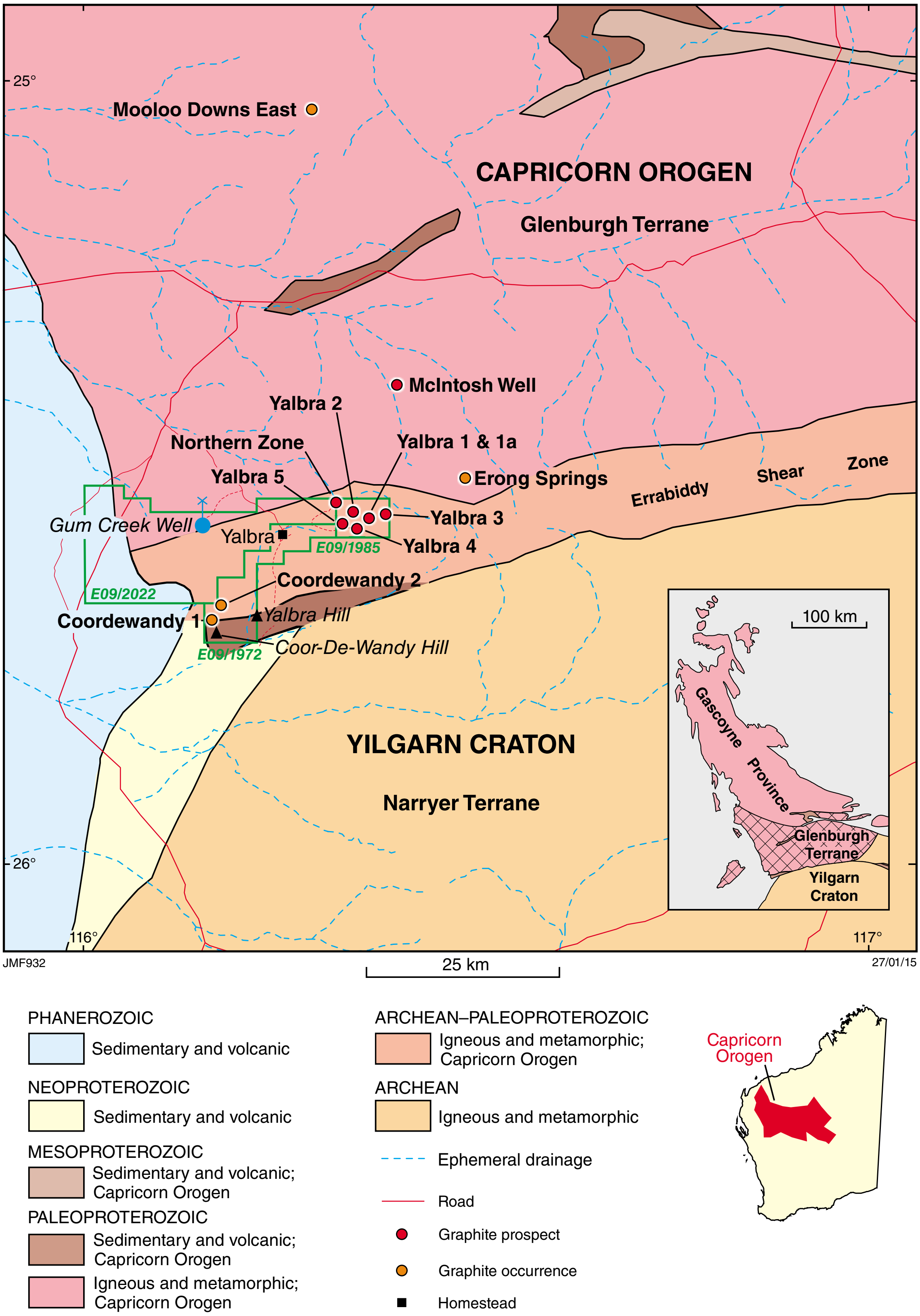



**Figure 19. Geological map of graphite prospects and occurrences in the Glenburgh Terrane and Errabiddy Shear Zone, Gascoyne Province (modified after Johnson, 2013)**

### Mineralogy

Microscopic mineralogical examination of four samples revealed each sample had a finely granular to flaky texture. Graphite was dominant in all samples (average 93% TGC) with minor quartz, feldspar, sericite, and clay minerals, and traces of hematite and other minor minerals.

## Yalbra prospects, occurrences, and exploration areas

Approximately 125 km east-southeast of Gascoyne Junction are graphite prospects, occurrences and exploration areas, near the Yalbra Homestead. This area is within the Errabiddy Shear Zone, along the southern margin of the Glenburgh Terrane (Fig. 19). The shear zone defines the boundary between the Archean Narryer Terrane, comprising the northwestern portion of the Yilgarn Craton, and the southern edge of the Glenburgh Terrane (Johnson, 2013). The shear zone contains deformed and metamorphosed components of both terranes including granite, granitic gneiss, ultramafic igneous rocks, and metasedimentary rocks including paragneiss and micaceous, graphitic schists.

### Coordewandy occurrences

Two closely spaced graphite occurrences (Coordewandy 1 and 2) are about 14 km southwest of Yalbra Homestead (Fig. 19). These occurrences were discovered in 1980 by Urangesellschaft Australia Pty Ltd during exploration for uranium mineralization. As part of their exploration program, the company carried out an extensive airborne EM survey over the area. The survey showed a number of anomalies that were attributed to graphite-rich rocks. This finding was later confirmed by subsequent drilling and costeaning. Results from drillhole samples were typically low-grade, mainly amorphous graphite although one sample returned 19.86% TC in drillhole CPDH6. Accordingly, the Coordewandy occurrences were assessed as being uneconomic at that time (O'Shea, 1980).

The Coordewandy area is held under exploration licence E09/1972 by Buxton Resources (Fig. 19). The 93 km$^2$ Coordewandy exploration area is along strike from the Yalbra graphite prospects to the northeast and is known to contain graphite localities with significant EM anomalies, which could indicate more buried graphite targets.

### Gum Creek exploration area

In addition to the Coordewandy area, Buxton Resources also holds a second contiguous exploration area, the much larger Gum Creek exploration area (E09/2022), covering 344 km$^2$. This area, also with graphite potential, is positioned along strike from and to the west of the Yalbra prospects (Fig. 19). To date, no new exploration for graphite in this area has been undertaken.

### Yalbra prospects

Approximately 10 km east-northeast of Yalbra Homestead, Buxton Resources is currently carrying out detailed investigations for graphite within exploration licence E09/1985. This area, spread over a strike length of 4 km east–west, contains six graphite prospects (Yalbra 1, 1a – Yalbra 5) (Fig. 19).

#### Early investigations at Yalbra

Carpentaria Exploration Company Pty Ltd first investigated the Yalbra graphite deposit in detail in 1974 (Shaw, 1975). At that time, the company drilled 21 percussion drillholes, inclined at 60° and which intersected zones of graphite mineralization extending from the surface to 53 m depth. The maximum continuous graphite interval encountered was 42.68 m in hole PD08, and the maximum fixed carbon recorded was 25.2% TC in PD09 (Buxton Resources, 2013a). Coarse flake graphite was identified as a component of the mostly amorphous graphite ore recovered from drillhole samples. A summary of significant graphite intersections from the percussion drilling program is shown in Table 3. Carpentaria Exploration's investigations revealed six discrete graphite prospects (Yalbra 1, 1a – Yalbra 5) within an area of Archean paragneiss and quartz–tremolite–chlorite–mica–feldspar schist. These prospects were found to be open at depth and in most cases, open along strike (Buxton Resources, 2012a). This area of graphite mineralization is known as the Yalbra Main Zone, occupying a tapering zone extending from east to west, and averaging 150 m wide at the eastern end to >600 m wide at the western limit (Fig. 20).

#### Follow-up investigations in 2012

Based on results from the 1974 drilling program, and surface traverses of outcrop and costeans over the 4 km strike length of the Yalbra Main Zone, Buxton Resources's investigations provided a conceptual estimate for the Yalbra target zone of 8–12 Mt of graphite ore at 7–11% TC. These values were subject to confirmation in 2013 following further drilling, surface, and electromagnetic exploration programs (Buxton Resources, 2012b).

#### VTEM electromagnetic survey

In October 2012, Buxton Resources completed a 371 line-km HeliVTEM (electromagnetic) survey that covered the entire Yalbra tenement (E09/1985). The helicopter survey was flown along flight lines at 100 m spacing with the system sensing loop positioned 30 m above ground (Fig. 21). Results from the survey highlighted very strong conductive responses over the graphitic-rich areas of the Yalbra Main Zone, especially over Yalbra 1, 1a, 2, and 4 prospects. These electromagnetic anomalies confirm the earlier drilling results that the graphitic orebodies remain open in both directions along strike. The VTEM survey also identified the presence of a second highly conductive zone approximately 2 km to the north. This newly discovered anomaly, named the Northern Zone, extends in an east–west direction over 6 km parallel to the Yalbra Main Zone (Figs 20, 22). The northern conductive zone extends over similar gneissic and schistose rocks present in the Yalbra Main Zone that may indicate possible target zones for buried graphitic mineralization in this area (Buxton Resources, 2012c).

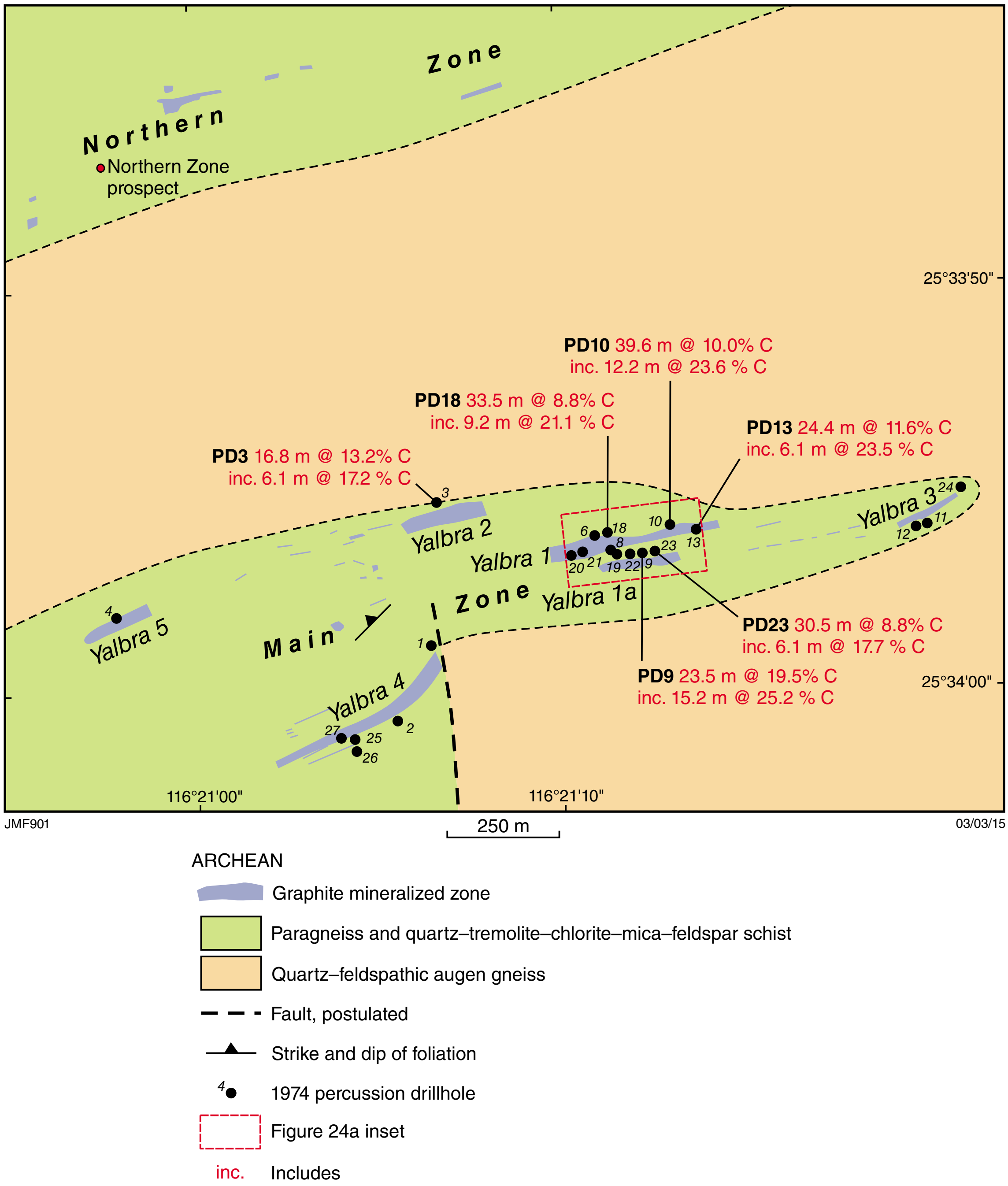



**Figure 20.** **Geological sketch map of the Yalbra Main Zone exploration area showing highlights of the 1974 drilling program (modified after Buxton Resources, 2012a)**


**Figure 21.** (left) Helicopter flying Yalbra HeliVTEM survey (Courtesy Geotech Airborne Pty Ltd, modified after Buxton Resources, 2012c)

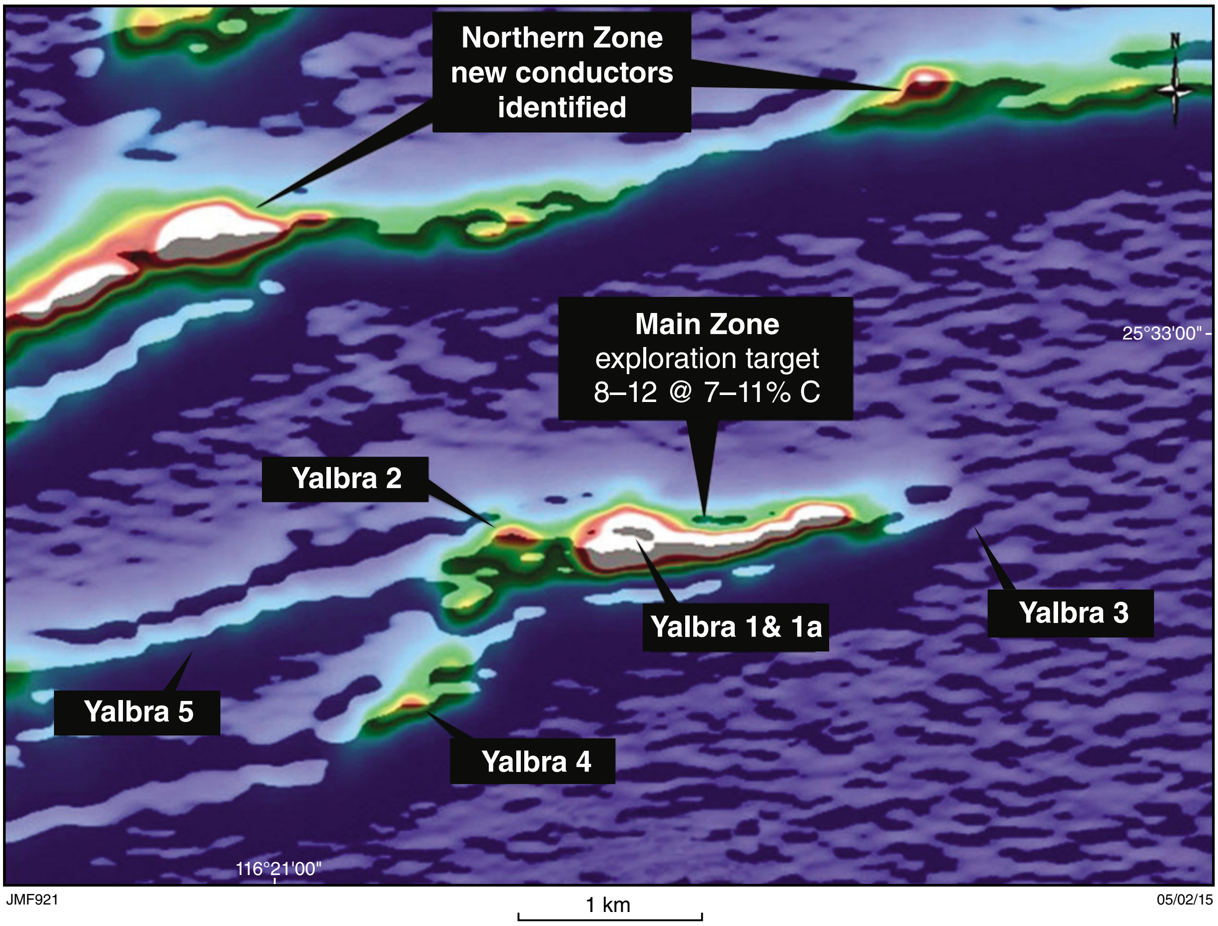



**Figure 22.** Electromagnetic (EM) response from HeliVTEM survey highlighting the Yalbra Main Zone exploration target, and newly identified conductors in the Northern Zone (modified after Buxton Resources, 2013a)

**Table 3. Significant graphite intercepts from Yalbra 1974 percussion drilling**

| *Hole ID (PD)* | *From (m)* | *To (m)* | *Graphite interval (m)* | *Total (fixed) carbon (% TC)* | *Comments* |
|---|---|---|---|---|---|
| 1 | 3.05 | 9.14 | 6.09 | 3.74 | Ended in graphite mineralization |
| 2 | 0.00 | 18.28 | 18.28 | 9.33 | |
| includes | 0.00 | 6.09 | 6.09 | 19.0 | |
| 3 | 15.24 | 32.00 | 16.76 | 13.2 | Ended in graphite mineralization |
| includes | 22.86 | 28.95 | 6.09 | 17.2 | |
| 4 | 6.09 | 30.48 | 24.39 | 7.87 | |
| includes | 16.76 | 22.86 | 6.10 | 13.12 | |
| 6 | 3.05 | 36.58 | 33.53 | 4.59 | |
| 8 | 9.14 | 51.82 | 42.68 | 7.96 | Ended in graphite mineralization |
| includes | 33.53 | 51.82 | 18.29 | 13.0 | |
| 9 | 6.09 | 29.57 | 23.48 | 19.5 | Ended in graphite mineralization |
| includes | 9.14 | 24.38 | 15.24 | 25.2 | |
| 10 | 3.05 | 42.67 | 39.62 | 10.0 | |
| includes | 3.05 | 15.24 | 12.19 | 23.6 | |
| 11 | 6.09 | 12.19 | 6.10 | 6.75 | |
| includes | 24.38 | 36.58 | 12.20 | 13.1 | |
| 12 | 6.09 | 12.19 | 6.10 | 6.75 | |
| 13 | 18.28 | 42.67 | 24.39 | 11.6 | |
| includes | 33.53 | 39.62 | 6.09 | 23.5 | |
| 18 | 18.28 | 51.82 | 33.54 | 8.84 | |
| includes | 42.67 | 51.82 | 9.15 | 21.1 | |
| 19 | 0.00 | 41.15 | 41.15 | 0.00 | |
| 20 | 6.09 | 27.43 | 21.34 | 7.80 | |
| includes | 9.14 | 18.28 | 9.14 | 10.9 | |
| 21 | 3.05 | 35.05 | 32.00 | 4.71 | |
| 22 | 6.09 | 30.48 | 24.39 | 8.73 | |
| includes | 21.34 | 30.48 | 9.14 | 12.7 | |
| 23 | 9.14 | 39.62 | 30.48 | 8.84 | |
| includes | 24.38 | 30.48 | 6.10 | 17.7 | |
| 24 | 0.00 | 30.48 | 30.48 | 0.00 | |
| 25 | 6.09 | 21.34 | 15.25 | 4.85 | Ended in graphite mineralization |
| | 33.53 | 53.34 | 19.81 | 10.4 | |
| 26 | 12.19 | 18.28 | 6.09 | 6.49 | |
| | 30.48 | 45.72 | 15.24 | 7.70 | |
| 27 | 9.14 | 24.38 | 15.24 | 6.50 | |

**SOURCE**: Modified after Buxton Resources (2013a)

### Geological reconnaissance and rock-chip sampling

In November 2012 Buxton Resources conducted a reconnaissance survey across the 4 km-wide Yalbra Main Zone to examine outcrop, pre-existing costeans, and drillhole sites, and to carry out a rock-chip sampling program over prospective areas. Twelve costeans were identified in the area and several of these combined with surface outcrop displayed high-grade graphite occurrences (Fig. 23). Twenty-six rock-chip samples were collected and subsequently sent for laboratory analysis (Buxton Resources, 2012c, 2013b). Highlights from the sampling survey included:

- peak result of 32.5% TGC
- average of 26 samples = 13.0% TGC
- average of 20 samples @ 5% TGC lower cutoff = 16.1% TGC
- average of 15 samples @ 10% TGC lower cutoff = 18.9% TGC.

### Exploration drilling program in 2013

The most recent phase of the Yalbra Main Zone exploration program took place in November 2013 in which Buxton Resources completed a reverse circulation drilling program of 15 holes, totalling 1674 m. Very high grade graphite intersections were obtained from 11 drillholes in the Yalbra 1 and 1a graphite prospects within the Yalbra Main Zone. Also, four drillholes were completed in the Northern Zone (Buxton Resources, 2014a).

### Yalbra Main Zone prospects Yalbra 1 and 1a

The 2013 exploration program within the Yalbra 1 and 1a prospects confirmed the presence of two major parallel, steeply dipping, high-grade graphite horizons extending along strike for more than 500 m in an east–west direction (Figs 20, 24a). These thick horizons are known to be open both at depth and along strike. Of the 11 reverse circulation drillholes drilled in this area, eight intersected substantial thicknesses of high to very high grade graphite in these horizons, illustrated in cross-section A–B (Fig. 24). Selected intercepts of high-grade graphite intersected in these drillholes are given in Table 4.

It was reported that grades of very high grade graphite intercepts averaging more than 30% TGC appeared consistent within the major northern graphite horizon at Yalbra 1 prospect as evidenced from intercepts from drillholes YBRC001, 012, and 015. Returns of very high-grade material were also consistent from the upper weathered saprolite zone at shallow depths as seen in drillhole YBRC014 (20–30 m), and in unweathered bedrock at depths to 180 m in YBCR015 (Fig. 24a) (Buxton Resources, 2014a).

### Graphite resources at Yalbra 1

In February 2014, Buxton Resources announced a maiden, very high grade, JORC-compliant inferred graphite resource of 2.27 Mt at 20.1% TGC. This inferred resource covers the two high-grade graphitic horizons to the west of the fault line in Yalbra 1 (Fig. 24) (Buxton Resources, 2014b).

An additional 15-hole drilling program, completed in July 2014, extended the very high grade graphite mineralization zone approximately 200 m to the west of the 2013 exploration program. At the conclusion of this program, the company announced an updated, JORC-compliant inferred graphite resource estimate over a 600 m strike length of 4.022 Mt at 16.17% TGC (using a 4% TGC lower cutoff grade) and a contained graphite content of 650 000 t. It was also stated that graphite mineralization remains open along strike and at depth (Buxton Resources, 2014c).

### Ore evaluation studies

Petrographic studies of material obtained from 2013 and 2014 drillhole samples indicated that graphitic horizons in the Yalbra 1 Main Zone prospect contain a significant proportion of medium and coarse grade flake graphite. Petrographic examination shows that the graphite typically appears within high-grade microbands as medium–coarse flakes mostly ranging from 100 to 500 µm in length and in some cases more than 1 mm. Accordingly, the crystal size of the Yalbra high-grade microbands has been shown to approach commercial standard for coarse flake graphite with a length >150 µm. Fine-grained graphite is also present in the Main Zone although it is confined to lower grade microbands. A metallurgical program on the high-grade graphite ore is currently underway (Buxton Resources, 2014a,c).

## Northern Zone prospect

In 2013, four reverse circulation drillholes (YBRC007–010) were drilled close to the Northern Zone graphite prospect site to test a targeted VTEM anomaly (Fig. 20). Although high-grade graphite intercepts were recorded as ranging from 7.0 to 17.1% TGC, graphitic zones intersected were comparatively small, ranging from 3 to 5 m in thickness. Despite these preliminary drilling results, the Northern Zone remains a target for future graphite exploration (Buxton Resources, 2014a).

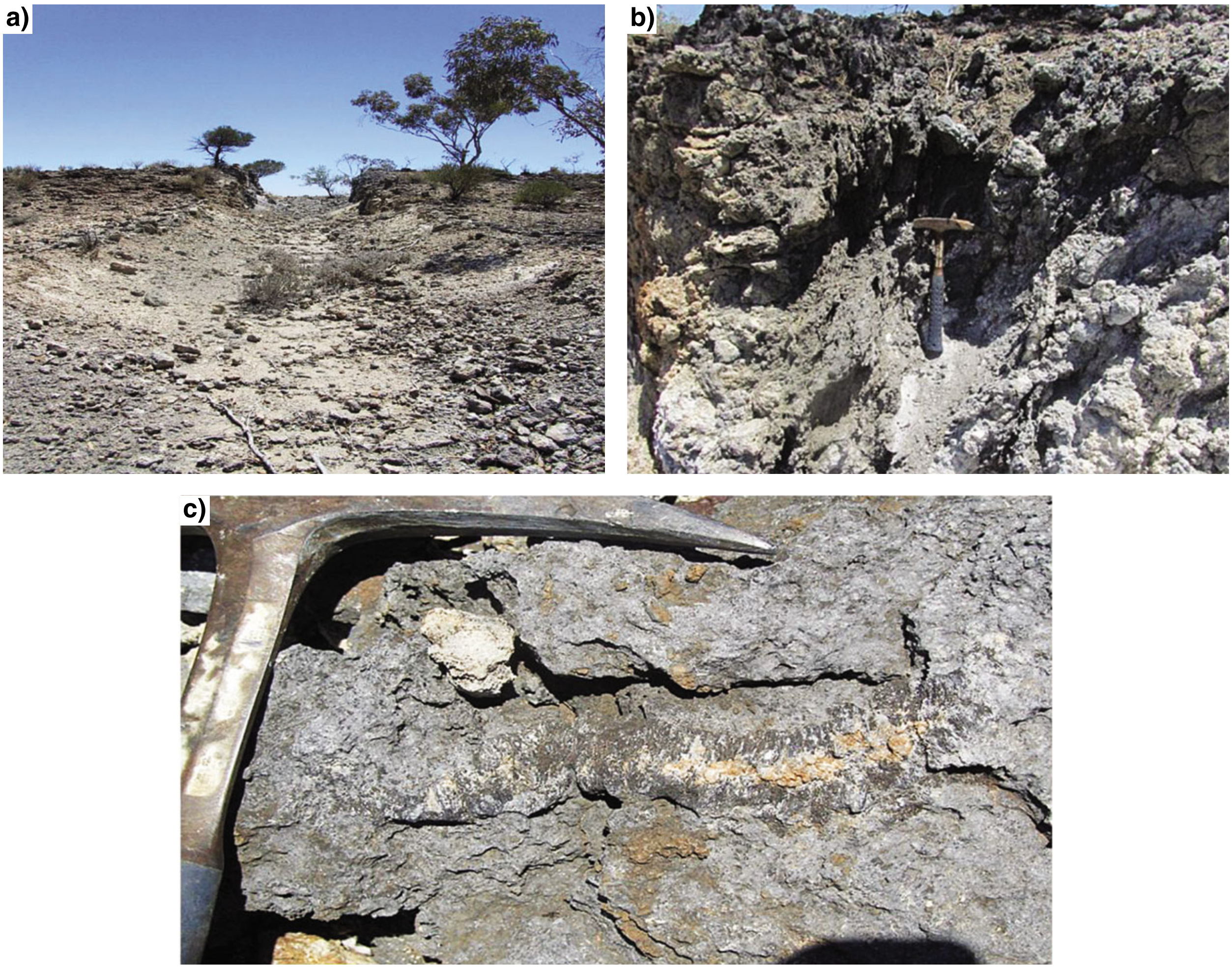



**Figure 23.** **Three photographs from graphite-rich zones within the Yalbra Main Zone: a) costean through near-surface graphite mineralization, Yalbra 1; b) graphite horizon, approximately 1.5 m thick, exposed in a costean wall; c) coarse, vein-hosted, flake graphite (centre) within fine-grained graphite rock (photographs courtesy Buxton Resources)**

**Table 4. Significant graphite intercepts from Yalbra 2013 drilling program**

| *Hole ID (YBRC)* | *From (m)* | *To (m)* | *Graphite intercept (% TGC)[(a)]* | *Including (% TGC)[(a)]* |
|---|---|---|---|---|
| 001 | 55 | 87 | 32 m @ 23.4% | 7 m @ 32.4% |
| 002 | 75 | 89 | 14 m @ 22.3% | 6 m @ 26.8% |
| 011 | 45 | 59 | 14 m @ 21.5% | 5 m @ 33.0% |
| 012 | 19 | 50 | 31 m @ 22.9% | 5 m @ 30.2% |
| 015 | 158 | 189 | 31 m @ 22.5% | 6 m @ 33.0% |

**SOURCE**: Modified after Buxton Resources (2014a)

**NOTE**: (a) Percent total graphitic carbon

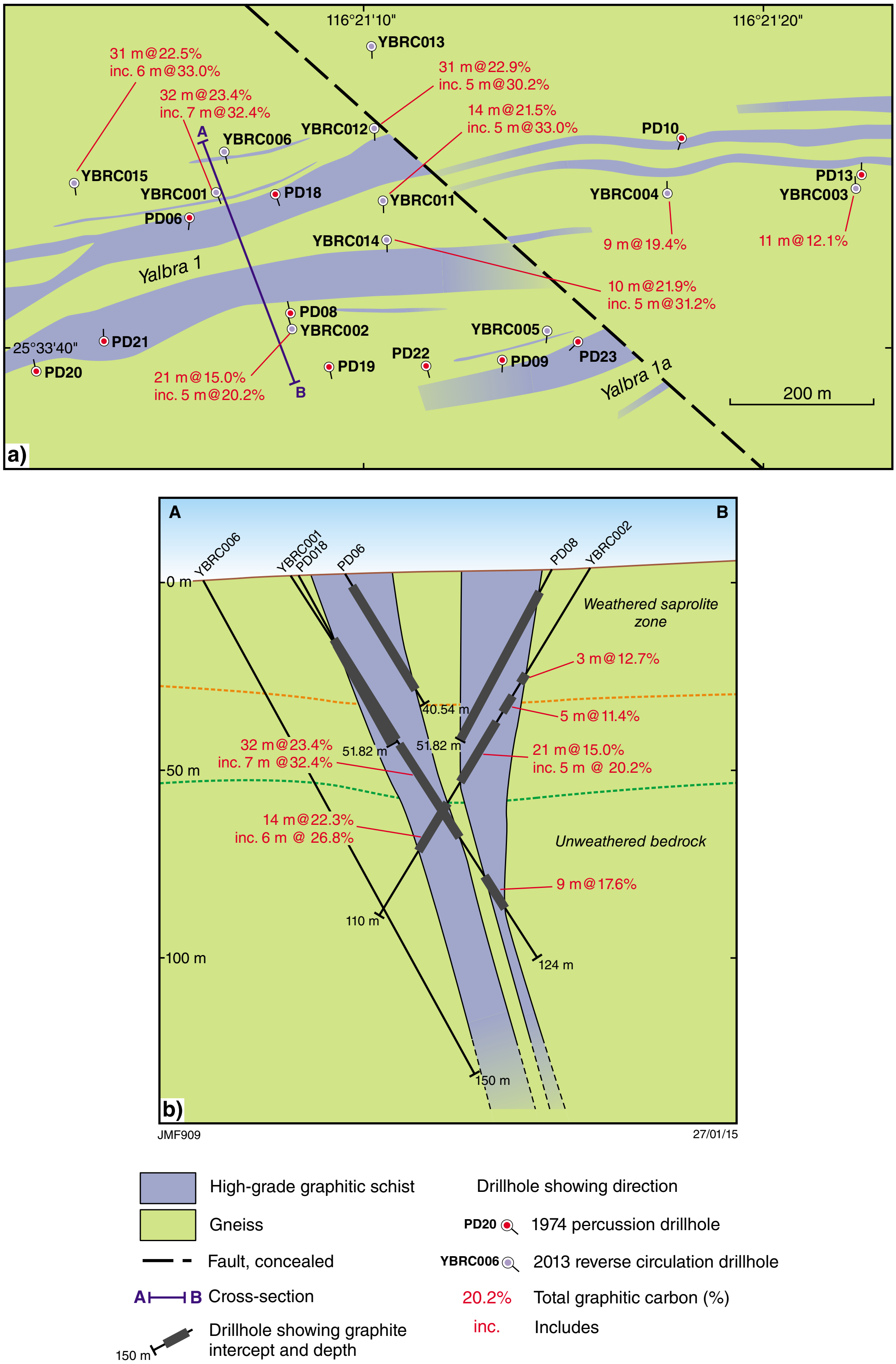



**Figure 24. Graphite exploration in the Yalbra Main Zone in 2013: a) map of Yalbra 1 and 1a showing location of reverse circulation drillholes with high-grade graphite intercepts; b) north–south cross-section through Yalbra 1 showing graphite drillhole intercepts (modified after Buxton Resources, 2014a)**

## Lamboo Province

The Lamboo Province is the oldest component of the Paleoproterozoic Halls Creek Orogen. The province extends for about 360 km in a north-northeasterly belt in the Halls Creek area of the east Kimberley region (Fig. 1). It comprises a series of igneous and low- to high-grade meta-igneous and metasedimentary rocks divided into the Western, Eastern, and Central Zones (Fig. 25).

The Western Zone is interpreted to have formed along the margin of the Kimberley Craton. The oldest rocks in the zone consist of a series of metamorphosed, fine–medium-grained turbidites of the Marboo Formation, dated at about 1872 Ma, overlain by the Whitewater Volcanics and intruded by granites of the Paperbark Suite.

The Eastern Zone overlays basement rocks dated about 1910 Ma comprising the Ding Dong Downs Volcanics and the granitic rocks of the Sophie Downs Suite. The basement is overlain by the Halls Creek Group, largely consisting of the Saunders Creek, Biscay, and Olympio Formations deposited between 1880 and 1845 Ma.

The Central Zone comprises the Tickalara Metamorphics, deposited around 1865 Ma. They were intruded by granite sheets and later overlain by sedimentary and volcanic rocks of the Koongie Park Formation between 1845 and 1840 Ma. The northeastern section of the Central Zone consists of medium- to high-grade metavolcanic and metasedimentary rocks of the Tickalara Metamorphics, intruded by tonalite and leucogranite sheets around 1863 Ma, and by granitic rocks and associated gabbros between 1830 and 1800 Ma (Sheppard et al., 1995; Tyler et al., 2012; Johnson, 2013).

## McIntosh project

The McIntosh graphite project is in the northeastern section of the Central Zone of the east Kimberley region, about 70 km north-northeast of Halls Creek (Fig. 26). The project area, adjacent to the Great Northern Highway and on Alice Downs and Mabel Downs pastoral leases, is divided into two exploration areas:

1. The McIntosh area, comprising four exploration licences (ELs) and one EL currently under application, which extend from the McIntosh Hills in the south for approximately 30 km in a north-northeasterly direction. The principal graphite targets (Targets 1–3, 5, and 6), defined by strong EM anomalies, are within ELs E80/3928, 3864, and 3906 (Fig. 26).
2. The Black Rock area, consisting of E80/4739, is contiguous with the northeastern edge of the McIntosh area.

The McIntosh graphite project has been owned and operated by Lamboo Resources Ltd since mid-2012. The company is currently pursuing an active exploration program and in 2014 announced an upgraded resource of high-grade, flake graphite for McIntosh Target 1 of 7.1 Mt at 4.73% TGC. While exploration continues on the five McIntosh target sites, Lamboo Resources is also in the developmental stage for future graphite mining and processing operations.

### Geology

The Paleoproterozoic Tickalara Metamorphics are host rocks for the McIntosh graphite prospects. The formation comprises schist, paragneiss, granite gneiss, calc-silicate rocks, amphibolite, and pyroxene granulite. In the McIntosh area these high-grade metamorphic rocks appear to reach upper amphibolite facies as indicated by the presence of sillimanite and evidence of original cordierite mineralization (Fig. 26). Within the gneissic rock units in the McIntosh area, Lamboo Resources has identified steeply dipping, northeasterly trending graphitic schist horizons up to 50 m in thickness that extend intermittently in excess of 10 km along strike.

### McIntosh exploration areas

#### *Target 1*

Target 1 is a linear body about 12 km north-northwest of Alice Downs Homestead (Fig. 26). This graphite-rich, tabular body comprises steeply dipping beds of graphitic schist, 20–40 m total width, intruded in part by leucogranite dykes, and contained within quartz–feldspar–biotite gneiss of the Tickalara Metamorphics (Fig. 27).

To date, Target 1 has been the main focus of graphite exploration by Lamboo Resources, which has conducted extensive ground sampling and three drilling programs, the first in 2012, which was followed by two further programs in 2013 (Figs 28a, b). Drilling has shown that well-developed bodies of flake graphite at this site extend to a vertical depth of at least 200 m and remain open at depth. Initial assays from the main graphitic horizon demonstrated that results from follow-up diamond drillholes were consistent with earlier reverse circulation drill samples with average values from drillhole 088 of 6.8% TGC over 43 m. This is equivalent to an estimated 8.2 vol.% of flake graphite. A summary of estimated volume percent and size range of flake graphite from several drillholes at Target 1 is given in Table 5.

Petrographic analyses of core samples have highlighted a number of mineral associations of flake graphite crystals within the graphitic schist host rock. In the first instance, flake graphite crystals align parallel to an anastomosing schistosity within the host schist, with distinct graphite aggregates or clumps associated with, or locally rimming, muscovite and quartz (Fig. 29a). In other areas, flake graphite clumps or lenses, commonly paralleling the local schistosity, are interlayered with sulfides, mainly pyrrhotite. It is proposed that these layering and clumping structures could be amenable to future beneficiation (Lamboo Resources, 2012a, 2013b).

Following analysis of the 2012 and Phase 1 2013 drillhole data for Target 1, Lamboo Resources announced a maiden JORC resource for flake graphite over a 400 m strike length covering most of the northeast section of Target 1. The total indicated and inferred resource estimate was 5.323 Mt grading 4.91% TGC (5.06% TC) for 264 400 t of contained graphite at a nominal 2% TGC cutoff grade (Lamboo Resources, 2013c).

In mid-2013, the Phase 2 drilling program was completed. This program comprised 10 reverse circulation holes for a total of 1068 m. The program was designed, in part, to infill existing drillholes to confirm true thicknesses of flake graphite horizons found to exceed 20 m. The program also investigated the extension of the flake graphite zone along strike to the southwest of the known area. Drilling confirmed an aggregate strike length of 1500 m.

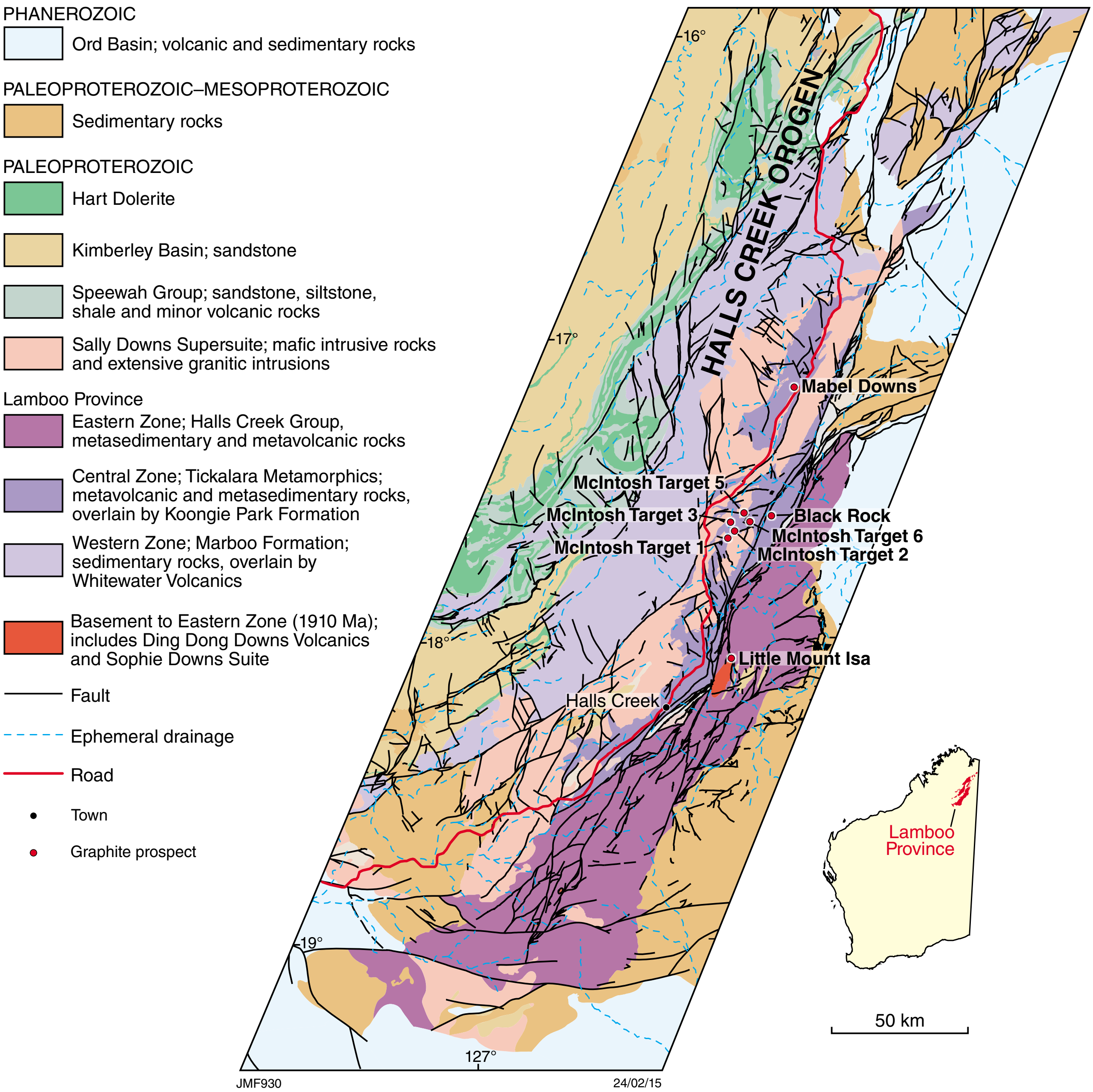



**Figure 25. Geological map showing graphite prospects in the Lamboo Province, Halls Creek Orogen (modified after Martin et al., 2014)**

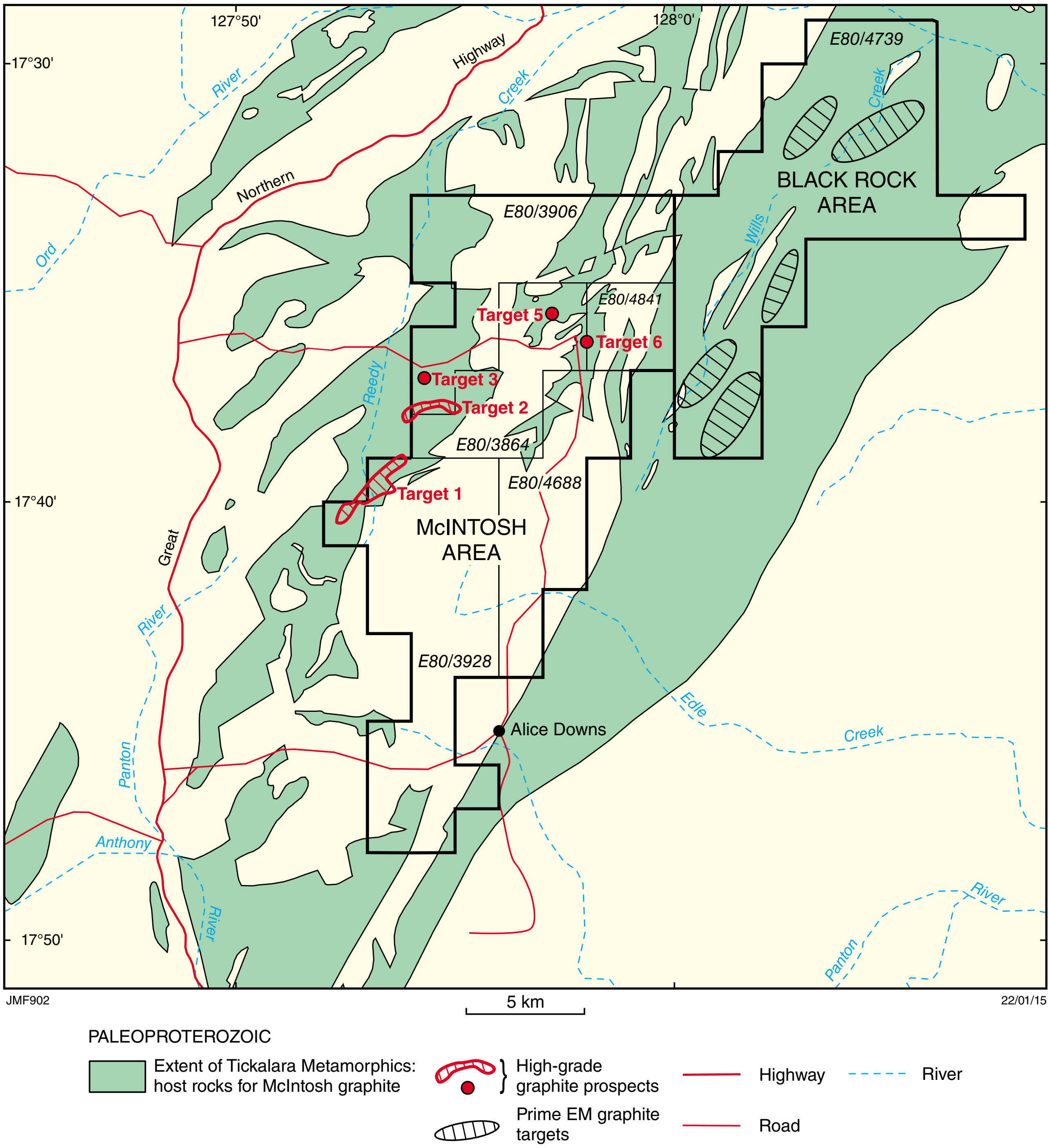



**Figure 26. Location of McIntosh and Black Rock exploration areas (modified after Lamboo Resources, 2013b)**

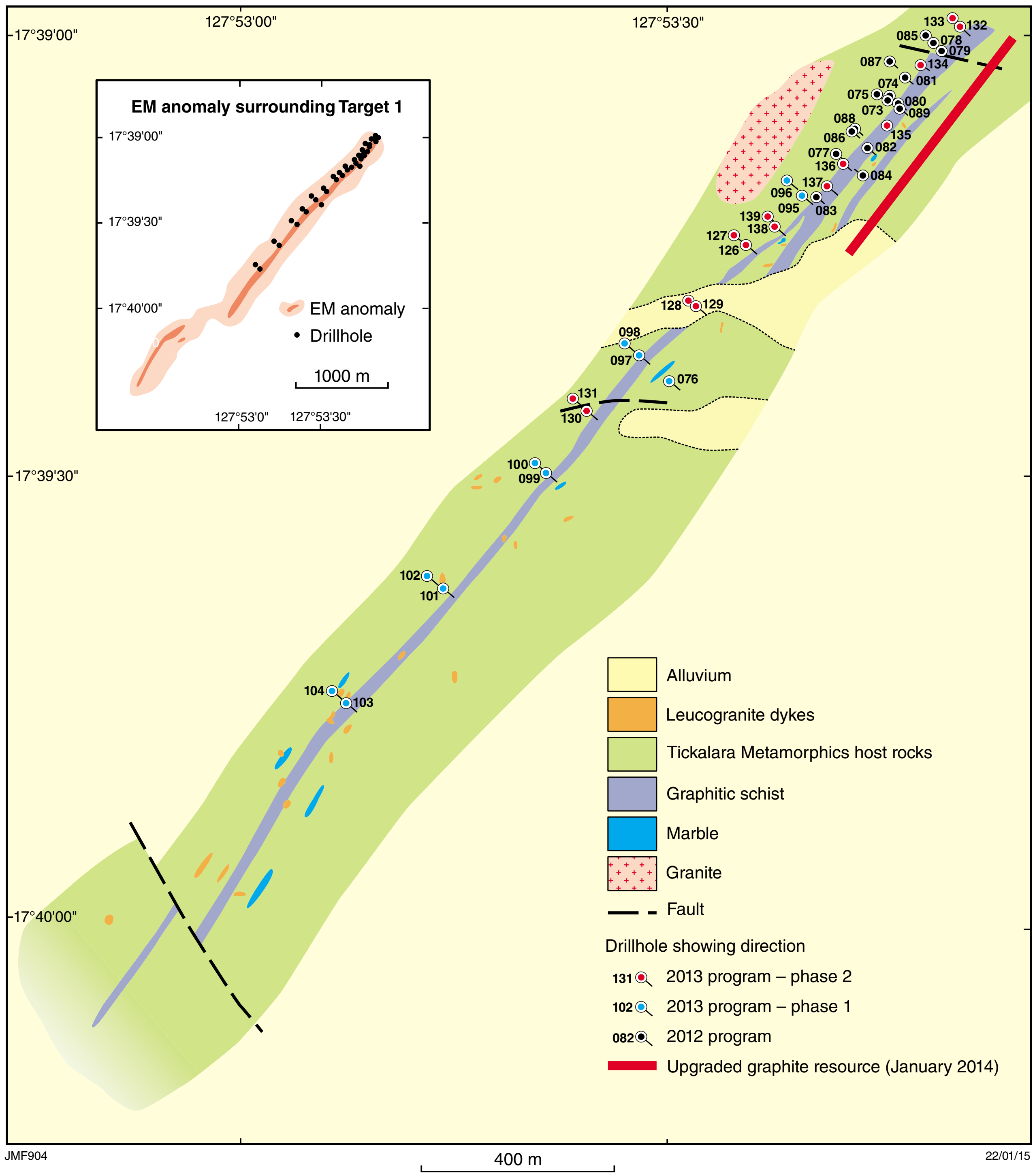



**Figure 27.** **Geological sketch map of McIntosh Target 1 exploration area and surrounding EM anomaly. The extent of the upgraded JORC-compliant resource as at January 2014 is highlighted by the red bar (modified after Lamboo Resources, 2014a).**


**Figure 28. Exploration activities at McIntosh prospects: a) diamond drill rig in operation at Target 2; b) graphite powder sourced from a Target 1 drillhole; c) detail showing graphitic gneiss host rock at Target 2; d) surface sample of well-developed flake graphite at Target 5 (photographs courtesy Lamboo Resources)**

**Table 5. Estimated volume percent and size range analyses of flake graphite crystals from McIntosh Target 1 drillcore samples**

| *Sample no.* | *Drillhole no.* | *Depth of sample (m)* | *Estimated flake graphite (vol.%)* | *Flake graphite size range (μm)* |
|---|---|---|---|---|
| 508481 | 089 | 23.8 | 12 | 40–130 |
| 508482 | 089 | 31.8 | 8 | 30–160 |
| 508485 | 085 | 92.02 | 5 | 40–160 |
| 508488 | 085 | 107.35 | 9 | 50–150 |
| 508489 | 085 | 114.77 | 8 | 30–120 |
| 508491 | 085 | 125.58 | 7 | 30–200 |
| 508492 | 085 | 127.44 | 8 | 15–150 |
| 508493 | 085 | 130.45 | 6 | 20–230 |
| 508497 | 084 | 83.51 | 9 | 20–160 |
| 508498 | 084 | 83.73 | 7 | 20–160 |
| 508499 | 084 | 87.88 | 6 | 30–160 |
| 508500 | 084 | 88.6 | 6 | 20–200 |
| 507223 | 084 | 92.14 | 9 | 20–160 |
| 507224 | 084 | 100.85 | 7 | 30–180 |
| 507225 | 084 | 102.41 | 8 | 15–200 |
| 507226 | 084 | 109.91 | 6 | 20–120 |

**SOURCE**: Modified after Lamboo Resources (2013a)

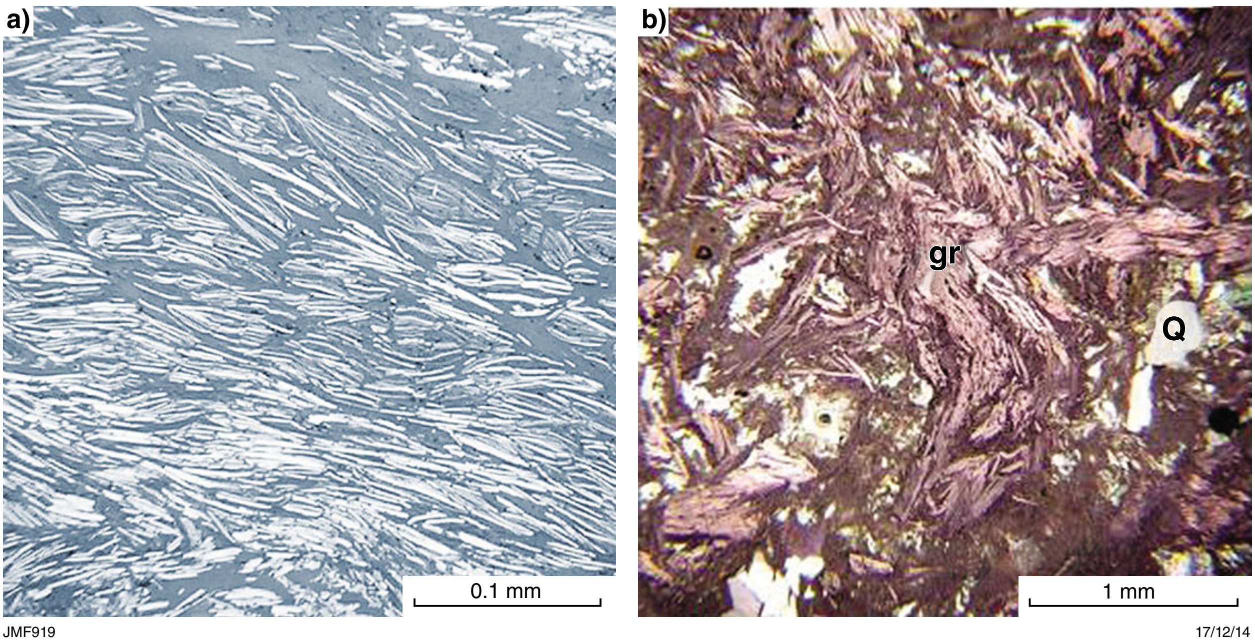



**Figure 29. Photomicrographs of McIntosh flake graphite: a) graphite flakes contained within a graphitic schist at Target 1; b) graphite flakes (gr) forming aggregates or clumps associated with minor quartz (Q) in graphitic schist at Target 6 (photomicrographs in plane polarized, reflected light, courtesy Lamboo Resources)**

In October 2013, a further 14 reverse circulation holes were drilled and confirmed a strike length extension of 2000 m to the southwest of the current resource and in areas directly to the south of the maiden resource estimate. This activity provided sufficient data to extend the maiden resource to cover a strike length of 580 m (shown by the red bar in Fig. 27) (Lamboo Resources, 2013b).

### *Targets 2 and 3*

Approximately 3 km north-northeast of Target 1, the graphitic body comprising Target 2 extends in an east–west direction over a distance of at least 1.5 km (Fig. 26). Also contained within quartz–feldspar–biotite gneiss of the Tickalara Metamorphics, the steeply dipping graphitic schist beds in Target 2 have been extensively prospected (Figs 28c, 30). By mid-2013, 49 drillholes had been completed at this site (Fig. 31a). The best drillhole intercepts, based on a 2% TC cutoff, included 25 m at 4.77% TC in drillhole 039, and 13 m at 4.71% TC in drillhole 001. The highest recorded TC was 8 m at 6.21% in drillhole 038 (Lamboo Resources, 2013a).

Target 3 is about 3 km north of Target 2 (Fig. 26). Target 3, a northeasterly trending prospect that may be up to 1.4 km in length, was covered by 23 drillholes early in 2013 (Fig. 31b). Graphite recoveries from these holes have been somewhat less than expected, with returns from 18 holes averaging 2.48% TGC (Lamboo Resources, 2013a). Accordingly, Target 3 has been set aside from the higher grade resource Targets 1, 2, 5, and 6.

### *Targets 5 and 6*

Targets 5 and 6 are about 9 km north-northeast and northeast of Target 1, respectively (Fig. 26). Both tabular, graphite-rich targets comprise steeply dipping beds of graphitic schist, intruded in part by minor leucogranite dykes, and hosted by quartz–feldspar–biotite gneiss of the Tickalara Metamorphics (Fig. 32). A para-amphibolite, also part of Target 5, on its southeastern side abuts a local granitic intrusion.

At Target 5, a geological mapping and sampling program, together with 16 drillholes, has demonstrated that the flake graphite horizon is up to 35 m wide, at least 100 m in depth, and extends over a strike length of 1200 m (Figs 28d and 32a). Highlights of the drilling programs include 17 m at 5.77% TGC, including 5 m at 10.73% TGC from hole 112 (Lamboo Resources, 2013d).

Target 6 is composed of graphitic schist horizons folded around an interpreted anticlinal structure plunging to the northeast. Broad graphitic schist horizons in this structure were initially indicated by induced polarization (IP) geophysical studies and subsequently confirmed by geological mapping and the first phase of reverse circulation drilling in 2012. As a result, two broad graphitic schist horizons were defined with an aggregate width of 150 m and strike length of 1 km (Fig. 32b). Regional EM data also indicate that the structure remains open to the northeast and southwest (Lamboo Resources, 2013d). The best drilling results to date from the high-grade flake graphite horizons are 32 m at 4.31% TGC and 13 m at 4.66% TGC, both from drillhole 123. Surface samples subjected to petrographic analysis have demonstrated the presence of high-grade flake graphite (>500 µm), which exists as clumps and aggregates in up to 15 vol.% volume of the sample (Fig. 29b).

Preliminary metallurgical flotation studies from different testing laboratories have achieved high flake graphite concentrates from samples sourced from Targets 5 and 6. In two studies, Target 6 concentrates achieved more than 81% and 87% TGC recovery levels. It is considered that these preliminary results could lead to improved grades, possibly matching lithium-ion battery grade flake graphite currently sold in China (Lamboo Resources, 2013b).

By January 2014, Lamboo Resources was working to establish an initial resource figure for Targets 5 and 6 with the view to combining potential resources from Targets 1, 2, 5, and 6 for an ultimate 20-year mine life for the McIntosh project (Lamboo Resources, 2014a).

## Graphite resources and future mining and processing

In January 2014, it was announced that the upgraded JORC-compliant resource for the McIntosh Target 1 exploration area over 580 m strike length (shown by the red bar in Fig. 27) for total indicated and inferred resources was 7.135 Mt grading 4.73% TGC (4.95% TC) for 337 700 t of contained graphite at a 2% TGC cutoff grade. The graphitic schist host rock also remains open both along strike and at depth. Currently, beneficiation testing is continuing on a one-tonne bulk sample from Target 1 to produce sufficient flake graphite for commercial testing (Lamboo Resources, 2014a). Currently, the company is working on an updated scoping study for a long-term mining operation sourced from Lamboo graphite targets. The study is focused on an expanded graphite exploration program prior to the construction of an on-site pilot processing plant.

Also in January 2014, Lamboo Resources entered an MoU with China Sciences Hengda Graphite Co. Ltd. The MoU establishes a partner relationship in which Hengda Graphite will supply Lamboo Resources with metallurgical data and mining and production expertise to produce high-grade, flake graphite from the McIntosh deposit, which would be exported through the port of Wyndham. Based on a positive outcome of the flake graphite production, Hengda Graphite would enter into an offtake agreement to purchase flake graphite concentrate products (Lamboo Resources, 2014b).

Lamboo Resources has also recently established a commercial arm in Australia, known as the Advanced Particle Group, in association with Monash University and other research institutes, which has been co-funded by Australian and Singaporean bodies. The new organization will research and develop new high-tech applications for the company's high-grade graphite concentrate (McDiarmid, 2014b).

In June 2014, Lamboo Resources announced that a binding offtake agreement had been signed with Hengda Graphite to supply the company with 50 000 tpa of flake graphite concentrate at 90% TGC sourced from the McIntosh project. This agreement is set to come into effect at least one month from the commencement of production and will run until the end of 2018 with a floor price of no less than US$2000/t delivered to Hengda Graphite's processing plant in China (Lamboo Resources, 2014c).

## Black Rock exploration area

The Black Rock exploration area, also in the Central Zone, is directly northeast of the McIntosh area. Black Rock potentially contains graphitic schist horizons within the Tickalara Metamorphics that extend for more than 20 km in a north-northeasterly direction, of which 15 km has been identified as containing priority graphite targets (Fig. 26).

Pre-existing, airborne EM geophysical data have clearly identified these horizons as prominent EM zones, with 147 strong EM anomalies identified along the 20 km strike of the Tickalara Metamorphics. These anomalies tend to highlight stratigraphic conductors that indicate potential graphite–pyrrhotite sedimentary conductors similar to those present in the McIntosh area. Lamboo Resources has identified five prime graphite EM targets in the area (Fig. 33). Many smaller anomalies with the potential to host significant graphite mineralization have also been identified.

A preliminary ground survey identified coarse flake graphite in the area although the grade has not been evaluated to date. Similarities between the potential host stratigraphy and structural setting of the Black Rock area and those for proven graphite deposits in the McIntosh area indicate the Black Rock area also has very high exploration potential for new graphite deposits (Lamboo Resources, 2013e). The Black Rock area is set down for follow-up exploration in the near future by Lamboo Resources.

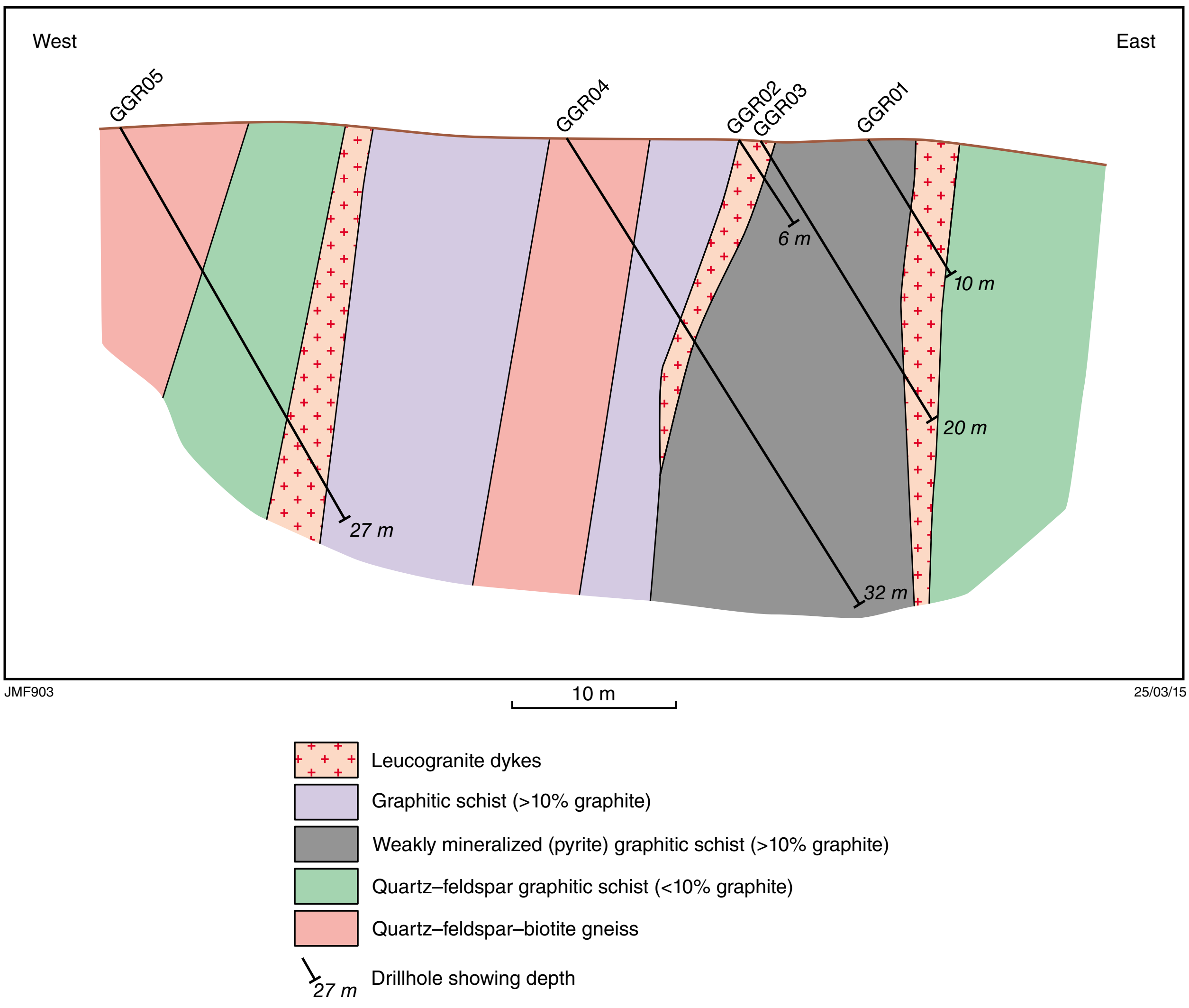



**Figure 30. Schematic cross-section of steeply dipping graphitic horizons in the McIntosh Target 2 area (modified after Lamboo Resources, 2012b)**

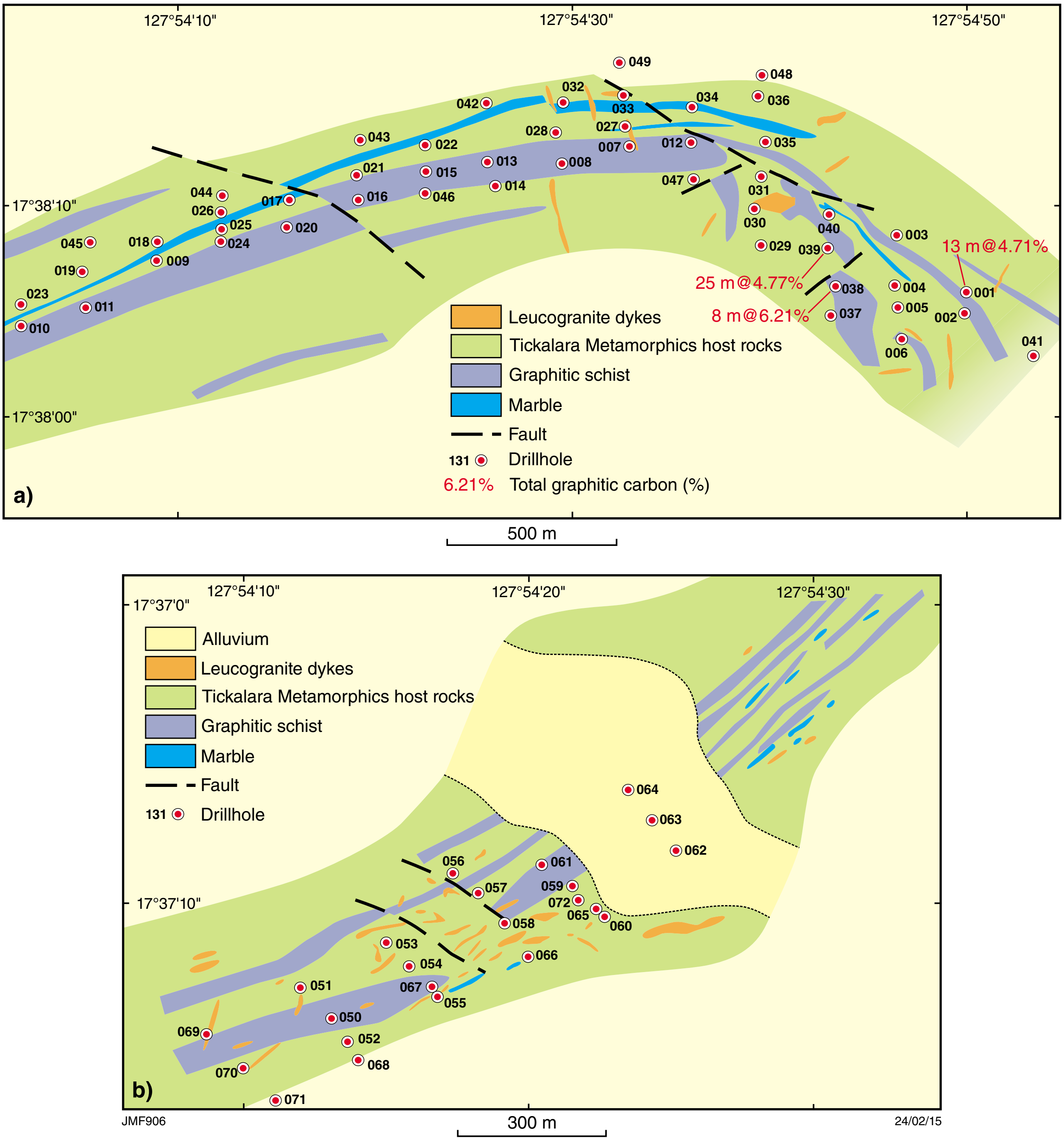



**Figure 31.** Geological sketch maps of McIntosh Targets 2 and 3 exploration areas: a) Target 2 area showing drillhole locations along graphite horizon; b) Target 3 area showing drillhole locations (modified after: a) Lamboo Resources, 2013a; b) Lamboo Resources, 2013f)

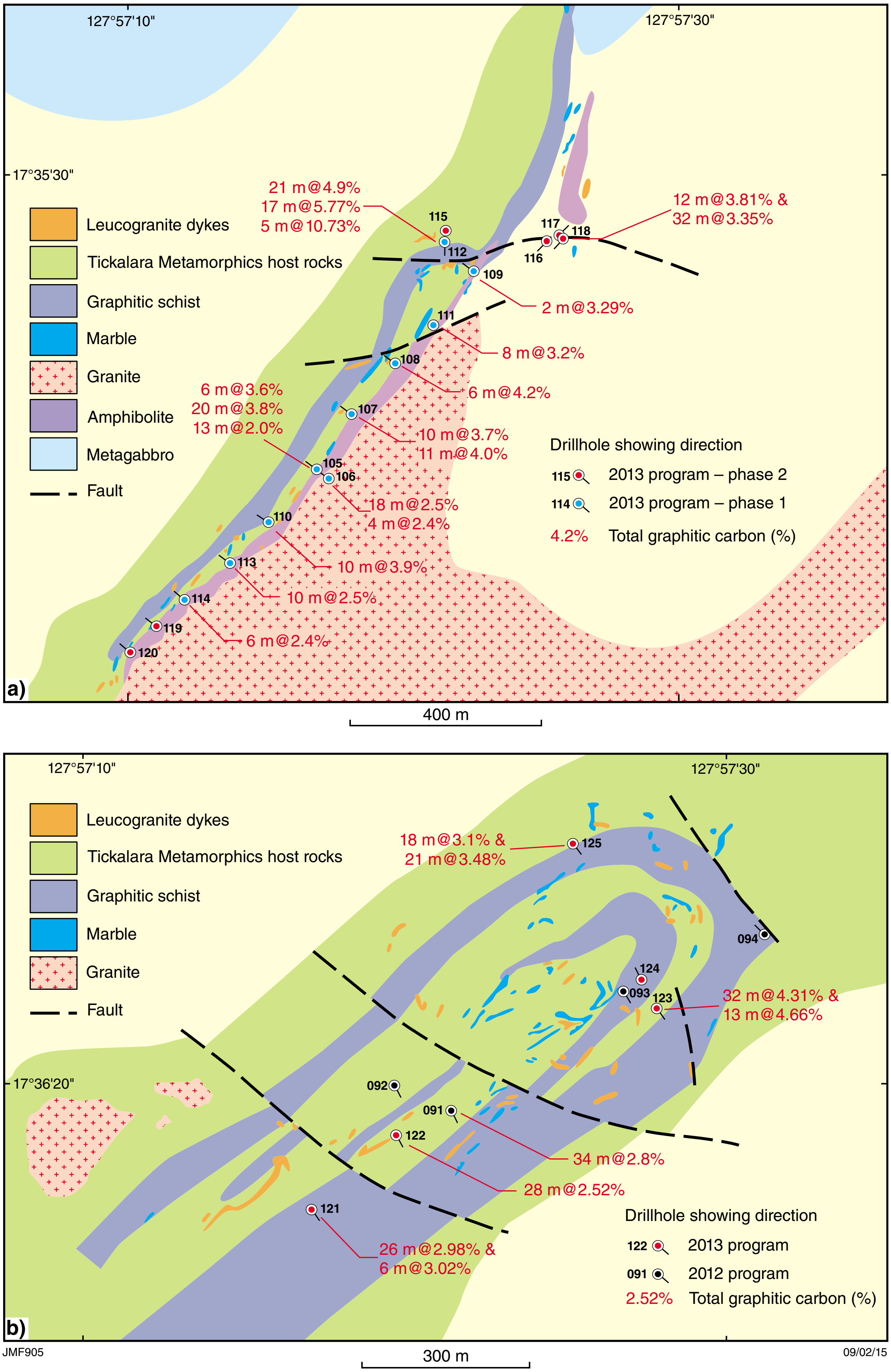



**Figure 32.** **Geological sketch maps of McIntosh Targets 5 and 6 exploration areas: a) Target 5 area showing drillhole locations with TGC intercepts; b) Target 6 area showing drillhole locations with TGC intercepts (modified after Lamboo Resources, 2013b)**

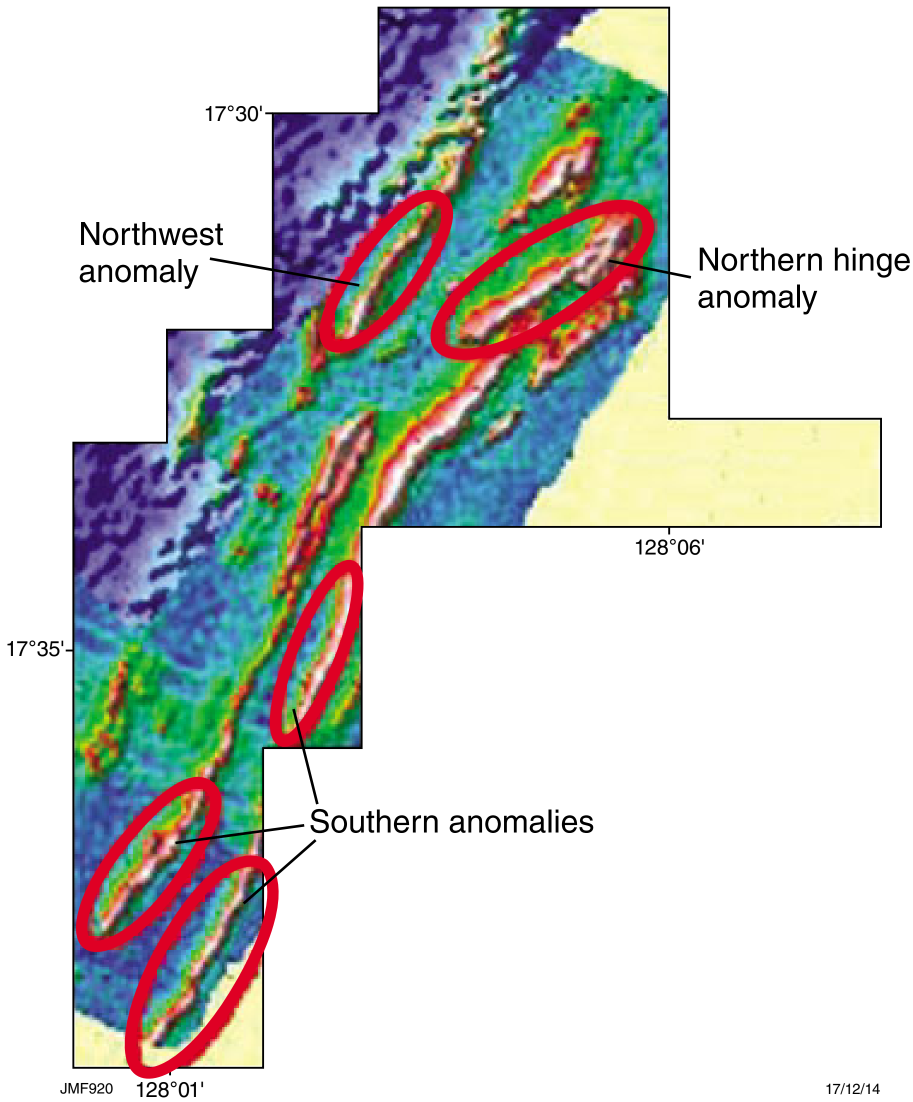



**Figure 33. Five prime electromagnetic (EM) targets for flake graphite exploration in the Black Rock project area (modified after Lamboo Resources, 2013e)**

## Mabel Downs prospect

The Mabel Downs graphite prospect is in the northeastern section of the Central Zone of the Lamboo Province, about 130 km north-northeast of Halls Creek in the west Kimberley region (Fig. 25). The prospective exploration area, owned by Lamboo Resources, forms part of exploration licence E80/4385, centred about 3 km north of Mabel Downs Homestead.

Although Lamboo Resources has not undertaken mineral exploration to date, the company has noted the area contains extensive lenses of graphitic schist within high-grade gneiss forming part of the Paleoproterozoic Tickalara Metamorphics. The graphitic schists in this area appear similar to those present in the McIntosh graphite-bearing schists 60 km to the south-southwest (Lamboo Resources, 2013e).

## Little Mount Isa prospect

The Little Mount Isa graphite prospect is in the Halls Creek Group within the Eastern Zone of the Lamboo Province, about 25 km northeast of Halls Creek (Fig. 25). In 2012, a rock-chip sampling program was conducted by Regency Mines Pty Ltd on former exploration licence E80/4046 at a site known as Target 2 – Area C within the Biscay Formation (Fig. 34).

The Biscay Formation is composed of metamorphosed sedimentary (commonly calcareous) and volcanic (mostly basaltic) rocks. At Target 2 – Area C, a small area of graphitic schist was located in an east–west zone measuring approximately 220 m wide. At this site, graphitic schist is contained within a series of north–south trending shear zones, each 50–60 m long and ranging in width from 1 to 10 m.

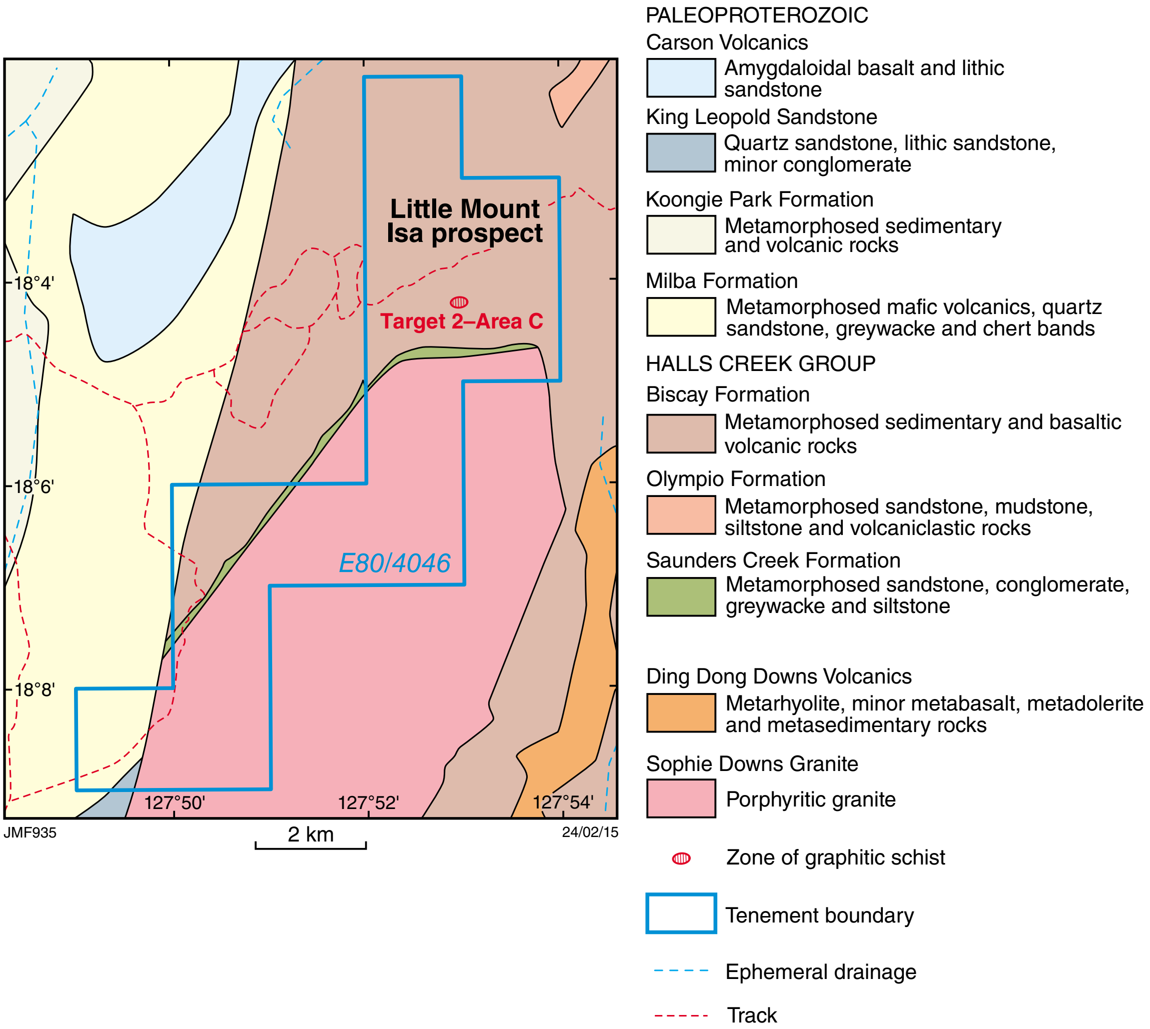



**Figure 34. Geological sketch map of the area around the Little Mount Isa graphite prospect (modified after Salmon, 2013)**

Regency Mines conducted a rock-chip sampling survey across the east–west zone and seven graphitic schist samples were collected from various shear zones along the traverse. Some samples were estimated to contain graphitic carbon at approximately 9% TC (Salmon, 2013). The rock-chip samples were subsequently submitted for analysis at a laboratory in Perth but results were not disclosed. The project was abandoned in early 2014 with the termination of the exploration licence.

The Mesoproterozoic Northampton Inlier forms part of the Paleoproterozoic to early Paleozoic Pinjarra Orogen (Fig. 1). The inlier is north trending, more than 160 km long, between Geraldton and north of Ajana on the State's central coast, and largely composed of deformed granulite-facies paragneisses intruded by porphyritic and migmatitic granite and pegmatite (Johnson, 2013). The area is well known for the historic mining of lead and lesser amounts of copper, zinc, and silver, starting in 1850 around Ajana and Northampton (Fig. 35).

Simpson (1951) noted numerous occurrences of graphite in the area especially in shear zones and pegmatites within garnet gneiss. Many of these sites for graphite prospects and occurrences throughout the region have not been positively identified and are shown with approximate locations.

## Ajana region

The Ajana region comprises the smaller, northern part of the Northampton Inlier extending from about 50 km north of Mary Springs Homestead south to the village of Binnu. In this region, three graphite locations are shown on the AJANA 1:250 000 geological map (Hocking et al., 1982). These include two disused graphite workings at Mary Springs South and Pindadanno, and graphite occurrences at Geraldine East (no information available) and in the Warribanno area (Fig. 35). Although there are no records for graphite production in the Ajana region, it is probable that small quantities were mined on an intermittent basis around the early part of the 20th century.

### Mary Springs South mine

Blatchford (1918a) reported the Mary Springs South site to yield 'graphite flake of a very promising nature' contained in veins and lenses 2–4 cm wide filled with coarsely foliated, iron-stained graphite stretching across the veins (Fig. 35) (Simpson, 1951).

### Pindadanno mine

At the former Pindadanno mine, about 2 km northwest of the Murchison River bridge on the North West Coastal Highway, Simpson (1951) noted a large ferruginous and clayey flake graphite (Fig. 35).

### Warribanno occurrence

Further south, about 8 km north-northeast of Ajana, the Warribanno graphite occurrence forms extremely narrow veins of fine, scaly graphite contained in a highly ferruginous gossan derived from a garnet gneiss outcrop, varying in width from about 3 to 7 m along its contact with mafic and pegmatite dykes (Fig. 35). The gossan was found to contain 11.94% fine flake graphite (Wilson, 1926; Simpson, 1951).

## Northampton–Geraldton region

The Northampton–Geraldton region, the larger of the two areas, extends about 100 km south from Binnu to the Walkaway area, south of Geraldton, with an average east–west width of 25 km (Fig. 35). In this region, numerous, mostly minor graphite occurrences have been noted. In the area, a number of gossans were found to contain graphite flakes mostly 0.2 – 0.6 mm in diameter. In other occurrences, graphite flakes are scattered throughout a limonite, quartz, mica, and garnet matrix, and others consist of rich, scaly graphite flakes. Potassium feldspar pegmatites contain minor graphite as coarse, scaly flakes up to 12 mm in diameter (Simpson, 1951). Although the location of several sites cannot be determined, others have approximate locations listed in Appendix 1.

### Bowes River occurrence

In 1848, the explorer AC Gregory originally discovered graphite in the area from an undetermined locality on the Bowes River. Specimens from this area were shown at the Paris Exhibition in 1878 and again at the Melbourne Exhibition of 1880, stated to be 'coming from an outcrop one mile from the (?) railway station' (Simpson, 1951).

### Isseka occurrence

At the Isseka occurrence, about 10 km south of Northampton, a costean was opened to a depth of around 8 m over a shear zone containing lenses of soft material impregnated with fine, black, iron-free graphite (Fig. 35). Chemical analyses revealed the material to contain 40–70% fine, graphitic carbon and whole-rock analyses yielded 8.8 – 21.3% flake graphite ranging from 0.2 to 0.6 mm in diameter (Simpson, 1951).

### Normans Well occurrence

Campbell (1910) noted that graphite had been found on Location 2674 (now 5392) about 2.4 km west of Normans Well in the Isseka area (Fig. 35).

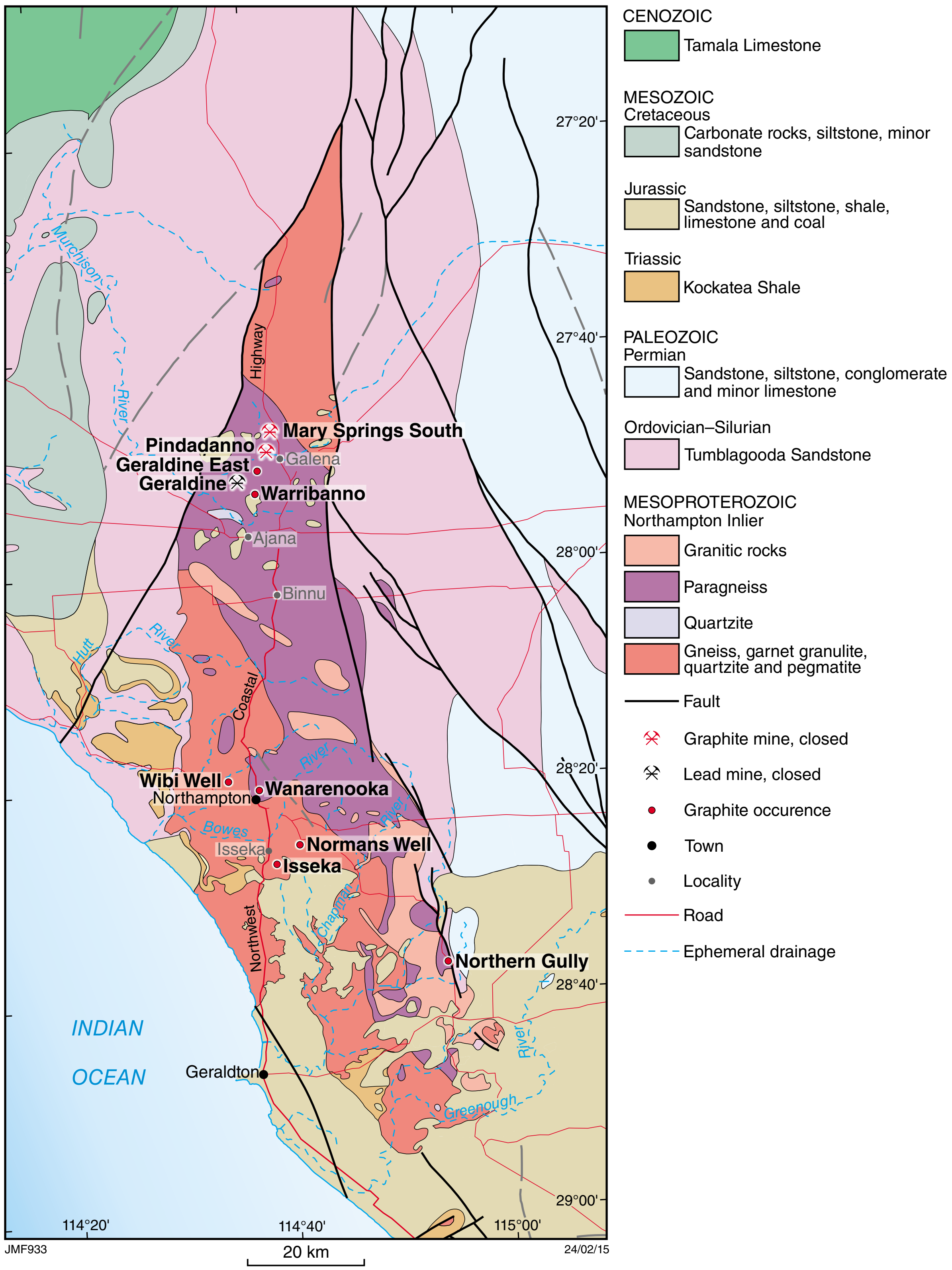



**Figure 35.** **Geological map of the Northampton Inlier showing the location of graphite occurrences and historic mines (modified after Martin et al., 2014)**

## Northern Gully occurrence

About 10 km north of the railway at Northern Gully, a zone of fine flake graphite is contained in an iron-rich rock consisting of limonite and mica (Fig. 35). Two analyses yielded 16.5 and 19.4% TGC (Simpson, 1951).

## Wanarenooka occurrence

Campbell (1910) states that graphite was found at the Wanarenooka copper mine about 1.7 km north of Northampton (Fig. 35).

## Wibi Well occurrence

Simpson (1951) records a graphite occurrence at Location 12 at Wibi Well, about 6 km northwest of Northampton (Fig. 35). Deeply weathered rocks at this site are composed of limonite, opal, jarosite, and alunite. Graphite flakes, 0.2 to 0.6 mm in length, are present either scattered through a limonite–quartz–mica–garnet matrix or as rich, scaly masses. Graphite samples from this site assayed between 12 and 79% TC although the graphite flakes are tightly interleaved within films of limonite and sheaths of mica, which would make separation difficult.

The Paterson Orogen in the central north of the State is a northwest-trending, arcuate belt of Paleoproterozoic to Neoproterozoic, structurally deformed and metamorphosed sedimentary and igneous rocks extending for about 1200 km (Williams and Bagas, 1999; Whitaker et al., 2010). The region contains five, widely scattered graphite occurrences between 170 and 275 km east-southeast of Nullagine in three different tectonic domains shown in Figure 36 and detailed in this chapter:

Yeneena Basin — Three Sisters and Yeneena BM1

Rudall Province, Talbot Terrane — Kintyre Rocks and May Creek

Rudall Province, Connaughton Terrane — Mount Cotton

# Yeneena Basin

## Three Sisters occurrence

The Three Sisters graphite occurrence is near the Three Sisters Hills about 200 km east-southeast of Nullagine (Fig. 36). In this area, graphite forms as small flakes orientated in the slaty cleavage of the Broadhurst Formation, which largely comprises metamorphosed, grey, carbonaceous shale and siltstone. Similar graphitic slate is also found interbedded in the basal conglomerate of the underlying, metamorphosed Coolbro Sandstone (Chin et al., 1979). These two units form part of the Neoproterozoic Throssell Range Group in the Yeneena Basin (Grey et al., 2005). Williams and Bagas (1999) state that strong dynamic metamorphism in this area has altered the shale and siltstone to quartz–sericite–chlorite schist and graphitic schist.

## Yeneena BM1 occurrence

In 2009, graphitic shale was located in the Yeneena BM1 exploration area about 170 km east-southeast of Nullagine (Fig. 36). The BM1 site, in exploration licence E45/2658, is owned and operated by Encounter Resources Ltd. In the exploration area the company drilled a number of holes in the Neoproterozoic Broadhurst Formation of the Throssell Range Group in an area considered prospective for base metals. In the BM1 target area, drillhole EPT057 was drilled in carbonates and black shales to 460 m depth to test for anomalous levels of copper in the sedimentary rocks (1755 ppm max. assay intersection) (Bewick and James, 2010).

Drillhole EPT057 also yielded 114 m of core between 349 m depth and the bottom of the hole at 460 m comprising graphitic grey and black shale together with carbonate, pyrite, and chalcopyrite mineralization. The thickness of these graphitic shales may indicate the presence of a much more extensive area of graphite mineralization in the Broadhurst Formation, which extends in a linear belt, between 3 and 6 km wide, over 40 km to the southeast of the area around the Three Sisters graphite occurrence.

# Rudall Province — Talbot Terrane

## Kintyre Rocks occurrences

In 2010, Mega Uranium Ltd drilled several holes on exploration licence E45/2690 in the search for blind uranium targets. The exploration area is about 210 km east-southeast of Nullagine and 4 km east-southeast of the Kintyre uranium deposit (Fig. 36).

During the exploration phase, Mega Uranium carried out an eight-hole diamond drilling program to target geophysical and lithological targets on E45/2690. In this program, two drillholes, 10KRD05 and 07 (Kintyre Rocks sites 5 and 7), were drilled along the northwestern boundary of the tenement within company-designated prospect ‘Area 1’. These holes drilled through up to 80 m of Permian tillite before intersecting up to 200 m of Paleoproterozoic gneiss, schist, and pelitic rocks of the Talbot Terrane. This zone consisted of garnet-bearing chlorite schists, carbonate units comprising calcite and dolomite flanked by graphite-rich fault zones, and alternating layers of micaceous, felsic gneiss. The graphite-rich fault zones (possible fluid mineralization pathways) and alternating gneissic layers were found to contain anomalous levels of uranium, silver, and base metals (Cox, 2010).

## May Creek occurrence

About 245 km east-southeast of Nullagine and 50 km southeast of the Three Sisters occurrence, the graphite occurrence at May Creek is present in the Paleoproterozoic Yandagooge Formation in the Talbot Terrane (Fig. 36). At this site, graphite mineralizes as a graphite–quartz schist (most probably derived from black shale) closely interlayered with quartzite, quartz–mica schist, banded iron-formation (BIF), and carbonate rocks. Chlorite, muscovite, biotite, and porphyroblastic garnet are common constituents of the host rocks (Chin et al., 1979). The higher metamorphic grade developed in these rocks has produced larger graphite flakes orientated in the schistosity than those present in the Three Sisters occurrence.

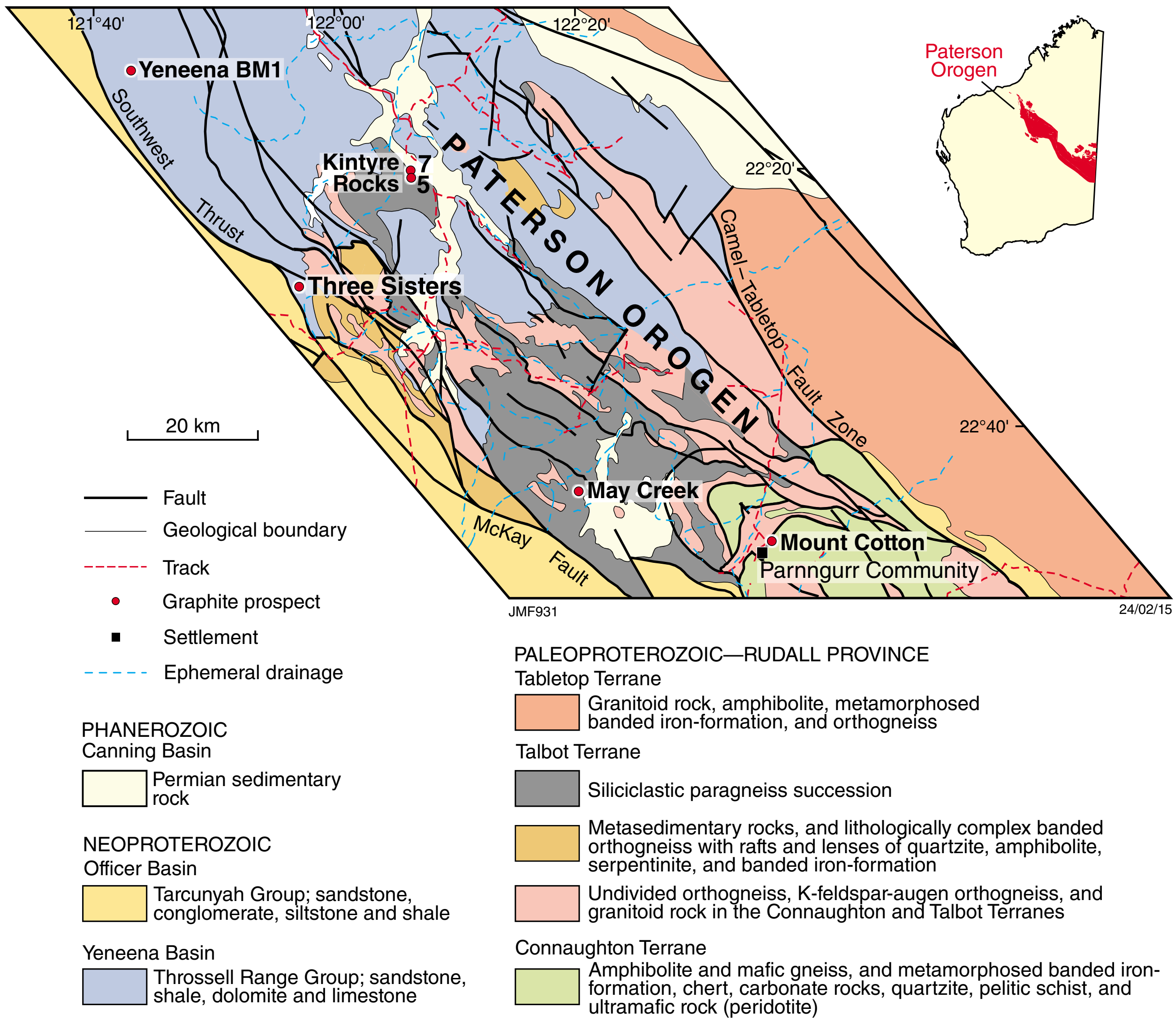



**Figure 36. Graphite occurrences in the Paterson Orogen (modified after Johnson, 2013)**

# Rudall Province — Connaughton Terrane

## Mount Cotton occurrence

The fifth graphite occurrence in the Paterson Orogen at Mount Cotton is about 275 km east-southeast of Nullagine and 30 km east-southeast of May Creek. This occurrence, at the summit of Mount Cotton, forms part of the older, Paleoproterozoic Connaughton Terrane of the Rudall Province (Fig. 36). At this site, graphitic and sulfidic schists are thinly interspersed with layers of quartz–mica–garnet schist, amphibolitic schist, minor chert, and quartz–carbonate rock. These extensively recrystallized, chloritized, silicified, and carbonated rocks are probably derived from metamorphosed and metasomatized black shales, BIFs, and other sediments from mafic volcanic rocks. The graphitic schist comprises mostly very fine graphite flakes contained in a matrix of quartz, mica, chlorite, and disseminated sulfides (Bagas et al., 2000).

# CHAPTER 9 Yilgarn Craton — Murchison Domain

## Dalgaranga

### Dalgaranga prospects

The Dalgaranga prospecting area around Gum Well is the only graphite locality identified to date within the Murchison Domain. The prospects are on or adjacent to former mining leases M59/184–186 about 12 km south-southwest of the disused Dalgaranga tantalum mine and about 80 km west–northwest of Mount Magnet (Fig. 37).

### Geology

The Dalgaranga area forms part of a northeast-trending series of Archean greenstones comprising metamorphosed sedimentary and felsic volcanic rocks intruded by a suite of gabbros, and later by Proterozoic dolerite (Fig. 38). The area is extensively covered by Cenozoic ferruginous duricrust. The graphite prospects in the Gum Well area are in valleys between northeasterly trending hills composed of gabbro. Material exposed on lower hillslopes and in creek beds consists of a ferruginized succession of metamorphosed Archean siltstones and sandstones with minor tuffaceous bands.

Following studies by Chapman and Groves (1979), it appears from the composition, relict textures, and structures of the metasedimentary rocks in the Dalgaranga area that they were predominantly chemical sediments of exhalative volcanic origin containing variable amounts of volcaniclastic material and possibly organic carbon. Over time, the carbon was altered through metamorphic processes to form zones of massive graphite (Carson, 1983).

### Exploration for nickel and graphite

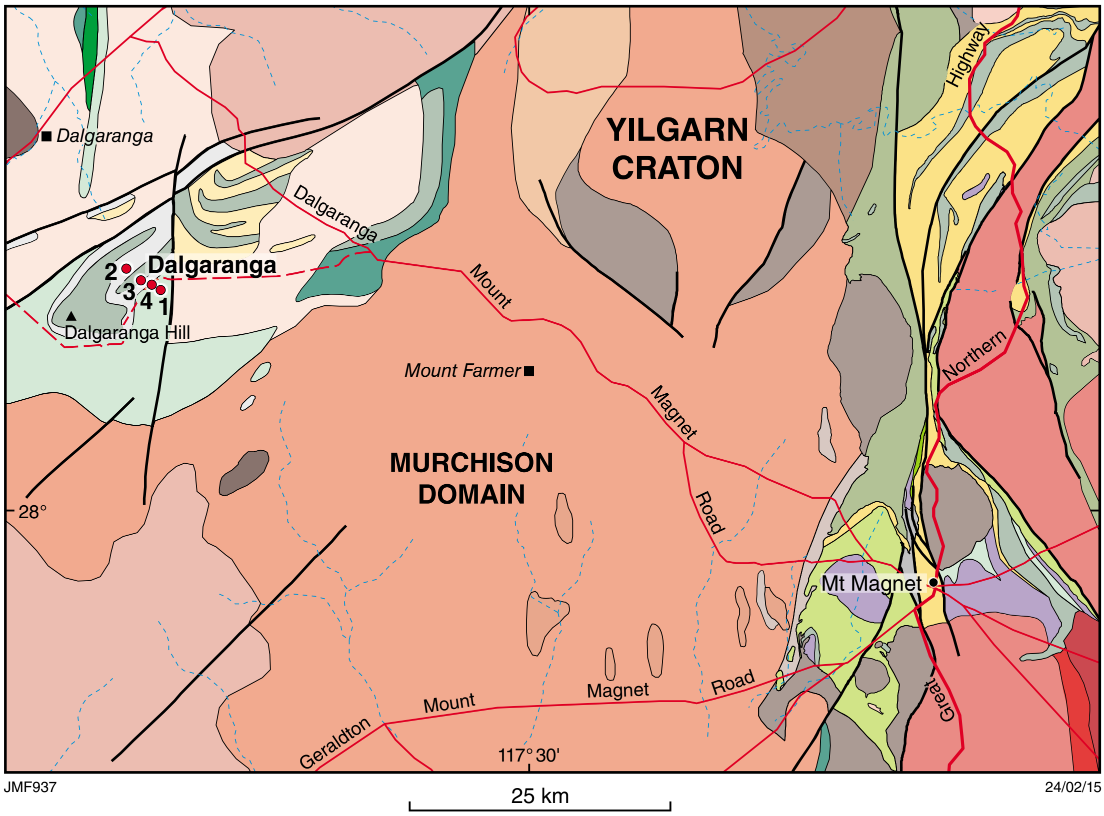
The Dalgaranga greenstone belt was extensively prospected mainly for nickel by numerous companies between 1969 and 1981. From 1969 to 1974, BHP carried out detailed nickel exploration in the Gum Well area that entailed geological mapping, geochemical and geophysical surveys, and percussion drilling of 42 holes. Although no significant nickel deposits were found, an induced polarization (IP) geophysical survey indicated zones of high electrical conductivity possibly related to the presence of concealed deposits of massive graphite. The graphite was confirmed by a follow-up program of percussion drilling in Dalgaranga 1–4 prospects.

In Dalgaranga 1 prospect, drillhole 1 intersected a massive graphite body 18 m in apparent thickness and in Dalgaranga 2, a second body of massive graphite, 16.5 m thick, was encountered in drillhole 6. Both holes were sited within previously defined IP anomalous areas. Because these graphite bodies were not fully drilled out, the graphite mineralization may be considerably thicker than that indicated in the drill logs. In addition, uncontaminated graphite bodies appear to have been encountered in drillholes 2–5 and 7–9 as being ‘homogenous and continuous in depth’ (Carson, 1983). Drillhole sites 3, 4, 8, and 9 are within Dalgaranga prospects 3 and 4 (Fig. 38).

The graphite bodies investigated at Dalgaranga are largely contained within three major IP anomalous zones. These graphite bodies were partly covered by three former mining leases. The largest graphite body, at Dalgaranga 2, is mostly within mining lease M59/186, which covers 200 ha. At this site, the upper surface of the massive graphite body is only 4.5 m below the surface, extending downwards to at least 21 m in places indicated by drillhole data. This body possibly extends to the northeast beyond the boundary of the mining lease (Fig. 38).

The graphite body at Dalgaranga 1 was intersected beneath a dolerite intrusion on mining lease M59/184 of 50 ha extent. At this site the graphite exists at 26 m depth extending to 44 m below the surface. Dalgaranga 3 prospect is a long, sinuous graphitic body of uncertain size, partly covered by the 30 ha mining lease M59/185. Another graphite prospect, Dalgaranga 4, is also a long, sinuous body midway between prospects 1 and 3 (Fig. 38).

Material from the drillholes indicated that the massive graphite ranged from a greasy and probably amorphous habit to a clayey, sulfide-contaminated form. Preliminary estimates for the Dalgaranga graphite deposits investigated at that time indicated a total graphite resource of 1.55 Mt (Carson, 1983).




ARCHEAN

Cullculli Suite
- Metatonalite, metagranodiorite and metatrondhjemite

Walganna Suite
- Monzogranite

Garden Rock Monzogranite
- Monzogranite to syenogranite

Ryansville Formation
- Conglomerate, sandstone and siltstone; metamorphosed

Murrouli Basalt
- Metabasalt

Yaloginda Formation
- Banded iron-formation, jaspilite, chert and shale; metamorphosed
- Felsic volcaniclastic rocks and banded iron-formation

Meekatharra Formation
- Basalt and komatiitic basalt

Big Bell Suite
- Equigranular monzogranite to syenogranite
- K-feldspar porphyritic monzogranite
- Metagranite including granodiorite and monzogranite
- K-feldspar–biotite–metamonzogranite

Crossroads Granodiorite
- Metagranodiorite to metamonzogranite

Tuckanarra Suite
- Metamonzogranite to metagranodiorite
- K-feldspar–biotite-metamonzogranite

Cundimurra Monzogranite
- K-feldspar–biotite-metamonzogranite

Youanmi Terrane greenstones
- Mafic volcanic rock with minor mafic and ultramafic intrusive rocks
- Komatiitic basalt
- Felsic volcanic or volcaniclastic rocks

Yilgarn Craton Granites
- Granitic rock; metamorphosed
- Gneiss

Youanmi Terrane Greenstones
- Metamorphosed ultramafic rock
- Metamorphosed mafic igneous rock
- Mafic intrusive rock; metamorphosed
- Clastic sedimentary rock; metamorphosed

- Fault
- Ephemeral drainage
- Road
- Town
- Graphite Prospect
- Homestead

**Figure 37. Geological map of a portion of the Murchison Domain between Dalgaranga and Cue (modified after Martin et al., 2014)**

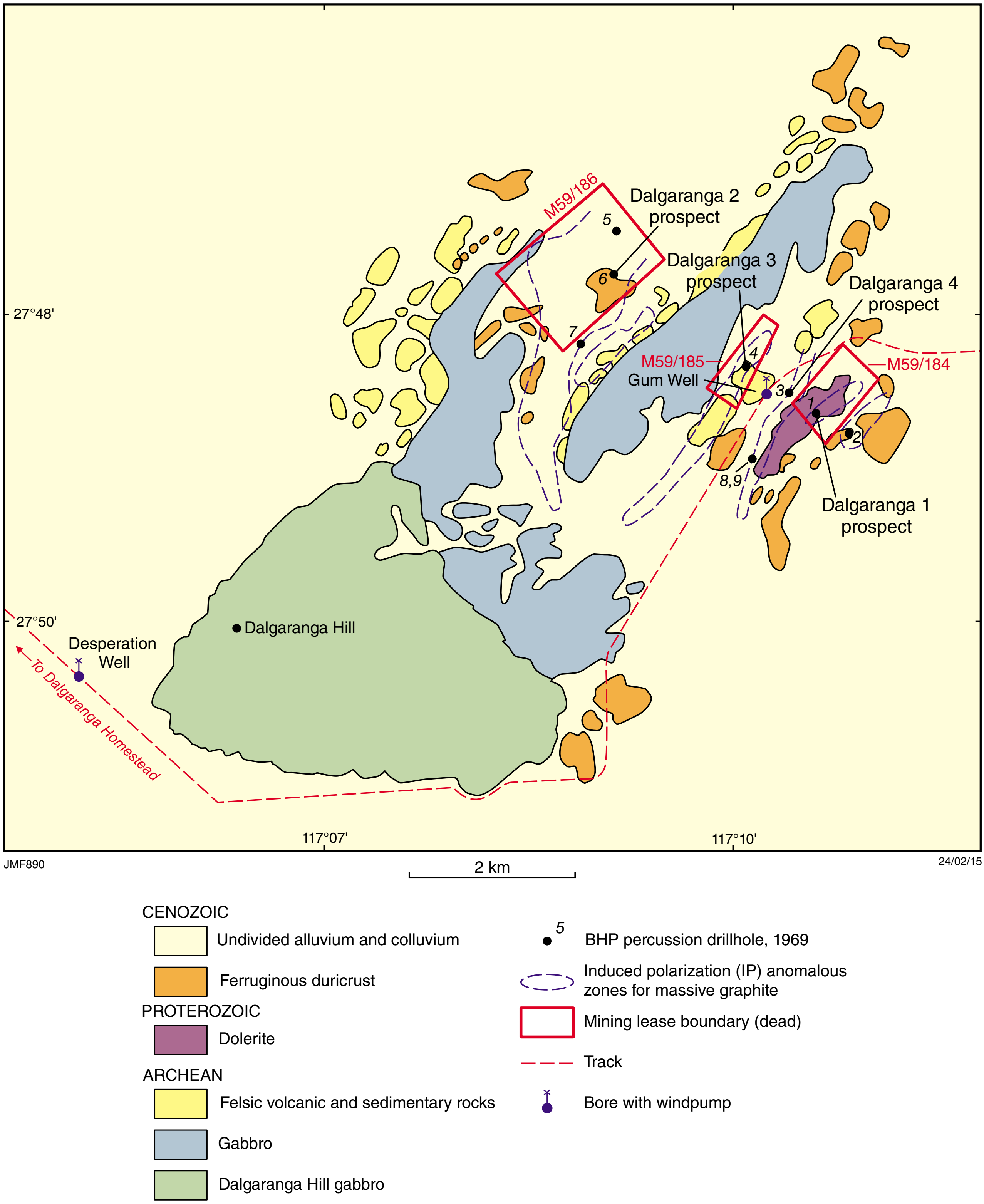



**Figure 38. Geological sketch map of the area surrounding the Dalgaranga graphite deposits (modified after Carson, 1983)**

## Southern Cross Domain

The Archean Southern Cross Domain extends in a continuous, north–south belt across the central part of the Yilgarn Craton (Fig. 1). The complex structure of this greenstone belt has made the regional stratigraphy difficult to establish. In general, the sequence consists of a lower succession of volcanic rocks up to 5 km thick comprising tholeiitic and komatiitic basalt, komatiite, and banded iron-formation (BIF), intruded by minor gabbro. The volcanic rocks are overlain by a succession of clastic metasedimentary rocks at least 2 km in thickness consisting of a basal black metamudstone overlain by a mixed succession of psammitic and pelitic rocks and minor quartzite and metaconglomerate (Fig. 39) (Doublier et al., 2012).

## German Well occurrence

The German Well graphite occurrence is about 96 km east-southeast of Meekatharra in the Southern Cross Domain and about 4 km east of German Well. In this area, graphite is present in the Gum Creek belt, a series of Archean, north-trending greenstones that form part of the Youanmi Terrane (Figs 39, 40). At this location, graphitic schist is interbedded in schistose amphibolite. According to Elias et al. (1982), the schist, consisting of fine-grained quartz, feldspar, chlorite, and sericite, was derived from carbonaceous shale. Minute graphite flakes in the schist were found to contain 4.5% TC.

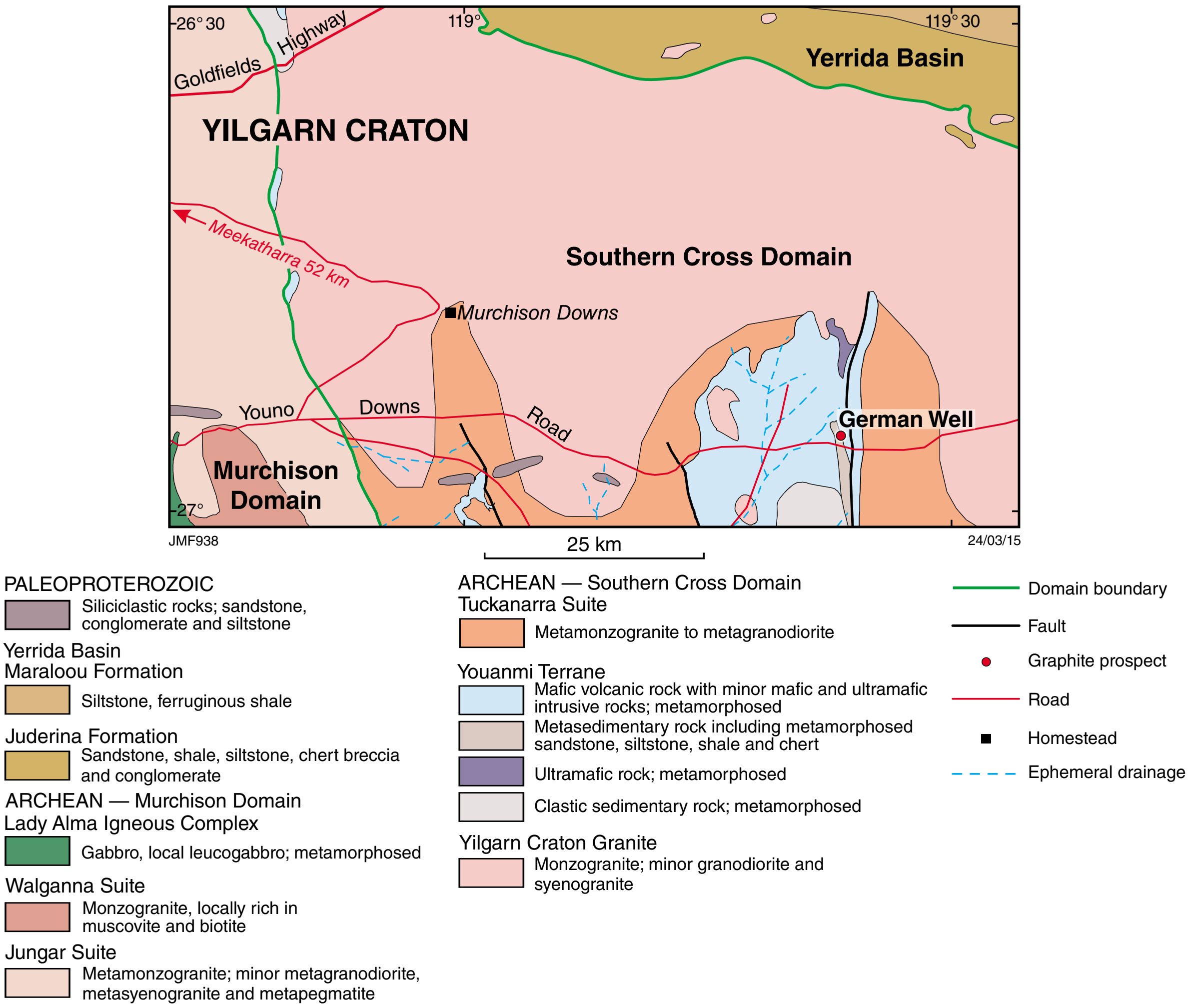



**Figure 39.** **Geological map of the Southern Cross Domain east of Meekatharra (modified after Martin et al., 2014)**

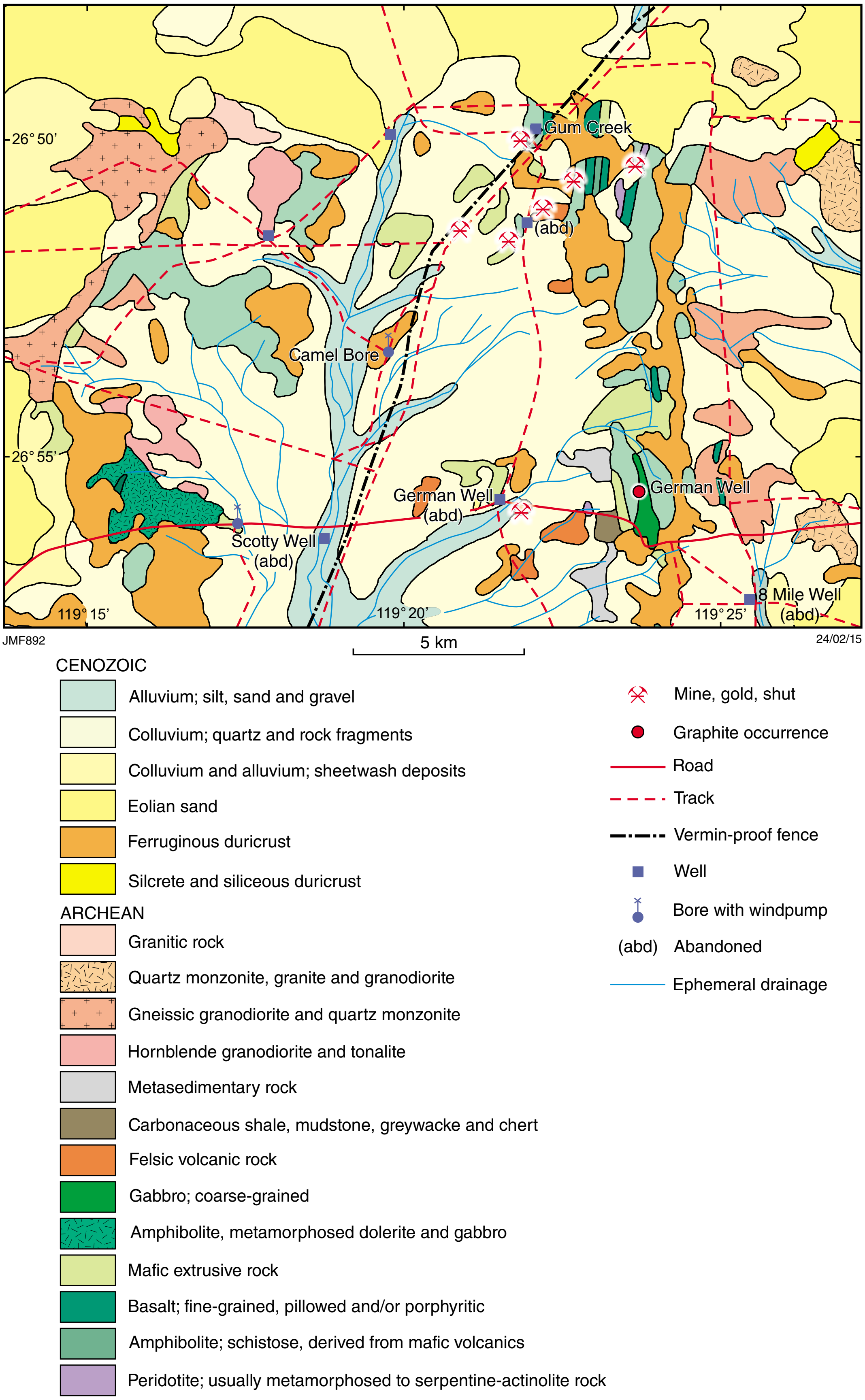



**Figure 40. Geological map of the area surrounding the German Well occurrence (modified after Bunting et al., 1981)**

# CHAPTER 11 Yilgarn Craton — South West Terrane

The South West Terrane of the Yilgarn Craton, shown in Figure 1, is partly composed of a number of highly deformed, Archean gneissic complexes comprising metasedimentary rocks, quartzo-feldspathic gneiss, amphibolite, calc-silicate gneiss, and ultramafic rock. These rocks have been mostly metamorphosed to amphibolite facies with local granulite assemblages of orthogneiss and paragneiss.

These older gneissic rocks have been intruded by two younger groups of Archean granites that form the largest component of the South West Terrane. The older of these granitic groups comprises weakly to moderately deformed granites metamorphosed to granulite or upper amphibolite facies, and the younger, late Archean group is made up of less-deformed granites, either partly or fully recrystallized to greenschist facies (Myers, 1990b). The southern half of the South West Terrane contains 11 graphite occurrences, a prospect, and two former graphite mines at Donnelly River (Fig. 41).

## Beverley region

Simpson (1951) identified three areas of graphitic mineralization in the area extending from Balkuling to Doodenanning and Greenhills northeast of the town of Beverley, and approximately 115 km east of Perth (Fig. 41). In this area, graphitic flakes have been reported from highly kaolinized rocks, originally Archean gneiss, and metasedimentary rocks.

### Balkuling occurrences

Simpson (1951) reported two graphite sites in the Balkuling area comprising minute flakes of graphite scattered through kaolinized rocks. The first of these is at Location 11008, approximately 4 km north-northwest of Balkuling (Fig. 41). The second site, stated to be on Location 11004, was not identified in this area.

At Location 11008, a graphitic kaolin pit contains minute graphite flakes distributed through completely kaolinized, foliated rock of possible metasedimentary origin. A specimen collected by Simpson from this site was found to contain 5% graphite flakes less than 0.2 mm in diameter, although a bulk sample of the same type of kaolinized material from Location 11004 contained almost 10% graphite.

### Doodenanning occurrence

The Doodenanning graphite occurrence is about 11 km northeast of Kauring (Fig. 41). At this site Simpson (1951) collected two different types of graphitic rock. One specimen contained 5.6% of fine, scaly graphite distributed through a white kaolinite rock. The second sample consisted of a coarser flake graphite (18.7% TGC) contained in a highly kaolinized, iron-stained, foliated rock.

### Greenhills graphitic zone

A graphitic zone in the Greenhills area extends for up to 20 km in an east-northeasterly direction from Greenhills railway siding towards Doodenanning (Fig. 41). In this zone, areas of completely kaolinized, slightly foliated, pale-grey rock contain fine to medium-grained flake graphite crystals interleaved with mica and limonite. Tests revealed the material contained 8.7% TC and approximately 10% of the flake graphite exceeded 0.6 mm in diameter (Simpson, 1951).

## Borden area

### Woolaganup Creek occurrence

This graphite prospect is in the area of Woolaganup Creek, adjacent to the Pallinup River, about 20 km south of Borden (Fig. 41). In this area, specimens of soft, ferruginous clay rock were collected by Simpson (1951). These rocks, with graphite flakes up to 2 mm in diameter, contained 8–14% TGC although the overall assessment was the material was of low grade, as it was interleaved with mica and limonite. At Location 1766, approximately 3 km to the east-northeast, Simpson (1951) also reported an outcrop of relatively unweathered granitic gneiss containing 8% of fairly coarse graphite flake, and a quartz vein containing a small proportion of scattered graphite flakes 1–2 mm diameter.

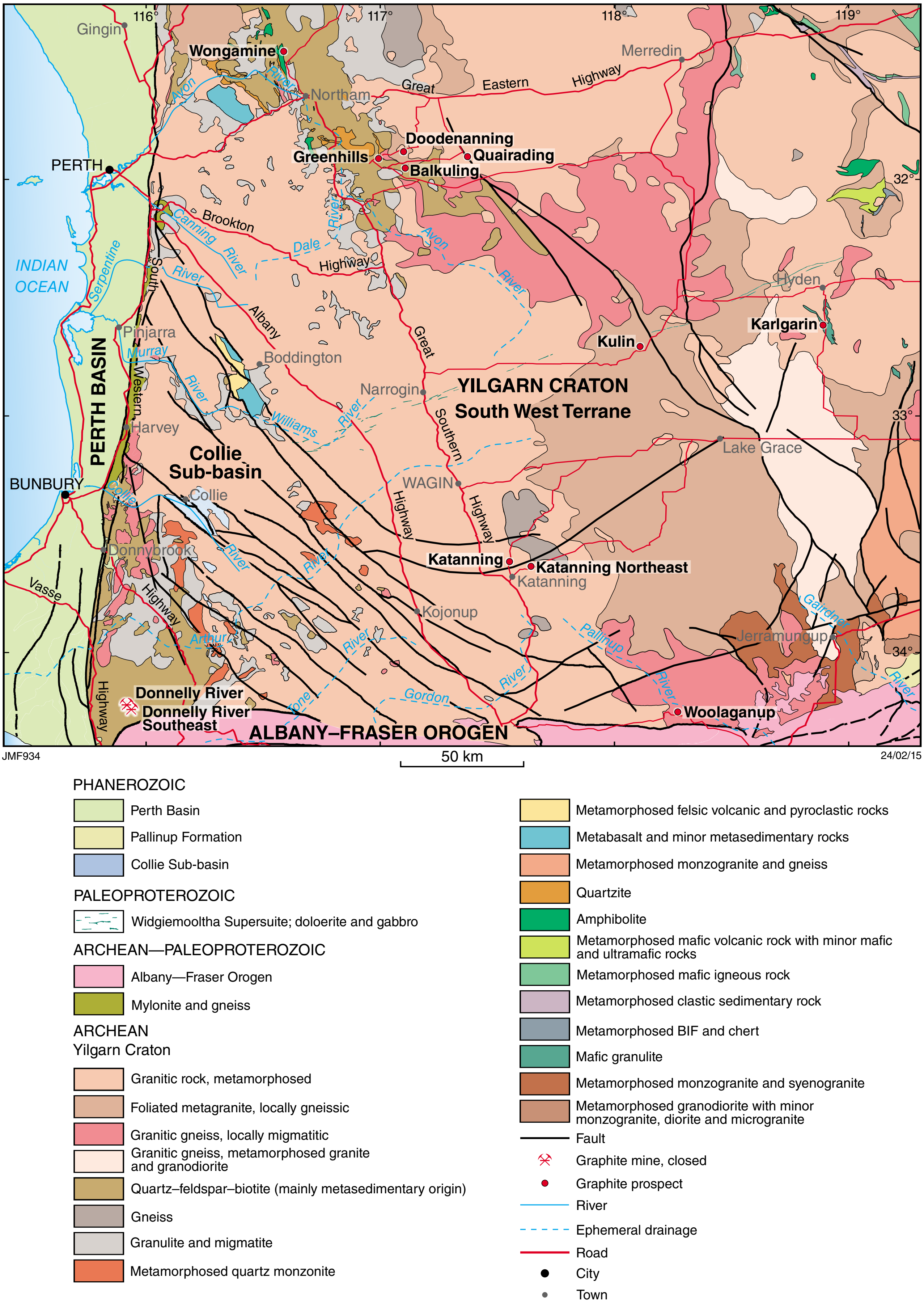



**Figure 41. Graphite localities in the South West Terrane, Yilgarn Craton (modified after Martin et al., 2014)**

# Karlgarin area

## Karlgarin occurrence

Graphite was reported 19 km south of the town of Karlgarin in the eastern wheatbelt (Chin et al., 1984) (Fig. 41). At this site on the eastern side of Aylmore Road, disseminated flakes of graphite are present in Archean, graphite–muscovite schist and phyllite and make up about 10% of the rock.

# Katanning area

## Katanning prospect and occurrences

Blatchford (1918b) reported the location of a graphite prospect and two occurrences close to the Dumbleyung–Katanning Road, about 8 km north of the town (Fig. 41). The principal site, the Katanning prospect, on Location 299, contained four exploratory shafts sunk to depths ranging from 3 to 14 m. The shafts were sunk in very weathered granitic or pegmatitic rock overlain by ferruginous duricrust. Small specks of flake graphite were distributed through the weathered rocks and also in nodular ferruginous duricrust at the surface.

Two other shafts were also sunk on the adjoining block to the north. These shafts, of 8 and 14 m depth, were sunk into the decomposed rock and once again, contained small graphite flakes distributed through the weathered granitic or pegmatitic material. A minor occurrence on Location 296, about 2 km to the east, contained specks of graphite flake in ferruginous duricrust.

## Katanning Northeast occurrence

The Katanning Northeast graphite occurrence is about 10 km northeast of Katanning on Location 4285, adjacent to Warren Road (Fig. 41). At this site, graphite was found in ferruginous duricrust and also in the underlying, very fine grained rock, possibly granitic gneiss. Most graphite was found close to local dolerite dykes, disseminated as fine flakes in the granitic rock and within the dykes. No graphitic concentrations in veins or within the granitic rocks were located at this site (Blatchford, 1918b).

# Kulin area

## Kulin occurrence

Simpson (1951) reported a granitic gneiss adjacent to the railway line, 6.5 km southwest of Kulin, containing up to 2.7% graphite in the form of lenses and scattered flakes (Fig. 41).

# Manjimup region

## Donnelly River mining area

The Donnelly River mining area is in the southwest of the State, about 20 km west of Manjimup and 2 km west-southwest of One Tree Bridge (Figs 41, 42). In 1882, graphite was discovered at the Donnelly River site, originally named 'Graphite Hill'. Shortly after the initial discovery, Woodward (1895) reported that 1.27 ton had been sent to England for testing.

### Geology

The Donnelly River deposit is in an area of high-grade metamorphic rocks formerly known as the Balingup Gneiss Complex in the extreme southwest corner of the Archean South West Terrane (Fig. 1). The metamorphic rocks mostly consist of metasedimentary rocks comprising interlayered quartzite, quartz–mica schist, banded quartz–feldspar–biotite–garnet gneiss, and BIF, together with minor quartzofeldspathic gneiss, amphibolite, calc-silicate gneiss, and ultramafic rock (Fig. 41). In addition, about 30% of this area is orthogneiss largely derived from deformed porphyritic granite.

### Mining operations 1904–16

From 1904 to 1916, efforts were made to develop the Donnelly River deposits into viable commercial enterprises. The first recorded graphite mining took place in 1904 when HJ Saunders opened a mine in the area and the first 65 ton of graphite was shipped to New York, USA. The material was tested by a number of graphite manufacturers and it was agreed that the graphite was too fine grained and the flakes too resistant in the concentration process for the material to be commercially viable (Sydney Morning Herald, 2004).

#### *Donnelly River Southeast*

Early in 1905, a mining operation was established at Donnelly River Southeast, about 1.5 km southeast of the Donnelly River mining area (Fig. 42). The Donnelly River Graphite Company established this operation on adjoining mineral claims MC70/26H (known as 'The Donnelly') and MC70/28H (known as 'Graphite Boulder'). At least four shafts were sunk on these leases although little is known about graphite production except for a brief mention in the West Australian newspaper of 9 August 1905 about shipping 180 bags of the company's graphite from Fremantle.

#### *Donnelly River mining area*

Operations at the Donnelly River mining area commenced soon after in 1905 with many operators opening many shafts and costeans on Graphite Hill, which continued until 1916 (Fig. 42). Of these operations, one of the best known was owned by the West Australian Graphite and Plumbago Company (also known as the Western Australian Graphite, Black Lead, and Plumbago Company Ltd).

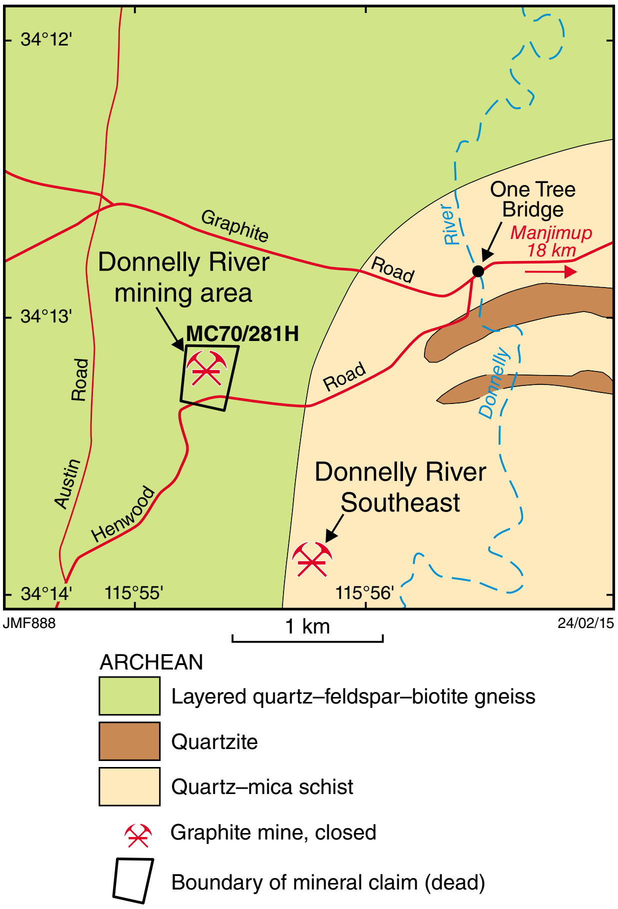



**Figure 42. Geological sketch map of the area around the Donnelly River graphite mining operations (modified after Martin et al., 2014)**

In April 1905, the company, headed by Mr Louis Benari, commenced operations. The West Australian newspaper announced on 1 August 1905 that of the company's initial production of 9 ton of graphite, 5 ton was for export to the USA, and the remaining 4 ton would be sent to Perth where the company was setting up a small testing plant. Five years later, another newspaper report stated that the company had arranged to ship 20 ton of graphite to England and at the same time had 90 ton of first-grade and 200 ton of second-grade graphite in stockpiles on-site. The article also stated the 1910 price for best graphite was £7 10s/ton (Western Mail, 1910).

Simpson (1951) summarized the Donnelly River material as mostly composed of very finely divided graphite showing practically no structure and complete resistance to concentration by flotation without the use of oil. The material contained a very small proportion of flake graphite, of which the best flake (5.4%) assayed at 99.6% TC. This material had been extracted from graphitic ore containing 33.4% TC. Simpson also noted that up until 1950, samples from Donnelly River had been sent to leading international graphite product manufacturers for testing. In those early years, using testing technologies of the day, no suitable applications for the material could be found.

## Exploration 1943–'70s

The Donnelly River graphite deposit, on mineral claim MC70/281H, was evaluated by Ellis in 1943. He observed the graphite deposit was above a swampy creek on the southern and southeastern slopes of Graphite Hill (Figs 42, 43). At this site, three well-defined, clayey graphite horizons were present. These horizons were described as trending across the hillslope to the east-northeast and dipping 37° to the northwest. Total thickness of the graphitic zone was estimated at approximately 120 m. A partially collapsed vertical shaft of 4 m depth in the upper graphite horizon contained 2.1 m of clayey, graphitic schist overlain by 1.8 m of red concretionary clay. At the surface, graphite was conspicuous being contained in ferruginous duricrust overlying graphite-rich chloritic schist (Ellis, 1952). Later laboratory testing showed that graphite contained in this deposit ranges from amorphous (an extremely fine-grained form of graphite) to medium-grained, flake graphite. The graphite flakes were commonly intimately mixed with quartz, feldspar, mica, clay, and iron oxide impurities (Carruthers, 1988). In past years these impurities had limited the effectiveness of the graphite recovery process and the uses to which the refined material could be applied.

During 1940–43, 18 ton of graphite was produced from the Donnelly River mining area (Carter, 1976).

## Exploration 1984–88

More recently, the site has been prospected for its graphite potential in 1984–86 by O'Brien and Giacci Bros Pty Ltd (O'Brien, 1985), and in 1986–88 by Cable Sands (WA) Pty Ltd, (Carruthers, 1988). O'Brien (1985) describes five graphite lodes identified, and the construction of tracks and costeans followed up by a program of reverse circulation drilling. The graphite lodes — Creek Lode (not previously worked), Lower Lode (the principal lode), and North West, Centre, and Top Lodes — are shown in Figure 43. The drilling program revealed that most lodes were capped on the hangingwall by a layer of hard, ferruginous duricrust, which limited the effectiveness of this form of investigation.

According to O'Brien (1985), the principal graphite body (Lower Lode) has a proven strike length of more than 100 m with a true thickness varying from 6 to 11 m. Vertical percussion drillhole DR6, shown in Lower Lode cross-section G–H, encountered 18 m of good-grade graphite, although the true thickness of the lode was estimated at around 11 m (Fig. 43). Lode samples yielded a carbon content ranging from 25 to 30% TC; however, it was thought that the overall grade would be closer to 20% carbon because of clay and soil contamination within the walls of the upper portion of the lode, although the grade may improve at depth. Based on a minimum depth of 10 m, it was estimated that about 9000 $m^3$ of ore could be extracted from the Lower Lode orebody with the potential to yield about 2000 $m^3$ of high-grade, fine-grained (amorphous) graphite after processing.

O'Brien (1985) considered the North West and Centre Lodes as part of a single, reverse folded orebody with a

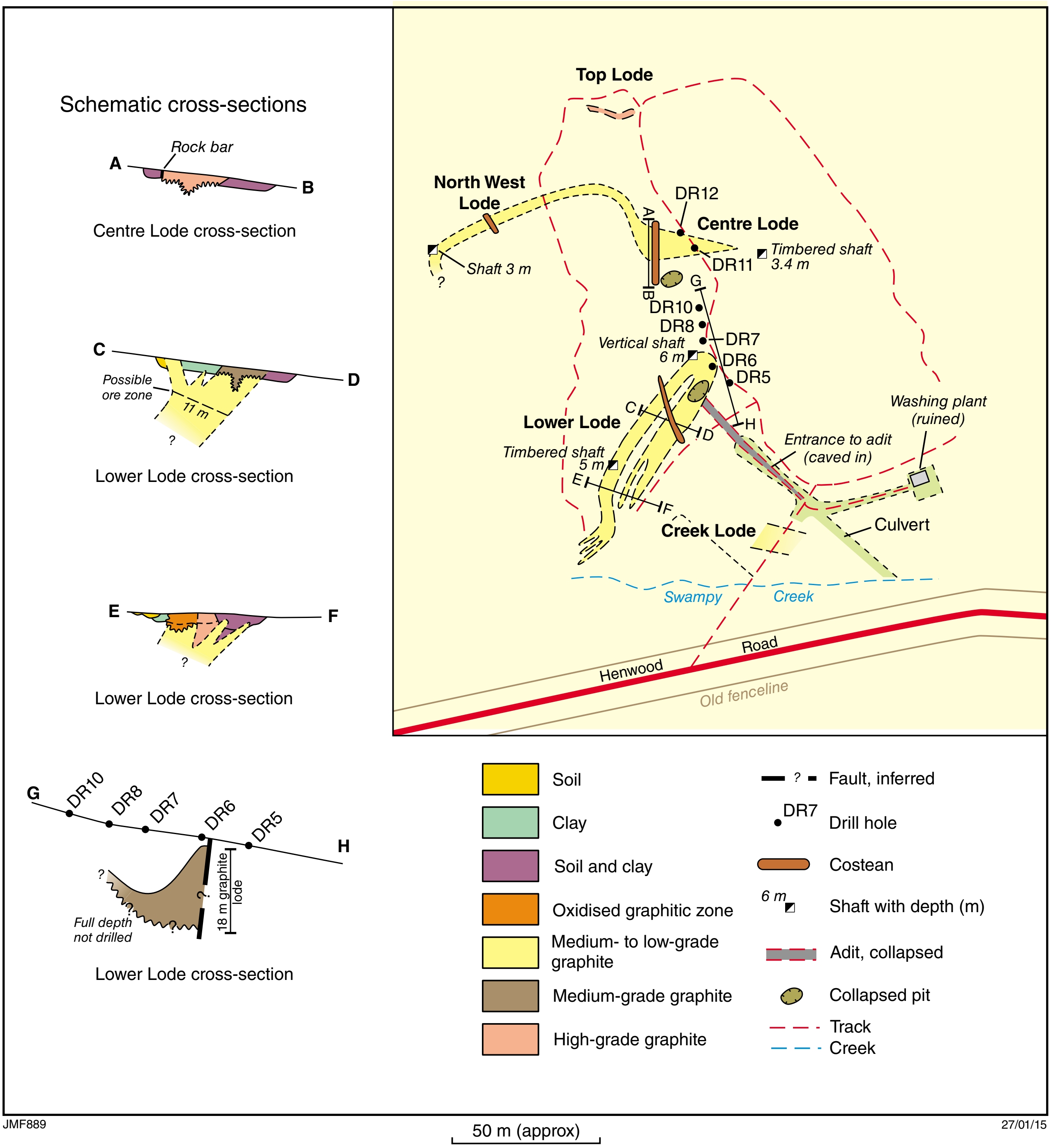



**Figure 43. Interpreted sketch map of the Donnelly River lodes (modified after Carruthers, 1988)**

strike length of at least 130 m and a thickness at depth ranging from 4 to 10 m. More evaluation is required to assess the graphite resource of this structure.

The Top and Creek Lodes were not fully tested in 1985, although it was noted that the Top Lode orebody was about 3–4 m thick with a strike length of 30–40 m and appeared higher grade with less clay than other lodes tested. The southernmost orebody, the Creek Lode, was investigated by drilling five shallow drillholes and a costean, which indicated the prospect contained clayey, low-grade graphite (Fig. 43).

In 1988, a second phase of exploration was carried out at the Donnelly River site. In the first instance, Carruthers (1988) made a preliminary estimate of the graphite resource that may be present in the four lodes at the Donnelly River site. These estimates were based on the approximate dimensions of mineralized zones of the four known graphite lodes and are shown in Table 6 as minimum and maximum estimates.

**Table 6. Graphite resource estimates from Donnelly River from 1988 exploration**

| *Estimate* | *Minimum* | *Maximum* |
|---|---|---|
| Total graphite volume ($m^3$) | 35 100 | 132 000 |
| Total graphite ore (t) | 50 000 | 200 000 |
| Total refined graphite (t) | 10 000 | 40 000 |
| Grade (% TC)[(a)] | 20 | |
| Bulk density ($t/m^3$) | 1.5 | |

**NOTE**: (a) Percent total (fixed) carbon % TC

Carruthers (1988) also proposed that by using a combination of flotation and gravity separation processes, it might be possible to obtain a refined graphite product of fine- to medium-grained, flake material (up to 90% TC) of 20 000 t (minimum) and 80 000 t (maximum).

### *Geophysical EM survey*

Also in 1988, a geophysical EM frequency domain survey was carried out to establish buried carbon conductors based on graphite's high electrical conductivity. The EM survey, carried out over a 100 m line spacing with a station interval of 25 m, highlighted three areas of buried conductors of primary interest (indicated by negative EM values) in addition to areas of known mineralization. Two additional buried conductors of secondary interest were also discovered (Fig. 44). According to Carruthers (1988), this discovery has the potential to exceed the previous preliminary resource estimates of graphite ore to 100 000 ton (minimum) and 400 000 ton (maximum).

# Quairading area

## Quairading occurrence

Simpson (1951) reported graphite (3%) in ferruginized rock and small quartz veins in an area of Archean gneiss, quartzite, and metamorphosed BIF approximately 12 km north-northwest of Quairading (Fig. 41).

# Toodyay area

## Wongamine occurrence

The Wongamine graphite occurrence is adjacent to Bejoording Road about 15 km northeast of Toodyay (Fig. 41). The graphite occurrence, associated with the historic Wongamine gold find, is sited on Location M513, directly north of the boundary of Location M499, which contained the former gold prospect. At this site, Feldtmann (1932) records several schistose bands of graphitic and ferruginous rock about 6 m in width, trending in a north–south direction. Later, Simpson (1951) described this zone as a siliceous gossan or ferruginous duricrust that contained small pockets or lenses of almost pure, fine-grained flake graphite. Simpson (1951) also described other sites on Location M499 as containing hard, white, brecciated kaolin containing streaks of very fine grained graphite, or as highly kaolinized graphitic schists.

The highest grade specimen collected from the Wongamine area yielded 12% TGC although it yielded only 1% of flake graphite in excess of 0.2 mm in the concentrate produced (Simpson, 1951).

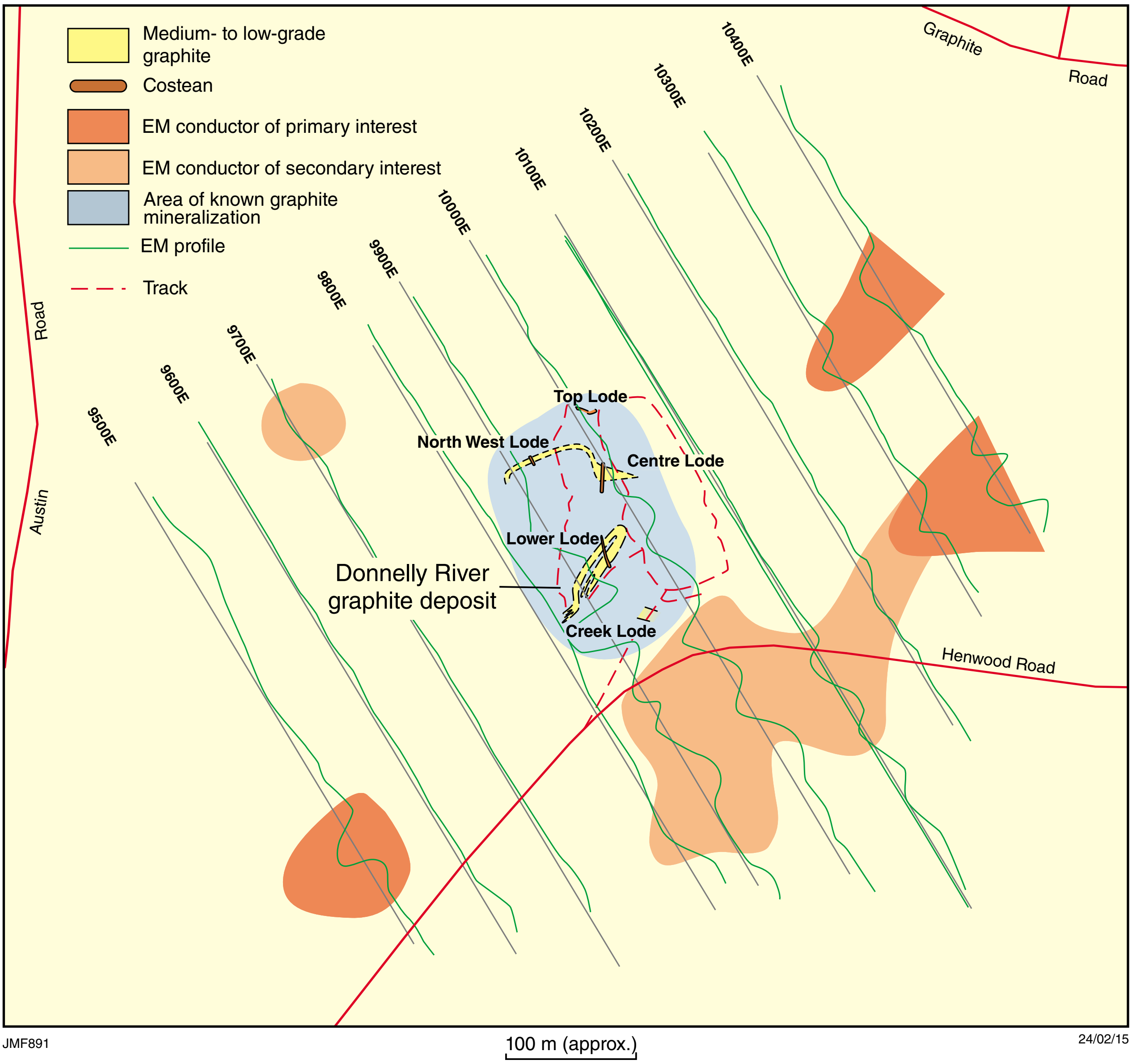



**Figure 44. Sketch map of the Donnelly River EM (electromagnetic frequency domain) survey showing possible carbon-conductive graphite zones (modified after Carruthers, 1988)**

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# INDEX OF GRAPHITE LOCALITIES

# APPENDIX 1 Graphite sites in Western Australia

| *Tectonic unit* | *Locality* | *Mine, prospect or occurrence* | *MGA easting* | *MGA northing* | *Zone* |
|---|---|---|---|---|---|
| Albany–Fraser Orogen | Albany area | Napier Creek occurrence | 587828 | 6145159 | 50 |
| | Buningonia area | Buningonia prospect | 562700[(a)] | 6519680[(a)] | 51 |
| | Fraser Range area | Fraser Range 1 | 542131 | 6517762 | 51 |
| | | Fraser Range 2 | 538133 | 6514034 | 51 |
| | Mount Barker area | Kendenup mine | 556456 | 6180472 | 50 |
| | | Martagallup mine | 545582 | 6189095 | 50 |
| | | Mount Barrow occurrence | 569119 | 6167507 | 50 |
| | | Shaws mine | 562440 | 6180933 | 50 |
| | Munglinup area | Blatchfords prospect | 302519[(a)] | 6273904[(a)] | 51 |
| | | Halberts mine | 301486 | 6272977 | 51 |
| | | Halberts South prospect | 301873[(a)] | 6271382[(a)] | 51 |
| | | Harris prospect | 302038[(a)] | 6273523[(a)] | 51 |
| | | McCarthys mine | 301605 | 6273840 | 51 |
| | | Munglinup Central prospect | 301828 | 6269806 | 51 |
| | | Munglinup North prospect | 305381 | 6284725 | 51 |
| | | Whites prospect | 302097 | 6274469 | 51 |
| | Muirs Bridge, Frankland River | Furniss mine | 489480[(a)] | 6182405[(a)] | 50 |
| | Pallinup River area | Pallinup River prospect | 664570 | 6187986 | 50 |
| | Walpole region | Long Point occurrence | 461372 | 6123774 | 50 |
| | Young River area | Young River prospect | 313777 | 6286089 | 51 |
| | | Young River East prospect | 332216[(a)] | 6269093[(a)] | 51 |
| Glenburgh Terrane | Erong Springs area | Erong Springs occurrence | 447910[(a)] | 7178940[(a)] | 50 |
| | Mooloo Downs Station | Mooloo Downs East prospect | 429220[(a)] | 7230630[(a)] | 50 |
| | Dalgetty Downs Station | McIntosh Well prospect | 440043 | 7191649 | 50 |
| | Yalbra area | Coordewandy 1 occurrence | 416610 | 7160049 | 50 |
| | | Coordewandy 2 occurrence | 417050 | 7160300 | 50 |
| | | Northern Zone prospect | 432624 | 7174556 | 50 |
| | | Yalbra 1 prospect | 434927 | 7172850 | 50 |
| | | Yalbra 1a prospect | 435138 | 7172761 | 50 |
| | | Yalbra 2 prospect | 434269 | 7173180 | 50 |
| | | Yalbra 3 prospect | 436429 | 7172960 | 50 |
| | | Yalbra 4 prospect | 433820 | 7172080 | 50 |
| | | Yalbra 5 prospect | 432619 | 7172459 | 50 |
| Lamboo Province | Halls Creek region | McIntosh Target 1 | 382784 | 8047938 | 52 |
| | | McIntosh Target 2 | 384500 | 8050230 | 52 |
| | | McIntosh Target 3 | 383903 | 8051620 | 52 |
| | | McIntosh Target 5 | 389059 | 8054491 | 52 |
| | | McIntosh Target 6 | 390360 | 8053131 | 52 |
| | Mabel Downs Station | Black Rock prospect | 398295[(a)] | 8055000[(a)] | 52 |
| | | Mabel Downs prospect | 406658 | 8102115 | 52 |
| | Halls Creek region | Little Mount Isa | 381844 | 8001622 | 52 |
| Northampton Inlier | Ajana region | Mary Springs South mine | 271115 | 6924118 | 50 |

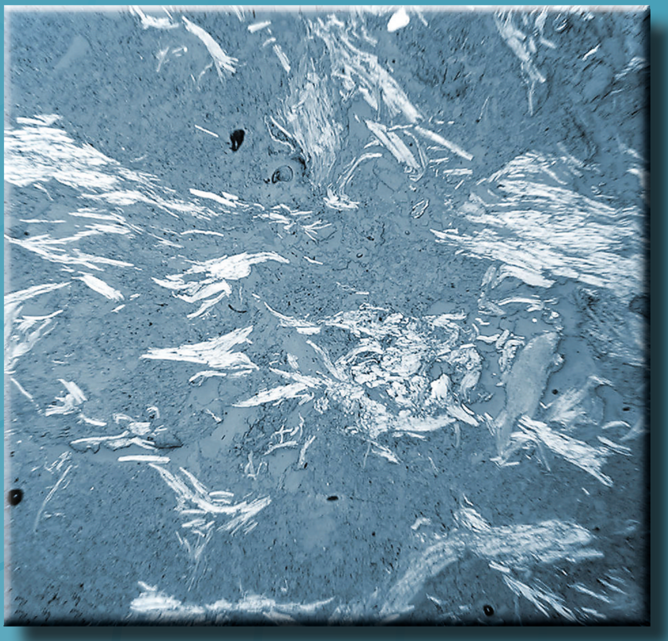
| Tectonic unit | Locality | Mine, prospect or occurrence | MGA easting | MGA northing | Zone |
|---|---|---|---|---|---|
| | | Pindadanno mine | 270682 | 6921006 | 50 |
| | | Geraldine East occurrence | 269131 | 6918228 | 50 |
| | | Warribanno occurrence | 270595 | 6914765 | 50 |
| | Northampton region | Isseka occurrence | 270048 | 6850106 | 50 |
| | | Normans Well occurrence | 273628 | 6853881 | 50 |
| | | Northern Gully occurrence | 295582[(a)] | 6832193[(a)] | 50 |
| | | Wanarenooka occurrence | 267756 | 6862847 | 50 |
| | | Wibi Well occurrence | 263167[(a)] | 6865174[(a)] | 50 |
| Paterson Orogen — Yeneena Basin | Rudall River region | Three Sisters occurrence | 392000[(a)] | 7513000[(a)] | 51 |
| | | Yeneena BM1 occurrence | 367988 | 7543122 | 51 |
| Paterson Orogen — Talbot Terrane | Kintyre area | Kintyre Rocks 5 occurrence | 407956 | 7528238 | 51 |
| | | Kintyre Rocks 7 occurrence | 408026 | 7528660 | 51 |
| | May Creek area | May Creek occurrence | 432000[(a)] | 7483700[(a)] | 51 |
| Paterson Orogen — Connaughton Terrane | Mount Cotton area | Mount Cotton occurrence | 459620[(a)] | 7476000[(a)] | 51 |
| Yilgarn Craton — Murchison Terrane | Dalgaranga area | Dalgaranga 1 prospect | 517459 | 6923769 | 50 |
| | | Dalgaranga 2 prospect | 515111 | 6925642 | 50 |
| | | Dalgaranga 3 prospect | 516732 | 6924478 | 50 |
| | | Dalgaranga 4 prospect | 517086 | 6924056 | 50 |
| Yilgarn Craton — Southern Cross Domain | Meekatharra region | German Well prospect | 737037 | 7019812 | 50 |
| Yilgarn Craton — South West Terrane | Beverley region | Balkuling occurrence | 509495 | 6464999 | 50 |
| | | Doodenanning occurrence | 509447[(a)] | 6472502[(a)] | 50 |
| | | Greenhills graphitic zone | 499332[(a)] | 6469285[(a)] | 50 |
| | Borden area | Woolaganup Creek occurrence | 617000[(b)] | 6209350[(b)] | 50 |
| | Karlgarin area | Karlgarin occurrence | 677694 | 6389992 | 50 |
| | Katanning area | Katanning prospect | 551324 | 6280247 | 50 |
| | | Katanning Northeast occurrence | 559713 | 6278010 | 50 |
| | Kulin area | Kulin occurrence | 603997[(a)] | 6380691[(a)] | 50 |
| | Manjimup region | Donnelly River mine | 400676 | 6212960 | 50 |
| | | Donnelly River southeast mine | 401406 | 6211679 | 50 |
| | Quairading area | Quairading occurrence | 535242[(a)] | 6470123[(a)] | 50 |
| | Toodyay area | Wongamine occurrence | 460855[(a)] | 6519373[(a)] | 50 |

**NOTES**: (a) Position approximate
(b) Position doubtful

Western Australia has many known graphite prospects. Previously, only small tonnages were mined, mostly from the Munglinup deposit in the far south of the State. Currently, two Australian companies are well advanced in the exploration for new high-grade, flake graphite deposits. In the east Kimberley region, the McIntosh deposit has been identified as having five high-grade graphite targets.

To date, open-ended McIntosh Target 1 has an identified resource of 7.135 Mt grading 4.73% total graphite. At Yalbra, in the central west of the State, six closely spaced graphite targets have been identified. Yalbra 1 is an open-ended target with a very high grade resource of 4.022 Mt grading 16.17% total graphite.

These potential mining operations, together with existing graphite deposits such as Munglinup, with an estimated resource of 1.47 Mt at 18.2% total carbon, should stand Western Australia in a favourable position for future exports of high-grade flake and finer grade graphite products into world markets.



Further details of geological publications and maps produced by the Geological Survey of Western Australia are available from:
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East Perth WA 6004
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