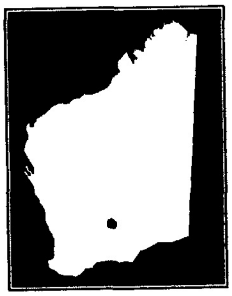

GEOPHYSICAL INVESTIGATIONS OF THE KALGOORLIE GOLDFIELD, WESTERN AUSTRALIA

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ABSTRACT

Leases held by Kalgoorlie Consolidated Gold Mines Pty Ltd over the Kalgoorlie Goldfield have an approximate area of 30 by 10 km, with the main production areas of Fimiston, Mount Charlotte and Mount Percy within the central portion of this tenement block. Due to the proximity of the leases to residential areas, significant portions of land are inaccessible for exploration. Near-surface contamination, as a result of historical mining and prospecting, also presents problems, as do the deep weathering profile and associated conductive overburden, which covers most of the Kalgoorlie Goldfield.

Due to the relatively small size of the lease holdings and the constraints detailed above, the currently employed geophysical techniques mainly involve detailed ground surveys and include petrophysical studies of the three principal styles of mineralisation and the surrounding host rocks. The aims of the surveys are improved definition of geological features, and indirect detection of the three principal styles of mineralisation recognised at Fimiston (Golden Mile), Mount Charlotte and Mount Percy.

The petrophysical data indicate that gravity, magnetics and induced polarisation can be used for the delineation of rock types whereas induced polarisation has potential to identify mineralisation. The combination of gravity and ground magnetic surveys at a prospect scale permits considerable refinement of the structural and lithological features in areas of poor outcrop. Studies are ongoing evaluating the potential use of downhole induced polarization for detection of Mount Charlotte-style stockwork mineralisation, and the use of ground penetrating radar to detect voids for underground mining.

KEY WORDS: Archaean lode gold, Eastern Goldfields Province, gravity, magnetics, induced polarisation, Kalgoorlie SH51-9, Kurnalpi SH51-10, petrophysics

INTRODUCTION

The Kalgoorlie Goldfield is located 595 km east of Perth, and immediately east of the city of Kalgoorlie-Boulder (Fig. 1). Gold was discovered in the area in 1893 and mining has continued ever since, historically by labour-intensive underground methods, but more recently by large-scale mechanised open-pit and underground operations. A total of 43 million ounces of gold have been produced from over 142 Mt of ore, with current resources exceeding 18 million ounces. Annual gold production exceeds 600,000 ounces from open pit and underground operations at Fimiston, Mount Charlotte and Mount Percy.

Kalgoorlie Consolidated Gold Mines Pty Ltd (KCGM) holds tenements covering most of the Kalgoorlie Goldfield. The company was formed in 1989 to manage the gold-mining operations owned by Gold Mines of Kalgoorlie Ltd (50%) and Homestake Gold of Australia Ltd (50%). Before 1989, the Kalgoorlie Goldfield was mined and explored by a number of independent companies, resulting in fragmented lease holdings and restricted exploration programmes.

GEOLOGY

The Kalgoorlie Goldfield is within the Archaean Norseman-Wiluna greenstone belt which trends north-northwest (Fig. 1). The detailed geology of the area has been well documented by other authors (*e.g.*, Clout *et al.*, 1990) so only a brief description is given here.

The stratigraphy at Kalgoorlie consists of a sequence of komatiitic to high-magnesium to tholeiitic volcanic rocks (Hannans Lake Serpentinite, Devon Consols Basalt and Paringa Basalt) with minor interlayered sedimentary rocks (Kapai Slate), overlain by a volcanic-sedimentary package (Black Flag Beds). Intruding the volcanic sequence are several differentiated gabbroic sills, including the Golden Mile Dolerite (Tables 1 & 2). The Golden Mile Dolerite (GMD) is the host rock for about 90 percent of historical gold production, and is subdivided into ten units on the basis of oxide and silicate mineralogy (Travis *et al.*, 1971).

The structure of the Kalgoorlie Goldfield is dominated by early, tight, northwest-trending upright folds with development of subvertical northwest-trending faults subparallel to lithological boundaries. The regionally extensive Boulder-Lefroy Fault is an example of such a structure. This sequence has been cut by late north-trending, west-dipping dextral strike-slip faults with displacements of the order of hundreds of metres (Fig. 2). The distribution of the Fimiston (Golden Mile), Mount Charlotte and Mount Percy styles of mineralisation (see below) appears to be strongly influenced by these later faults.

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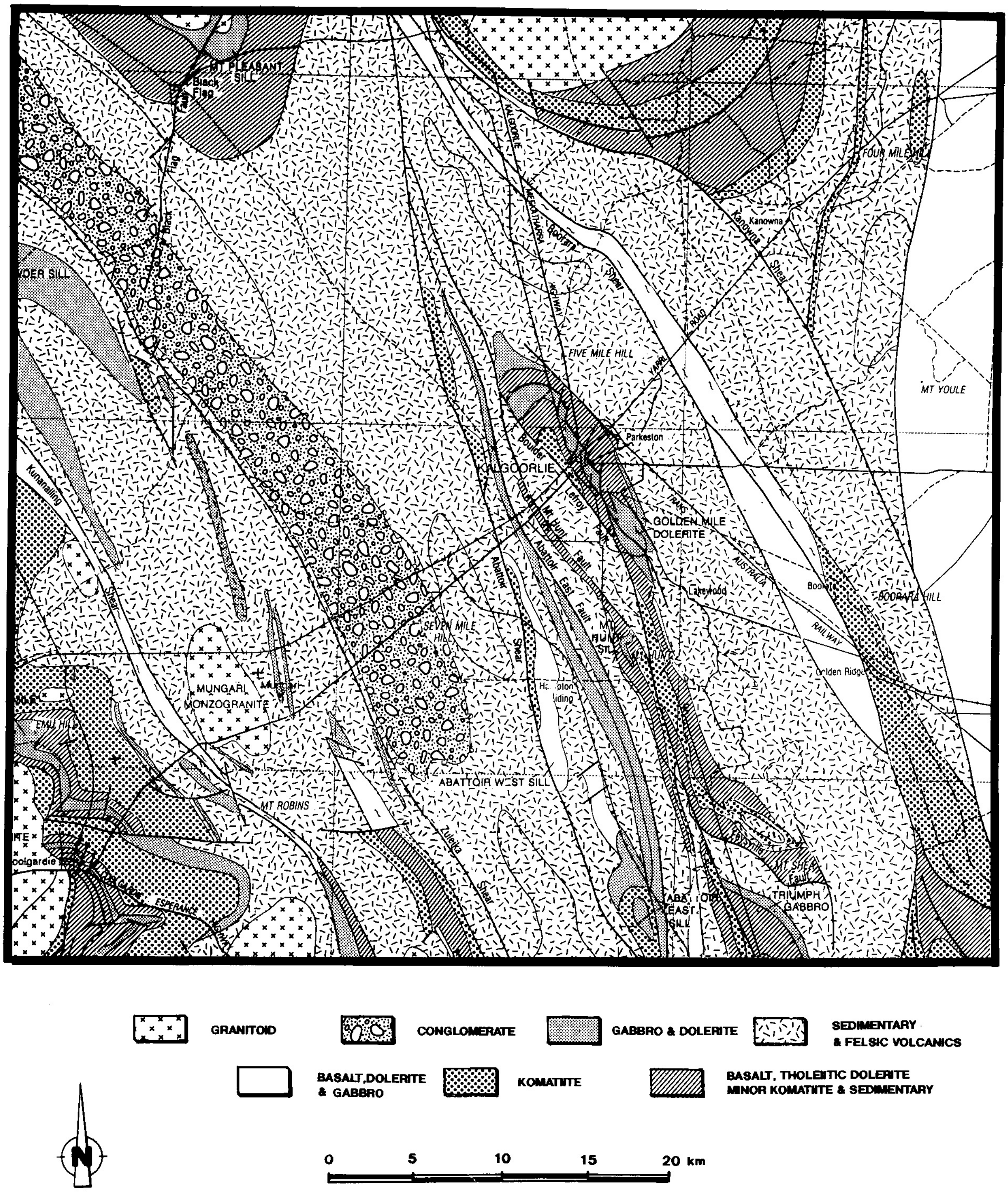

FIGURE 1 Geology of the Archaean Kalgoorlie Terrane. After Swager & Griffin (1990).

MINERALISATION

Regionally, the rocks of the Kalgoorlie Goldfield have been metamorphosed to upper greenschist facies. Later extensive (kilometre-scale) chlorite-calcite alteration associated with mineralisation overprints the metamorphic assemblage (Clout *et al.*, 1990).

At Fimiston, mineralisation is controlled by a complex pattern of shear zones developed in the GMD and Paringa Basalt. Four dominant lode-shear orientations are recognised, with individual shears attaining dimensions up to 1800 m in length, 1200 m vertical height and 10 m width. The lodes consist of carbonate-bearing siliceous zones containing 5 to 10 vol. % fine-grained disseminated pyrite with minor to trace tellurides, chalcopyrite, arsenopyrite, tetrahedrite, stibnite, sphalerite and galena. Most gold is present within the pyrite grains (Clout *et al.*, 1990). Surrounding the high-grade lode cores are lower-grade mineralised alteration halos.

At Mount Charlotte, economic mineralisation is bounded by the north-trending Charlotte and Reward Faults within the quartz-granophyre Unit 8 of the

TABLE 1 Stratigraphic succession at Kalgoorlie. Adapted from Clout *et al.* (1990).

Unit	Thickness (m)	Major rock type
TOP OF STRATIGRAPHY		
Black Flag Beds	1000	Sedimentary rocks, felsic volcanic rocks
Aberdare Dolerite (AD)	600-700	Weakly differentiated gabbroic sill
Golden Mile Dolerite (GMD)	600-940	Differentiated gabbroic sill
Paringa Basalt (PB)	850	Basalts
Federal Dolerite (FD)	85-100	Differentiated gabbroic sill
Eureka Dolerite (ED)	50-220	Weakly differentiated gabbroic sill
Williamstown Dolerite (WD)	250	Differentiated gabbroic sill
Kapai Slate (KS)	1-5	Shale
Devon Consols Basalt (DCB)	200	High magnesium basalt
Hannans Lake Serpentinite (HLS)	+700	Ultramafic sequence
BASE OF STRATIGRAPHY		

GMD. Gold is associated with carbonate-pyrite/pyrrhotite alteration halos around stockwork quartz veins with minor free gold in the quartz veins. Individual quartz veins are commonly 2 to 50 cm wide with mineralised alteration halos up to 1 m wide (Clout *et al.*, 1990). The sulphides are typically present as 1 to 2 mm disseminated grains within the carbonate alteration halo. The stockwork zones tend to form pipe-like bodies up to 60 m wide, 150 m long and 800 m deep, thus making them amenable to mechanised mining techniques.

At Mount Percy, mineralisation is hosted in the lowermost units of the stratigraphy, within porphyries intruding the Hannans Lake Serpentinite and within the Devon Consols Basalt. The mineralisation appears to be influenced by the north-trending Mystery, Charlotte and Reward Faults and associated splay faults, and is confined to stockworks and shears within the porphyries, and as shears within the basalt. Gold is associated with quartz-sulphide-carbonate veins and adjacent bleached zones. The dominant sulphide is pyrite, with trace chalcopyrite, arsenopyrite, sphalerite and tellurides (Johnston *et al.*, 1990). The sulphides are typically present as fine-grained disseminations associated with shears and/or quartz veins within the mineralised zones.

GEOPHYSICAL TECHNIQUES

Leases held by KCGM cover an area of about 30 km by 10 km, with the main production areas of Fimiston, Mount Charlotte and Mount Percy located within the central portion of this tenement block. Due to the proximity of the leases to residential areas, significant portions of land are inaccessible due to housing, roads and other surface infrastructure. Near-surface contamination as a result of historical mining and prospecting also presents problems, as do the deep weathering profile (30-60 m) and associated conductive overburden that covers much of the Kalgoorlie Goldfield.

Considering the relatively small area under exploration, plus the constraints outlined above, all of the geophysical methods employed involve detailed prospect-scale ground surveys aimed at improving definition of geological features, and indirectly detecting the three principal styles of mineralisation recognised in the field.

Petrophysics

Before commencing geophysical surveys, petrophysical studies were undertaken to determine the mass, magnetic, electromagnetic, acoustic and radioisotopic properties of unweathered rock samples collected from the three production areas. Tests were also conducted on the unmineralised host rocks proximal to the orebodies and the surrounding unmineralised country rock (Emerson, 1993).

A summary of this work is presented in Table 3. The density data indicate that at Fimiston and Mount Charlotte, the mineralised rocks are slightly denser than the surrounding unmineralised rocks, while at Mount Percy the results are equivocal in that the broad range in rock types and limited number of samples prevent meaningful conclusions. Densities over the total sample set ranged from 2.73 g/cm^3 for mineralised porphyry at Mount Percy to 3.54 g/cm^3 for unmineralised Kapai Slate, with values typically in the range 2.9±0.1 g/cm^3.

Acoustic velocities for all of the rock samples var-

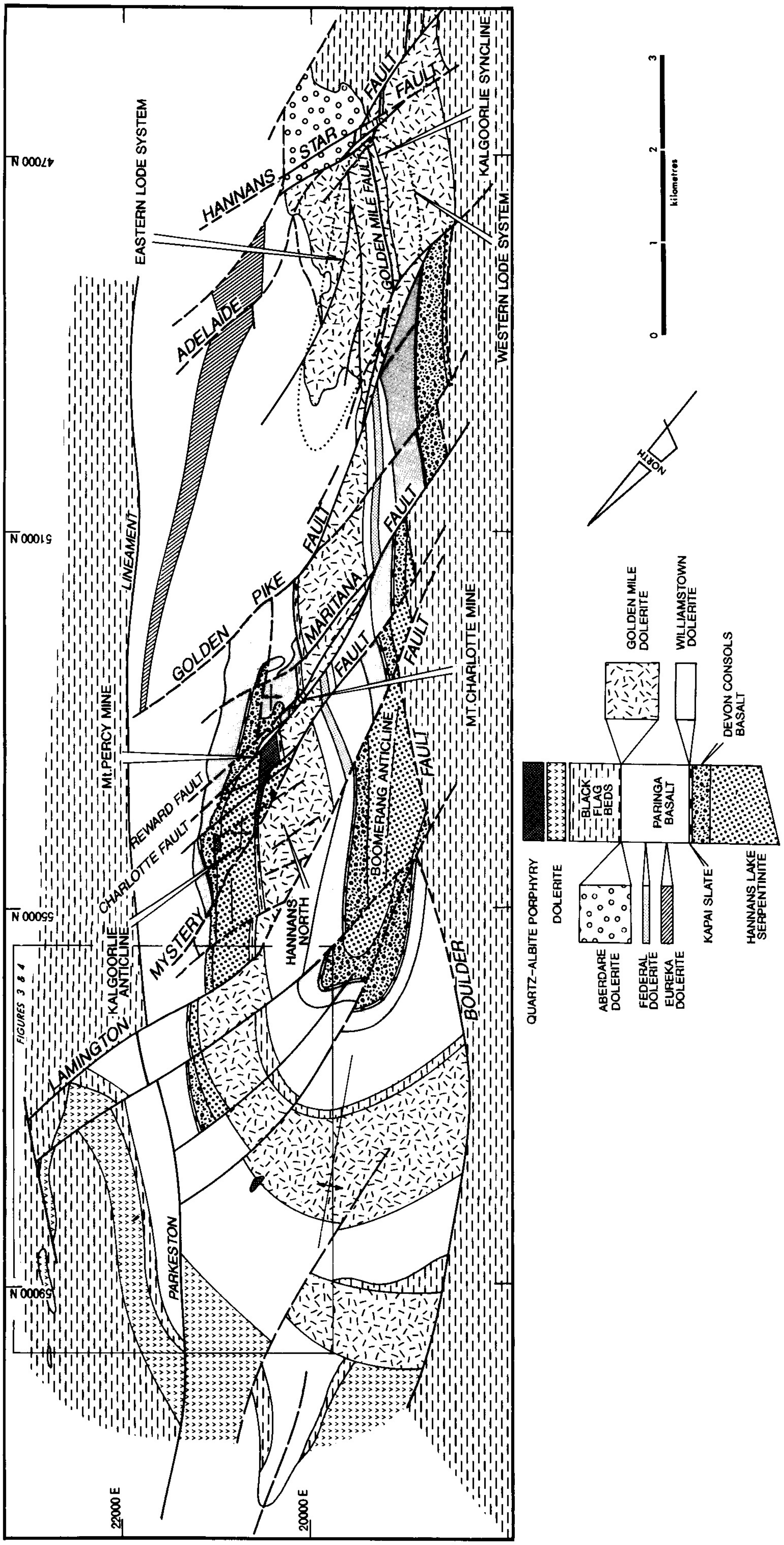

FIGURE 2 Interpreted geology of Kalgoorlie Goldfield. Adapted from Clout *et al.* (1990). The grid shown on the figure is the KCGM grid. The azimuth of grid north is 323°.

TABLE 2 Unit subdivisions within the Golden Mile Dolerite. After Travis *et al.* (1971).

Unit	Thickness (m)	Major features
10	2-14	As for Unit 1
9	80-400 (?)	Reverse of Units 2-6
8	20-110	Granophyric intergowths of quartz and feldspar
7	60-200	Fine-grained variant of Unit 6
6	15-100	Iron rich with mg euhedral magnetite common
5	0-110	Ophitic texture with stubby feldspars
4	40-250	Skeletal leucoxene, quartz rich (*cf.* Units 3 and 5)
3	10-80	Mg actinolite laths, sparse skeletal leucoxene
2	30-60	Ultramafic unit, coarse actinolite common
1	2-14	Chilled margin of the sill, variolitic texture

ied from 4097 to 6418 m/s, with most values exceeding 5000 m/s. This identifies the sample suite generally as competent rocks. There appears to be no obvious relationship between acoustic velocity and rock type.

Magnetic susceptibility and remanent magnetisation results were quite variable, with the Fimiston suite exhibiting a weak magnetic response, whereas the Mount Charlotte suite are moderately magnetic, particularly the pyrrhotite-bearing samples, for which remanence is an important factor. The Mount Percy samples are weakly magnetic except for the ultramafic (Hannans Lake Serpentinite) sample which has a moderate induced magnetisation. There appears to be no obvious magnetic contrast between mineralised and unmineralised samples from the three areas.

The electrical response of the samples is variable, with samples generally having high resistivities. The mineralised pyrrhotitic Mount Charlotte sample, the Kapai Slate, and the ultramafic Hannans Lake Serpentinite exhibit moderate EM conductivities. At low frequency the mineralised Fimiston samples have high resistivities and moderate IP effect due to the presence of disseminated sulphides. The Mount Charlotte mineralised samples are characterised by relatively low resistivities and high IP effect; typical of disseminated sulphide orebodies. In contrast, the unmineralised rocks at Mount Charlotte are highly resistive with low IP effect. The Mount Percy mineralised samples show low to moderate IP effects whereas the barren country rocks exhibit high-resistivity or low-phase characteristics. Overall, the IP results indicate that some contrast exists (which is different for each deposit style) between the mineralised samples and surrounding country rock.

Gamma ray counts on all samples were generally low, as expected because of the low uranium and thorium contents in mafic rocks. There is, however, some relative enrichment in uranium, potassium and thorium in mineralised samples, compared to the peripheral dolerites and ultramafics. This is most likely a result of the observed hydrothermal alteration and potassic metasomatism associated with mineralisation.

The results of these studies indicate that gravity, magnetics and IP would be useful tools for the delineation of rock types, while IP has potential to identify mineralisation (particularly Mount Charlotte style).

Gravity

Ground gravity surveys have been routinely conducted over tenements north and south of the mining operations at a station spacing of 200 m by 50 m along grid lines oriented perpendicular to the stratigraphic trend. Before collection of the data, the only commercially available gravity data were collected by the BMR, at a station spacing of 11 km, in 1969. The broad station spacing of these data does not permit resolution of individual lithological units nor prospect-scale structural features, and therefore has limited use for KCGM.

The recent datasets have been acquired with a Lacoste and Romberg G series gravity meter and Digibar digital barometers. The base line of each grid is optically levelled and, with this control and proprietary in-house software and processing, it is possible to obtain 0.3 m accuracy with the barometers.

An example of the residual Bouguer gravity (2.67 g/cm^3) data for an area north of the Mount Percy mining operations (Fig. 2) is shown in Figure 3. The denser basalts and dolerites are easily distinguished from the less dense ultramafic, felsic volcanic and sedimentary rocks. The eastern limb of the Boomerang Anticline (Fig. 2) is defined by the GMD gravity high trend in the central western area of the figure. A prominent northwest-trending fault is also recognisable north of the Boomerang Anticline, within the central area of the figure.

The gravity data reflect density contrasts in the unweathered rocks and also variations in the thick-

TABLE 3 Petrophysical data for Kalgoorlie Goldfield rocks.

Sample		No. Samples	Dry Bulk Density (g/cm^3)	P Wave Velocity (m/s)	Magnetic Susceptibility (SI x 10^{-6})	Resistivity 0.1 Hz ohm m	Phase Lag 0.1 Hz m rad	Radiometrics		
								K (%)	U (ppm)	Th (ppm)
Fimiston	Mineralised	5	2.86 - 3.00	5560 - 5960	140 - 1460	540 - 9360	34 - 141	0.8 - 4.1	0.5 - 2.3	0.6 - 4.1
Fimiston	Unmineralised									
	Host Rock	1	2.81	6238	640	12260	9	0.3	0	2.4
	Country Rock	4	2.80 - 2.88	5438 - 6156	570 - 720	260 - 2090	10 - 16	0.6 - 0.8	0 - 0.7	0 - 3.2
Mt Charlotte	Mineralised	3	2.59 - 3.10	4097 - 5538	90 - 21560	700 - 1860	440 - 560	rel high	rel high	rel high
Mt Charlotte	Unmineralised									
	Host Rock	2	2.86 - 2.93	5761 - 6133	34240 - 79900	10600 - 39670	27 - 111	rel low	rel low	rel low
	Country Rock	6	2.71 - 2.95	5035 - 6253	630 - 87340	500 - 22940	9 - 47	rel low	rel low	rel low
Mt Percy	Mineralised	2	2.73 - 2.93	5374 - 5603	60 - 290	440 - 5140	9 - 60	1.5 - 2.8	1.1 - 1.2	0.6 - 11.3
Mt Percy	Unmineralised									
	Host Rock	1	2.79	4366 - 4850	51890	125	8	0	0	3.6
	Country Rock	3	2.85 - 2.88	6217 - 6418	480 - 550	3600 - 9970	10 - 22	0 - 0.1	0 - 0.5	1.9 - 4.9

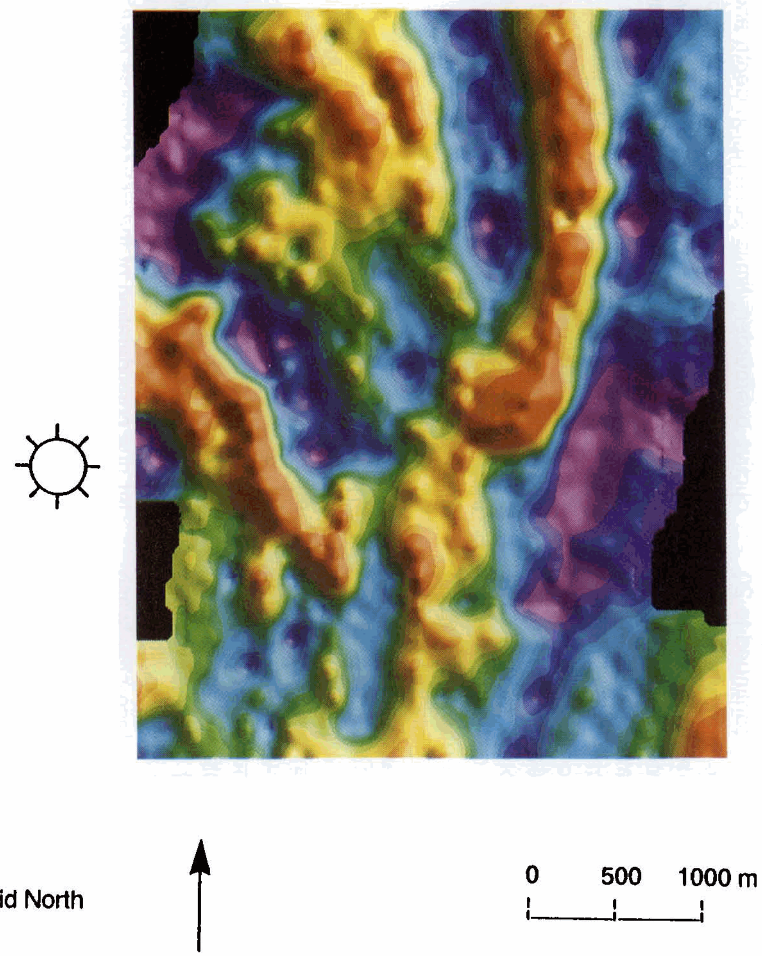

FIGURE 3 Processed ground gravity data, collected at 200 m by 50 m spacing, 1 km north of the Mount Percy mining operations (sun angle as indicated). The azimuth of grid north is 323°. See Figure 2 for location.

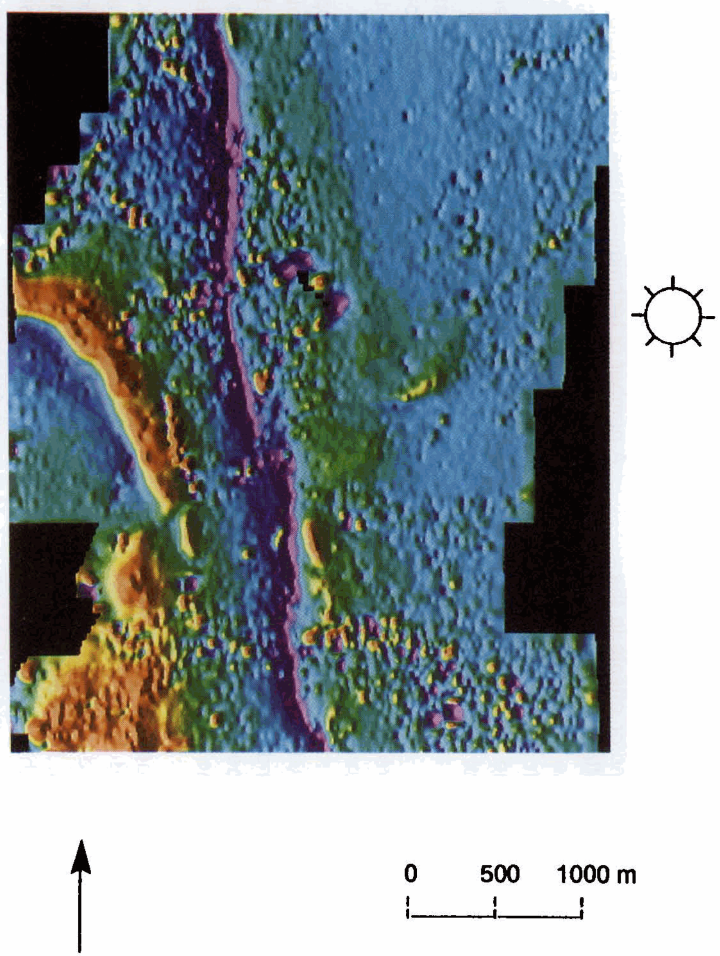

FIGURE 4 High-cut filtered and upward-continued to 20 m ground magnetics data, collected at 50 m by 0.5 m spacing, 1 km north of the Mount Percy mining operations, covering the same area as Figure 3 (sun angle as indicated). The azimuth of grid north is 323°. See Figure 2 for location.

ness and composition of the regolith. These surveys have been useful for the delineation of rock units with density contrasts of greater than 0.1 g/cm^3, but are not sufficiently detailed to distinguish internal variation within a lithological unit. Breaks and/or offsets in the gravity trends are interpreted to reflect structural features. Scale of resolution is of the order of tens of metres, which is directly related to station spacing. Experience has shown that, in the Kalgoorlie area, this technique is a useful lithological mapping tool.

Ground magnetics

Ground magnetic surveys have been conducted in conjunction with ground gravity surveys over exploration areas north and south of the mining operations. The application of combined gravity and magnetic surveys to better define geology and gold mineralisation in areas of poor outcrop has been studied previously at Corsair, 10 km east of the Kalgoorlie Goldfield (Whitaker *et al.*, 1987).

Examinations of pre-existing aeromagnetic data generated by the BMR (1965) and Aerodata (1983-84) over the Kalgoorlie Goldfield defined the major lithological and structural elements, but lacked definition of prospect-scale features which were considered relevant to identification of new prospective areas within the KCGM tenement block.

Data were initially acquired using a TM-3 caesium vapour rapid-sampling magnetometer. This was replaced by a GEM Systems GSM-19F rapid-sampling Overhauser magnetometer. More recently the 19F has been replaced by an in-house built Overhauser system. All units are continuous recording and locate themselves with cotton-feeding distance measuring devices, stretch corrected to base lines. Data have been collected on 50 m by 1 m and 50 m by 0.5 m spaced grids on traverses oriented perpendicular to the regional stratigraphic trend (330° magnetic).

The high-cut filtered and upward continued to 20 m, ground magnetic data presented in Figure 4 cover the same area as in Figure 3, and highlight a number of interesting features not immediately obvious in the gravity data. The most obvious feature is the grid N-S-trending magnetic low which maps out the Parkeston lineament, a major regional structure (Fig. 2). This lineament is characterised by a reversely-magnetised gabbroic dyke of Proterozoic age. The magnetite-rich Units 6 and 7 of the GMD are also distinguishable in the left centre area of the figure, but are slightly offset from the gravity high in Figure 3. The arcuate, noisy magnetic high area near the bottom of the figure reflects an old drainage system with concentrations of magnetite and/or maghemite.

The detail seen in these surveys allows recognition of individual magnetic units within the GMD in addition to gross lithological trends. Breaks in the magnetic trends, due either to faulting or destruction of magnetite, allow identification of structural features and/or potential zones of alteration respectively. Magnetite and maghemite present as surface sheetwash and in shallow palaeodrainages, can interfere with and mask the bedrock magnetic trends.

Void detection

The expansion of the open pit operations at Fimiston over the past three years has required the development of techniques for the detection of underground mine workings in advance of the mining operations, for geotechnical, scheduling and safety reasons (Loubser, 1993).

A number of techniques have been employed, including seismic refraction, high-resolution ground magnetics, and ground penetrating radar. The key requirements were ease of equipment operation, speed of operation and output, robustness of equipment, accurate definition and depth penetration.

Seismic refraction was found to be successful in detecting voids between vertical drillholes, however the high cost of drilling precluded systematic use of this technique.

Detailed ground magnetics at a sample spacing of 1 by 0.2 m detected some of the workings (via metallic objects such as rails) but identification and positioning of voids to the detail required was not achieved because of the variable magnetic character of the rocks surrounding the voids.

A number of surface ground penetrating radar trials were conducted using a variety of receiver and transmitter configurations. Results to date are encouraging in that penetration depths up to 15 m have been achieved in detecting mine workings. The system is adversely affected, however, by clay and saline water. Ground-penetrating radar appears to offer the best potential for void detection with acceptable accuracy and depth penetration at this time. Further trials are ongoing.

Induced polarisation

Petrophysical data indicate that the application of IP may be a useful tool for the detection of disseminated pyrite or pyrrhotite associated with Mount Charlotte style mineralisation. Previous ground IP surveys in the Kalgoorlie area suggest that cultural effects from the surface infrastructure, combined with conductive overburden, limits penetration depth and clarity of signal response from underlying lithologies. Trials have begun to evaluate the potential of downhole IP as an exploration technique for the identification of disseminated sulphides within specific structural or stratigraphic locations. Results to date are encouraging in that the deeper penetration arrays, such as pole-pole, appear to be detecting disseminated pyrite ore located some 30 to 40 m from the drillhole. Further trials will be conducted to determine the practical application of this technique in exploration.

CONCLUSIONS

The application of petrophysical studies before embarking on geophysical surveys has proved a useful, cost-effective procedure for characterising the physical properties of various styles of mineralisation and how these may contrast with surrounding country rock. The geophysical techniques employed and the data collection parameters have been determined after due consideration of the petrophysical results and the geological and geomorphological environment of the survey areas.

The combination of gravity and ground magnetic surveys at prospect-scale permits considerable refinement of the structural and lithological features in areas of poor outcrop. The data, in combination with

geological mapping and geochemical data, provide a multi-faceted approach to target generation.

Additional field trials are being undertaken to determine the application of downhole IP for detection of Mount Charlotte-style mineralisation. Further development is required before this technique can be considered a viable exploration tool, however, results to date are encouraging.

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