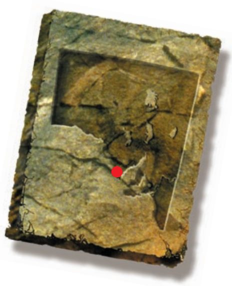


Uley graphite
— a world-class resource

John Keeling (Principal Geologist, Mineral Assessment Branch, Office of Minerals and Energy Resources, PIRSA)

Introduction

Uley Mine, 18 km west-southwest of Port Lincoln on southern Eyre Peninsula, is located in Australia's largest known resource of crystalline flake graphite, the Mikkira Graphite Province (Fig. 1). In 1993, the mine was placed on care and maintenance by International Carbon (Aust.) Pty Ltd following a sharp decline in world graphite prices in 1992. Since 1994, prices have stabilised at less than half those of 1991–92 and presently average US$500–550 (A$870–960) per tonne for crystalline flake graphite of 85–95% carbon content. For the past four years, the current owner, Eagle Bay Resources NL, has sought a purchaser or joint venture partner to reopen the mine. From a small number of expressions of interest, all from overseas companies, Eagle Bay announced in late 1999 that it had entered into a joint venture agreement with Harbin Liumao Carbon Technical Development (HLC) of China, currently the world's largest producer of graphite. HLC will earn a one-third interest in the mine through a $6 million refurbishment of the plant and a $0.5 million production trial expected to commence late in 2000.

Background

Graphite mineralisation at Uley was discovered in the 1910s and the Uley Mine has operated intermittently since the late 1920s. During the 1980s, exploration by CRAE Pty Ltd on EL 812 and 1139 identified substantial additional graphite resources. This led to reopening the mine from 1986 to 1993 and production by International Carbon of ~1000 t of graphite product (McNally, 1997). Indicated resources at Uley are 2.87 Mt grading 13% graphite, which include 1.49 Mt at 15% graphite (Rowe, 1993). Total resources of >350 Mt at 6–7% graphite were inferred by CRAE from geophysical surveys and drilling around Uley and at the nearby Salt Lake, Eastern, Kacey and Fishery prospects (McNally, 1997). These define the Mikkira Graphite Province (Fig. 1), an area of ~50 km^2, which contains the largest recorded graphite resource in Australia and a significant size resource in global terms.

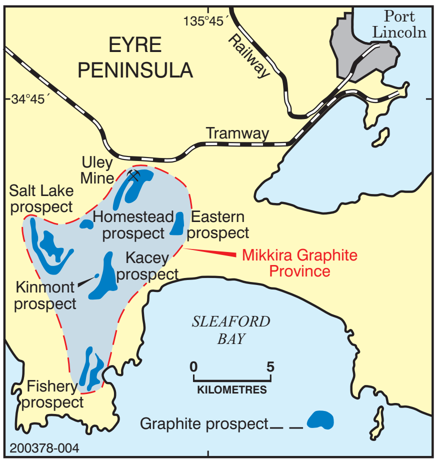


Fig. 1 Location of the Uley Mine and other prospects in the Mikkira Graphite Province, southern Eyre Peninsula.

Geology

Uley is a disseminated crystalline flake graphite deposit hosted by Proterozoic metasediments which were crystallised under upper amphibolite to lower granulite grade metamorphism. Graphite flakes of 0.1–2 mm occur within a sequence of biotite–quartz schist and medium to coarse-grained quartz–feldspar–biotite±garnet gneiss. The rocks are equated with Cook Gap Schist (Lower Middleback Subgroup) of the Hutchison Group metasediments of Palaeoproterozoic age (~1900–1850 Ma). Graphite ore zones (>6% graphite) are up to 12 m thick and are largely stratigraphic, being high-grade metamorphic equivalents of original carbonaceous sediments (Taylor and Berry, 1990). Graphite content of some ore lenses exceeds 30%.

The distribution of graphite at Uley was determined by airborne and ground electrical surveys, and 68 fully cored drillholes. The conductive graphite layers give a pattern of elongate anomalies that outline a broad north-northeasterly plunging anticline, consistent in style with D_3 folds mapped in Palaeoproterozoic rocks along eastern Eyre Peninsula. Open-pit mining operations during 1986–93 were sited on a strong anomaly centred over earlier underground workings located on the hinge of the anticline (Fig. 2). Only one other anomaly, immediately south of the pit, has been fully tested by drilling to confirm substantial additional reserves of graphite.

High-grade graphite ore shoot developed in a small-scale interference fold, eastern pit face, Uley Mine. (Photo 47519)

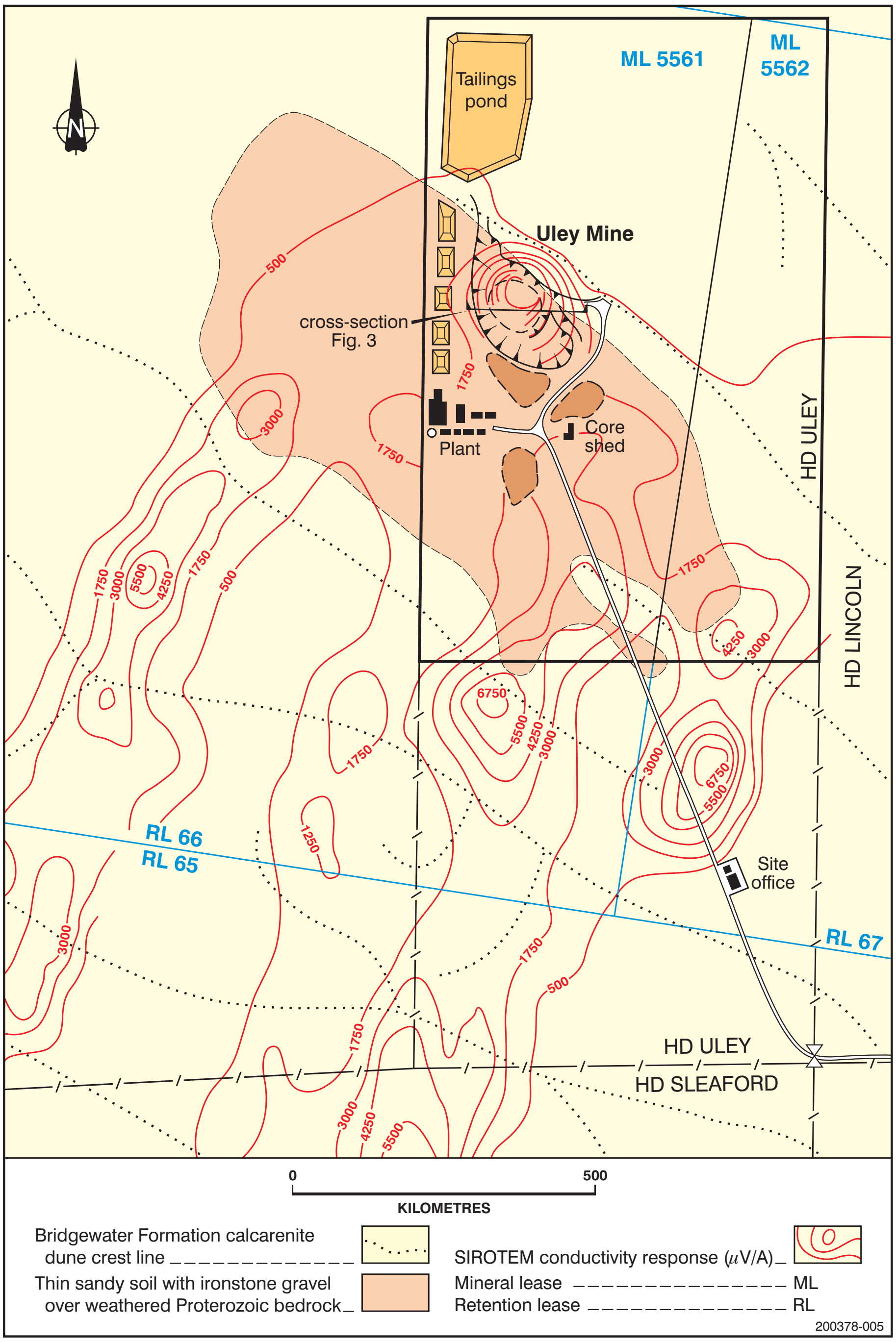


***Fig. 2** Uley Mine surface geology and contours of SIROTEM survey data used to outline subsurface graphite distribution.*

The main Uley pit is 120 x 100 m across by 20 m deep, and exposes graphite ore in highly weathered rock in which the primary silicate minerals (mica, feldspar and garnet) are largely altered to kaolin and iron oxides. Throughout the upper 10 m of the pit, patchy zones of calcite cement are present, and in places form massive hard bands to >1 m thickness. The cement which displaces and replaces kaolin and quartz was precipitated from vadose and phreatic groundwaters containing high levels of calcium leached from Bridgewater Formation calcareous dunes. These dunes, which cover large areas of basement rock on southern Eyre Peninsula, were formed by deflation of marine carbonate sediments exposed to erosion during low sea-level stands in Pleistocene and Holocene times.

Graphite production was principally from an 8–12 m thick, highly weathered biotite–quartz–graphite schist unit with finely interlayered gneissic bands and lenses. Geological mapping and drillhole data indicate that the graphite orebodies are a series of tightly folded graphitic gneiss and schist units that form part of an anticlinorium where the intervening synclines are largely attenuated by shearing along graphitic layers (Fig. 3).

Graphite ore in the plasmic weathering zone extensively re-cemented by groundwater carbonate. (Photo 47520)

Mining and processing

Previous operations at Uley involved contract mining by DK Quarries Pty Ltd of Port Lincoln using a bulldozer to strip overburden and a bucket excavator to extract the ore and waste rock. Graphite ore zones were outlined initially by fully cored holes drilled on an approximate 30 x 40 m grid. Grade control was by geological mapping and channel sampling across the pit floor. On-site sample preparation and analytical laboratory facilities were developed for graphitic carbon analyses.

Loading graphite ore by bucket excavator at the Uley Mine. (Photo 47521)

Stockpiled ore was fed by front-end loader onto a 250 mm fixed grizzly, then conveyed to a vibrating grizzly with 50 mm slots. Oversize from this was crushed in a Hazemag Impact Crusher and returned to the circuit. Clayey ore was broken down in a log washer with the aid of sodium silicate dispersant. The crushed ore was transferred to a large capacity holding bin from which the feed was controlled to a 2.4 x 3.6 m rod mill. The mill discharge was pumped to a cyclone then screened to provide

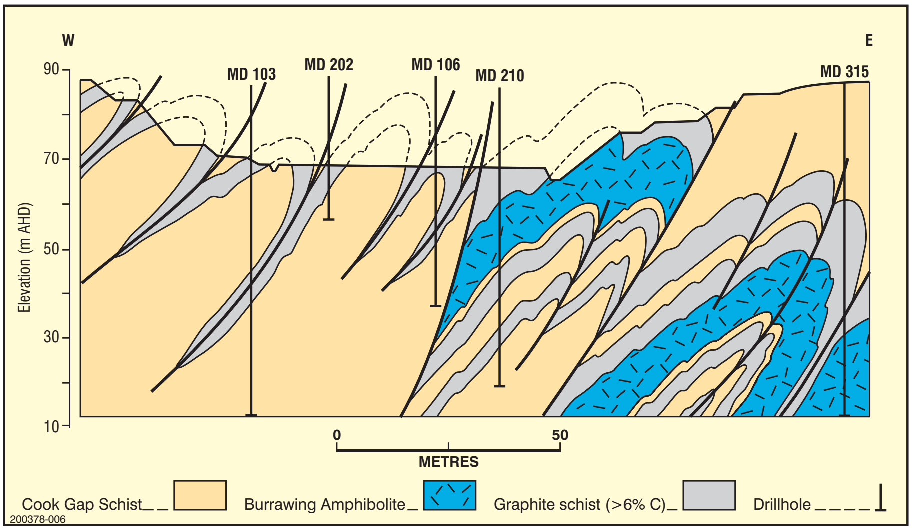


Fig. 3 *Geological cross-section showing graphite distribution in the Uley Mine area.*

classified feed at the required solids content for the beneficiation circuit.

Beneficiation was by flotation using rougher and scavenging tanks and four cleaning stages. Diesel fuel was the principal flotation reagent. Improved separation of graphite and gangue was achieved by rod milling the ore concentrate between cleaning stages. Small dedicated rod mills were used with a short residence time for the concentrate to minimise reduction of the graphite flake size. Concentrate from the flotation circuit was further upgraded using Wilfley tables to reduce impurities and control product grade. Clean product from the tables was passed through a wet, high-intensity magnetic separator (WHIMS) to reduce iron oxide content.

Beneficiated product at 30% solids was dewatered using a high-capacity thickener followed by centrifuge, dried using a fluid bed drier, and screened on a Rotex screen. Final product was bagged in multiwall paper bags or in bulker bags for dispatch. A range of graphite products were prepared in grades 85–94% C and flake sizes of 75, 150 and 250 µm (full details are provided in McNally, 1997, table 1).

HLC proposes modifications to the plant which will simplify the circuit and increase product output from a previous design of 14 000 t/year to 20 000 t/year. Higher volumes of fluid will be used to disperse and separate clay-sized contaminants with the aims of improving liberation of graphite flakes, increasing the recovery of coarse graphite, and minimising time spent in the primary grinding circuit. This will require much more water than in the previous operation. All process water for the plant is currently accessed from the Uley–Wanilla pipeline network which supplies Port Lincoln and much of lower Eyre Peninsula. Availability of this water resource is carefully monitored and quotas are applied to industrial uses. Process water is a significant cost component of the Uley graphite operation. For future mine operations, the possibility of using treated effluent water from Port Lincoln township is being investigated by engineering consultants Gutheridge, Haskins and Davey Pty Ltd.

Graphite markets

Total world production of natural graphite in 1998 was ~600 000 t (Kalyoncu, 1999). Of this, approximately half was crystalline flake with the remainder being microcrystalline (amorphous) graphite from metamorphosed coal seams, and ~1% crystalline vein graphite sourced entirely from Sri Lanka. China is the main producer of flake graphite followed by India and Brazil, with smaller but important production of quality grades from Madagascar, Canada and Zimbabwe. Almost half the world's crystalline flake graphite production is used in the manufacture of refractories, principally for the iron and steel industry. Magnesia–graphite (mag-carbon) refractories are used in basic oxygen steel converters and the slag line of electric arc furnaces. Alumina–graphite refractories are mainly used in continuous casting plants. Mag-carbon pressed bricks are the refractory of choice for the highly aggressive environment of the slag zone in steel furnaces. However, the overall improved performance and resultant longer life of refractories has seen a decrease in their production despite an increase in steel manufacture. Flake graphite content of mag-carbon refractories varies from 5 to 20%. Other graphite markets in foundries, brake linings, lubricants, batteries, electrical uses and crucibles show declining or only small growth demand for natural flake graphite. Any substantial growth for flake graphite in the short term is likely to be from increased demand for refractories. In particular, current research into development of an effective spray-on (gunnable) or castable mag-carbon refractory

Graphite concentrate being collected from flotation cells at the Uley Mine, February 1993. (Photo 47522) product offers significant potential cost savings over pressed bricks, and could substantially increase the demand for suitable grades of flake graphite.

Quality of Uley graphite

Based on this assessment of potential market growth, PIRSA commissioned CSIRO Manufacturing Science and Technology to undertake preliminary tests to compare Uley graphite with commercially available graphite currently preferred by refractory manufacturers. In mag-carbon refractories, graphite provides properties of a high melting point of 3500°C (under non-oxidising conditions) and resistance to wetting by molten slag, thereby retarding corrosion of the magnesia grains that comprise the bulk of the refractory brick. In the extreme environment of the slag zone in the upper part of the furnace melt, resistance to oxidation by graphite is crucial to extending refractory life. Oxidation resistance is essentially a function of particle size but may also be influenced by degree of crystal perfection and the thermal properties of contaminant phases present with the graphite. A measure of oxidation resistance therefore provides an indication of the relative performance of graphite sourced from different localities.

Flake graphite products produced at Uley during 1993 were examined together with commercial refractory graphite of similar size and grade from Canadian and Chinese sources. Differences and similarities in graphite crystallinity and chemistry of ash phases were compared and related to oxidation rate at selected temperatures over the range 750–900°C. All samples showed a high degree of graphite crystallinity and, at 900°C, oxidised at similar rates. Variation in oxidation rate at lower temperatures correlated most closely with small differences in particle size, graphite crystallinity and the amount of ash phase present. Differences in ash chemistry and the relative refractoriness of ash phases appeared to have little influence on the rate of graphite oxidation. For all samples there was a sufficiently high degree of similarity in crystallinity and oxidation behaviour to indicate that Uley graphite should find acceptance in a wide range of refractory applications including mag-carbon products (Hoad and Stone, 1998; Hoad *et al.*, in prep.).

Geological factors affecting graphite grade and recovery

Graphite is essentially inert and extremely stable to chemical weathering in the natural environment. At Uley, graphite is present throughout the weathering profile and graphite grades show no evidence of variation due to weathering processes. Therefore, no differentiation of graphite ore was made in initial mining operations during the late 1980s. During a lengthy commissioning and fine tuning of the beneficiation plant, difficulties were experienced in achieving consistent graphite product grade and quality. Ultimately, an important cause of variation was traced to the presence of carbonate impurity in some of the graphite ore (Keeling *et al.*, 1992). Upgrading the beneficiation circuit and exclusion of carbonate-cemented ore during 1992 resulted in significant improvement in the consistency of graphite recovery and grade.

Following closure of the mine in 1993, the company retained a small team to complete a detailed analysis of the grade and recovery characteristics of graphite ore intersected in the latest drilling program of 30 holes. Results from these tests were taken, together with data obtained from two student Honours projects sponsored by PIRSA (Dunne, 1996; Pugh, 1999), to evaluate the effects of weathering and structural geology on Uley graphite and how this impacts on the recovery, quality and grade of graphite separated in the plant.

Weathering

Uley Mine is situated on a bedrock high surrounded by dunes of Bridgewater Formation (Fig. 2). A thin sandy soil with ferruginous pisoliths and gravel fragments overlies deeply weathered bedrock. The weathered profile was subdivided into five zones — mottled, plasmic, saprolite, saprock and fresh rock (Fig. 4). Fresh rock is only observed in drill core at depths >50 m below ground surface. A sixth unit (carbonate zone) is recognised as an irregular zone of groundwater carbonate cement which

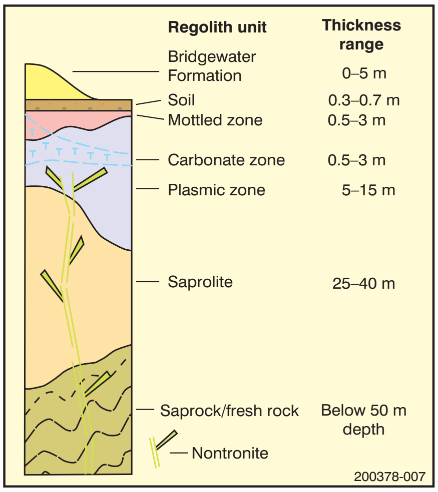
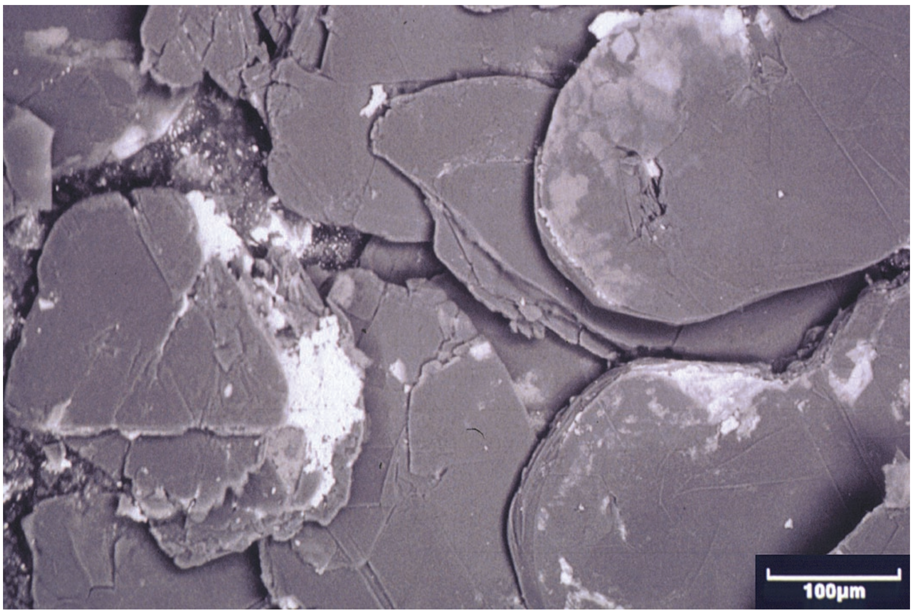


Fig. 4 *Generalised section showing the relationship between regolith units and the distribution of nontronite formed by hydrothermal alteration.*



Electron micrograph showing calcite contaminant (white) in graphite product recovered from ore in the carbonate zone. *(Photo 47523)* overprints part of the mottled and plasmic zones.

The graphite intervals from 12 drillholes were examined and categorised with respect to the weathering subdivisions. Results of head grade, grade of flotation concentrate, flotation recovery and graphite particle size were compared and averaged for samples in each category (Figs 5a,b). While the average grade of graphite from the various zones is similar at ~12% C, the grade of the flotation concentrate is significantly lower for graphite from the carbonate and fresh rock zones due to trapped impurities. For the carbonate zone, the poor concentrate result is compounded by lower than average graphite recovery and a high generation of graphite of fine particle size (<150 µm). Ore from the plasmic and saprolite zones provides the most consistent product. The coarse flake index (CFI), derived from screen size analysis, provides a comparative measure of flake size in which the higher CFI number indicates a higher proportion of large diameter flakes. The results show that a minimum reduction in flake size is achieved for ore from the saprolite zone (Fig. 5b). While the bench flotation tests do not duplicate the levels of grinding and upgrading done in the plant, the results clearly underscore the need to adopt mining practices that take account of variations inherent in the different weathering zones.

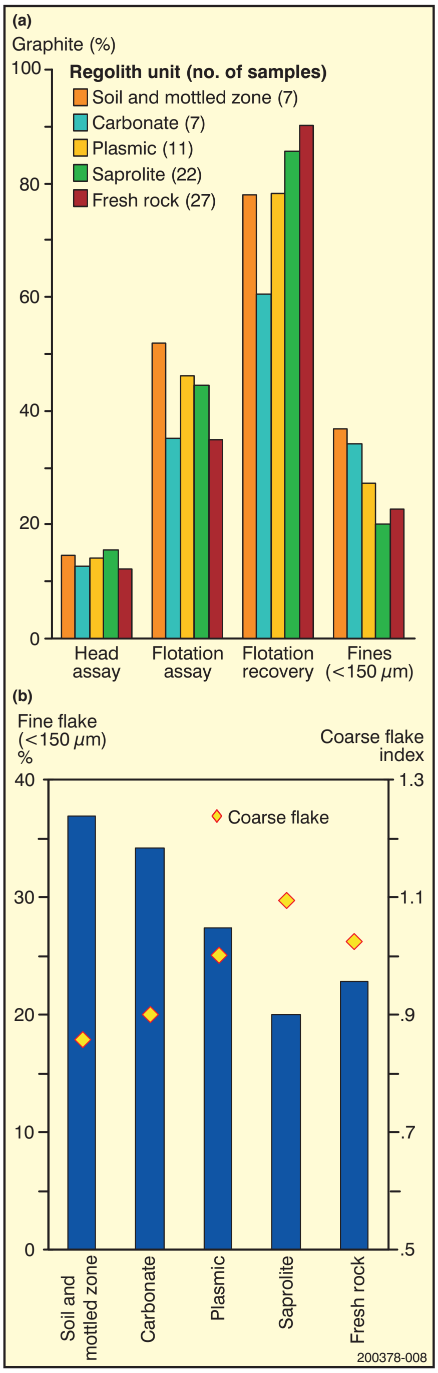


Fig. 5 (a) Influence of weathering on graphite grade and recovery. (b) Effect of weathering on graphite flake size.

During the course of investigations, it was shown that the weathering profile at Uley overprints an earlier hydrothermal alteration characterised by nontronite, an iron-rich smectitic clay (Keeling *et al.*, in press). Bright green and dark brown nontronite infill vein and fracture networks, and replace patches of biotite in graphitic schist. The nontronite is readily separated from graphite but needs to be monitored in the plant feed. High levels of nontronite could increase the viscosity of the slurry to the point where the need for dilution affects the plant settings for optimum graphite recovery.

Structure

The influence of geological structure on graphite grade and recovery was assessed in a manner similar to that used for weathering. Only samples from the plasmic to fresh rock zones were included. These were categorised on visual estimates of intensity of shearing. The results show that, while the grade of graphite ore in highly sheared zones is generally lower, the effect of shearing on recovery and particle size is comparatively minor (Fig. 6).

Observations in the pit suggest that other structural factors do influence graphite particle size but are mostly small-scale or localised effects that were not differentiated in the drillhole sampling. In particular, the coarsest graphite flakes were observed marginal to pegmatite lenses, formed by localised melting, and in the hinges of small-scale folds generated by interference of D_3 and D_4 fold structures. By contrast, graphite incorporated in late-stage, high-angled fault breccia is typically very fine grained.

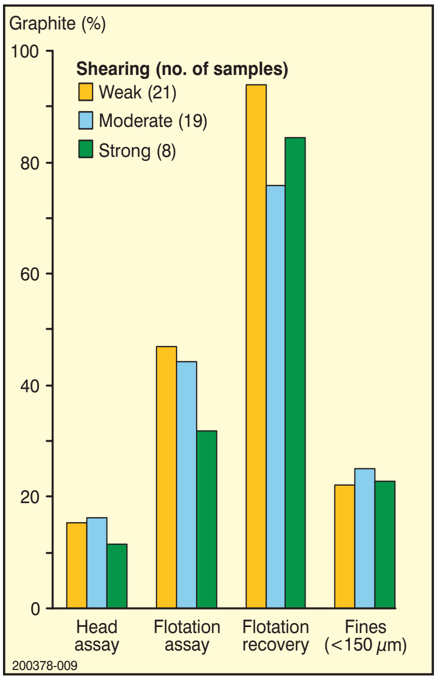


Fig. 6 Influence of structural geology on graphite grade and recovery.

The experience of mining operations during the early 1990s and subsequent studies provide a comprehensive picture of the factors controlling graphite distribution, quality and recovery. The data support views expressed by others with past involvement in Uley mining operations of the unrealised potential of this very substantial resource. In the short term, developments to revive the mine will focus on reducing mining and processing costs. Knowledge gained to date is critical to the success of this process and to maintaining or improving graphite recovery and grade. Market demand for flake graphite and developments in the refractories industry, in particular, will influence the longer term future of the mine and ultimately any new developments in the huge Mikkira Graphite Province.

Acknowledgements

Access to the Uley Mine for student projects was encouraged and facilitated by Tony Rechner, Managing Director, Eagle Bay Resources NL and supported on site by Mel and Elaine Wilson.

For further information contact John Keeling (ph. 08 8463 3135) or Tony Rechner, Eagle Bay Resources NL (ph. 09 481 3322).

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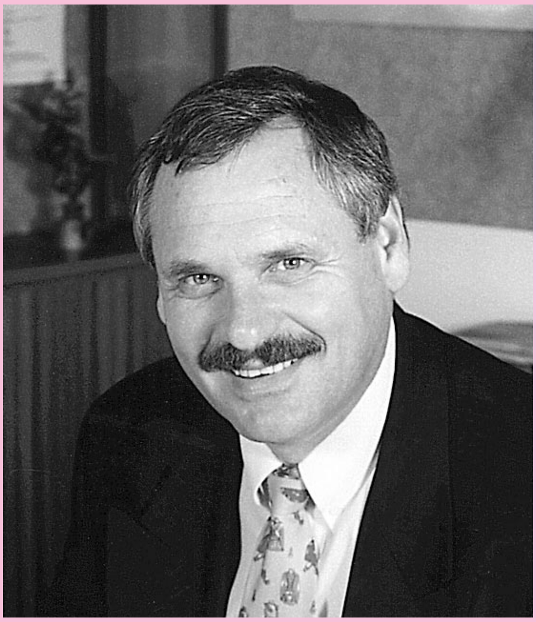
Dr David Blight

Executive Director, Office of Minerals and Energy Resources

Dr David Blight has been appointed Executive Director of the Office of Minerals and Energy Resources in PIRSA, and will be instrumental in providing a greater focus on mineral and petroleum exploration and production in SA as he implements the recommendations of the Government's Response to the Resources Taskforce Report.



Dr David Blight, Executive Director, Office of Minerals and Energy Resources. (Photo 47524)

David brings to the position considerable experience in both the public and private sectors of the geoscience industry. Between 1976 and 1982 he worked for the Geological Survey of WA, initially as a petrologist. Later he undertook regional mapping, an experience that gave him a good understanding of the importance of regional maps and availability of data sets to unlock the mineral potential of that State. He has co-authored three 1:250 000 geological map sheets with explanatory notes, and is the author or co-author of several papers on metamorphic geology in WA.

From 1982 to 1994, David held senior positions with several mining companies, including Union Oil Development Corp. Ltd, Hampton Australia Ltd, Noble Resources, and Dallhold Resources operating in SA, WA and NT. In May 1994, he accepted the position of Deputy Director of the Geological Survey of WA, and was appointed Director in May 1998.

During the late 1980s and early 90s, David and his family spent several years in Kalgoorlie during the boom time in gold exploration, when there were announcements of new gold discoveries. At that time he also chaired the Management Committee of the Museum of the Goldfields.

David comes from Adelaide and undertook his tertiary studies at the University of Adelaide, where he graduated with a BSc (Hons) in geology and chemistry, and was awarded a PhD in 1975. His work in Antarctica provided the basis for his doctorate thesis.

His other interests include scuba diving and wining and dining. He is married with two children.