The nickel-copper deposit at Radio Hill, Karratha, Western Australia

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ABSTRACT

The Radio Hill nickel-copper deposit is located 30 km south of Karratha. It is a new discovery in an area where similar mineralization had been previously discovered at Mt. Scholl and Ruth Well. Radio Hill is the first massive Ni-Cu sulphide deposit of economic significance to have been located in the Western Pilbara.

Preliminary studies indicate that the sulphide mineralization occurs within gabbros, pyroxenites and peridotites of a basic igneous cumulate layered sequence. Primary sulphides have been subsequently remobilized and concentrated as stringer and massive mineralization. This is tentatively attributed to the intrusion of a further gabbroic body.

The deposit appears to be of the gabbroic association type with a Ni:Cu ratio varying from 1:4 in the outer parts of the mineralized envelope to 1:0.9 towards the central zones. In drill core observations, chalcopyrite surrounding pyrrhotite was noted in many instances.

Drilling has so far delineated a body developed over a strike length of [illegible] m and a horizontal width of up to 25 m. The mineralization plunges [illegible] to the southwest with a southerly dip varying from 75° in the west to about 20°-30° in the east.

The deposit is a leaf-shaped ore zone, plunging southwest from a vertical depth of 17 m in the north to 300 m in the south. The massive sulphides occur as lensoid masses within this zone. A geological resource of up to 2.5 million tonnes at 1.5 per cent Ni and 1.4 per cent Cu is indicated. The predominant sulphides are pyrrhotite, chalcopyrite and pentlandite, with significant cobalt, platinum group metals and gold. Tellurides of Pd, Bi and Pb were detected by scanning electron microprobe within the pyrrhotite and other trace metals include Zn and native tin. Massive magnetite is sometimes associated with the massive pyrrhotite intersections.

A test on one composite massive sulphide sample showed that pyrrhotite is present mainly as the non-magnetic hexagonal variety and only 10 per cent is present as magnetic monoclinic pyrrhotite.

The deposit has no surface expression and its identification was based mainly on drilling targets generated by geophysical methods. No secondary minerals have been observed in association with the primary sulphides, even though the deposit is only 17 m below surface in the northern part.

Keywords: *Archean, cumulate layered sequence, gabbroic related deposits, geophysics, hexagonal pyrrhotite, magmatic differentiation, massive Ni-Cu sulphides, Pilbara, sulphides*

INTRODUCTION

The Radio Hill Ni-Cu deposit occurs within a layered basic/ultrabasic igneous intrusion, which is one of several such complexes occurring in the Archean Pilbara Block of Western Australia.

Radio Hill, a topographic feature about 180 m high, is located at latitude 20° 59'S and longitude 116° 53'E, 30 km south of Karratha and near to the railway line used to transport iron ore from the Mt. Tom Price and Parabardoo mines of Hamersley Iron Ltd. to the port of Dampier (Fig. 1). The township of Karratha was established in 1970 by the Western Australian Government to complement the company-owned township of Dampier, then at the limits of its capacity, and more recently to service the Northwest Shelf hydrocarbon project. The port of Dampier ships 35 million tonnes of cargo each year, almost all of it being iron ore.

The topography is characterized by low relief with hills reaching a maximum of approximately 180 m above sea level. An arid steppes type of climate prevails, having a dry warm winter (typical daily maximum 25-30° C) and a hot summer reaching more than 40° C. Southwestward tracking summer cyclones sometimes cross the coast, causing disruption to normal activities. Rainfall is generally low and irregular, averaging 300 mm annually and the annual evaporation rate ranges from 2,300 to 2,600 mm (Ryan, 1966).

The Radio Hill area was first pegged by Whim Creek Consolidated N.L. in 1969, following interest aroused by the Ni-Cu mineralization discovered by their geologists at Ruth Well and Mt. Sholl. It was examined under various joint venture exploration programmes between 1969 and 1974.

Samim Australia Pty. Ltd. a subsidiary of Samim S.p.A. (E.N.I. Group, Italy) have been acting as managers since 1983 for the Karratha Joint Venture (KJV) which was originally formed in 1981 between Whim Creek Consolidated N.L., Teck Explorations Limited and Samim Australia Pty Limited.

During this period, exploration work confirmed an extension to the south of the known Ni, Cu mineralization at Mt. Sholl B2 (Mathison and Marshall, 1981) and geophysical work indicated additional anomalous areas. Since 1983, a further southward extension of the Sholl B2 South mineralization has been identified, a new deposit of possible economic interest has been outlined at Radio Hill, and the presence of cobalt, platinoids and gold has been noted.

This paper presents the geological setting of the massive sulphide occurrence at Radio Hill with particular reference to its economic aspects as defined in the course of the exploration phase managed by Samim. The evaluation work is continuing and the data described here are of a preliminary nature.

REGIONAL GEOLOGY

The Radio Hill Ni-Cu deposit is hosted in one of several basic-ultrabasic intrusions emplaced in the western portion of the Pilbara Block, a well defined geological complex comprising folded tracts of Archean volcanic, sedimentary and intrusive rocks, interspersed with large domal multiphase granitic batholiths (Gee, 1975; Binns et al., 1977; Hickman, 1983; Groves and Batt, 1984). Figure 1 shows the regional geological framework based on Landsat imagery interpretation, and Table 1 presents a synopsis of the west Pilbara volcano-sedimentary succession modified after Hickman (*op.cit.*).

Archean granite and granite gneiss represent up to 60 per cent of the rock types in the Pilbara region, with compositions ranging from alkali feldspathic to tonalitic; these rocks are generally emplaced as domal batholiths which have partially assimilated

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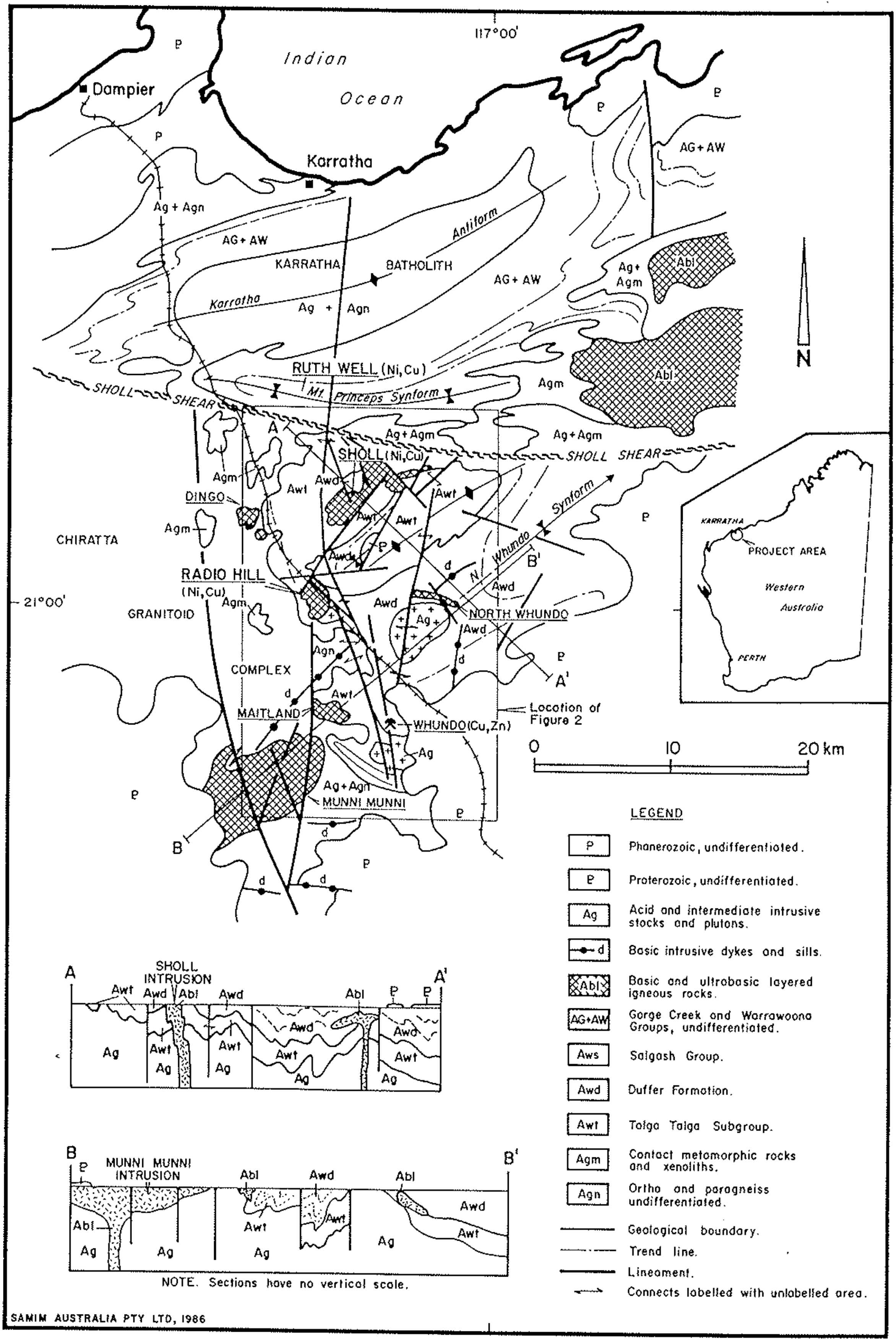

FIG. 1—Regional geology.

TABLE 1
Stratigraphic synopsis of the Pilbara Supergroup, modified after Hickman, 1983.

AGE	SUPER GROUP	GROUP	SUB-GROUP	FORMATION	LITHOLOGY	General Thickness (km)
ARCHEAN	PILBARA SUPERGROUP			NEGRI VOLCANICS	Mafic to intermediate lava flows.	0·2
					UNCONFORMITY	
				LOUDEN VOLCANICS	Basaltic and ultramafic rocks.	1·0
					UNCONFORMITY	
		WHIM CREEK GROUP			Metasediments overlying felsic & basic volcanics.	0·9
					UNCONFORMITY	
		GORGE CREEK GROUP			Sedimentary sequence with interbedded chemical sediments and pillow basalts.	12·5
					LOCAL UNCONFORMITY	
		WARRAWOONA GROUP		WYMAN FORMATION	Felsic volcanics.	1·0
					LOCAL UNCONFORMITY	
			SALGASH SUB-GROUP		Basic & felsic volcanics overlying chemical sediments & high magnesian basalts.	5·5
				DUFFER FORMATION	Felsic volcanics.	5·0
					LOCAL UNCONFORMITY	
			TALGA TALGA SUB-GROUP	MOUNT ADA BASALT	Basalt.	2·0
				MC PHEE FORMATION	Carbonate - chlorite - quartz rock.	0·1
				NORTH STAR BASALT	Basalt and dolerite.	2·0

or stoped into the volcano-sedimentary assemblages forming the supracrustal sequence (Pilbara Supergroup). The granite and granite gneiss rocks are divided into three main categories.

1. a granitoid complex with a last stage of metamorphism dated at about 3,000 m.y.
2. a porphyritic adamellite and granodiorite
3. post-tectonic granite and adamellite plutons and stocks, emplaced 2,700 to 2,600 m.y. ago

The volcano-sedimentary and associated intrusive rocks of the supracrustal sequence are named the Pilbara Supergroup and comprise two major stratigraphic units.

1. the Warrawoona Group, a predominantly volcanic assemblage of felsic, mafic and ultramafic rocks with subordinate chert overlain by
2. the Gorge Creek Group, a sedimentary sequence of sandstone, conglomerate, greywacke, shale and banded iron formation with subordinate basalt and gabbro.

In the west Pilbara, an upper volcanic unit, named the Whim Creek Group, unconformably overlies both Groups. Two other formations, the Louden Volcanics and Negri Volcanics, unconformably overlie the Whim Creek Group.

Volcanic assemblages within the Pilbara Supergroup include ultramafic volcanics and high magnesian basalts (komatiites), which attain their best development in the Salgash Subgroup. Similar rock types are also well represented in the Louden Volcanics (Arndt *et al.,* 1979).

Intrusive basic rocks are emplaced, preferentially along unconformities, lithological contacts and/or major fault zones, at various stratigraphic levels within the supergroup in the form of sills and dykes, in places forming layered mafic to ultramafic intrusions. Rock types of the layered intrusions range from peridotite and pyroxenite, through to gabbro, norite and anorthosite depending on the composition and the degree of fractionation of the parent magma. Their original texture and mineralogy are often preserved, the rocks having undergone only mild metamorphism and moderate autometasomatism, with development of talc, tremolite, chlorite and carbonate minerals. Locally, contact metasomatism caused by acid and basic intrusions is present with the development of phlogopite and amphibole.

The absolute age of the mafic-ultramafic layered intrusions has not been determined. However, the rocks lack penetrative deformational fabric and frequently exhibit a primary mineralogy with or without serpentinization. In addition, the intrusions seem to be preferentially located, at least in the KJV area, along the contact between the Talga Talga Subgroup and the younger Duffer Formation.

This observation and the fact that there is no indication of regional metamorphic imprint suggest that the layered intrusions could post-date the last major deformation which, according to Hickman (*op. cit.*), occurred between 2,700 and 2,600 m.y. and resulted in the deposition and subsequent tectonism of the Whim Creek Group.

The possibility of a parental relationship between the mafic-ultramafic layered intrusive rocks and the mafic-ultramafic units of the Louden Volcanics should be further investigated.

Flat-lying to open-folded late Archean or early Proterozoic basalts and andesites, products of feeder dykes and terrestrial flows, overlie the Archean rocks. Permian glaciation products and Tertiary laterite have largely been removed by subsequent erosion and the landscape now is one of remnant lateritic mesas and moderately fresh rock outcrops emergent from a thin mantle of Quaternary and Recent alluvial, colluvial and calcrete deposits.

GEOLOGY OF THE KARRATHA JOINT VENTURE (KJV) AREA

Data from a regional Landsat interpretation and a 1:40,000 mapping programme conducted south of the Sholl Shear Zone have been collated, simplified and presented in Fig. 2, to show the geology of the Karratha Joint Venture (KJV) area.

Two strongly folded lithological successions have been identified and appear to equate with Hickman's (*op. cit*) nominated subdivisions of the Warrawoona Group, viz. Talga Talga Subgroup and Duffer Formation. The two successions have been invaded regionally by granite batholiths and locally intruded by granite plugs, layered basic-ultrabasic bodies and medium to coarse grained basic igneous rocks. Remnant Proterozoic (Mt. Roe?) basalts unconformably overlie the sequence and have in turn been extensively intruded by dolerite sills and dykes (Cooya Pooya Dolerite).

Two major N-S features, the Munni Munni – Radio Hill and the Whundo – Nickol lineaments, have been detected from Landsat interpretation along with several NW and NNW trending linear features and, in most instances, outcrop displacement indicates faulting to have occurred along them.

Two of the NW features include faults mapped during the 1:40,000 mapping programme. Some of these, for example the Railway Fault, have a direct influence in the areas of mineralization.

In particular, the Railway Fault appears to have considerable significance on the distribution of the geological formations located on either side of it: a thick sequence of Duffer Formation is present north-east of the fault, while it is practically absent to the south-western side. Also, layered basic igneous intrusions south-west of the Railway Fault more commonly comprise coarsely crystalline basal facies than those to the north-east which are mostly upper level gabbroic phases. These observations suggest

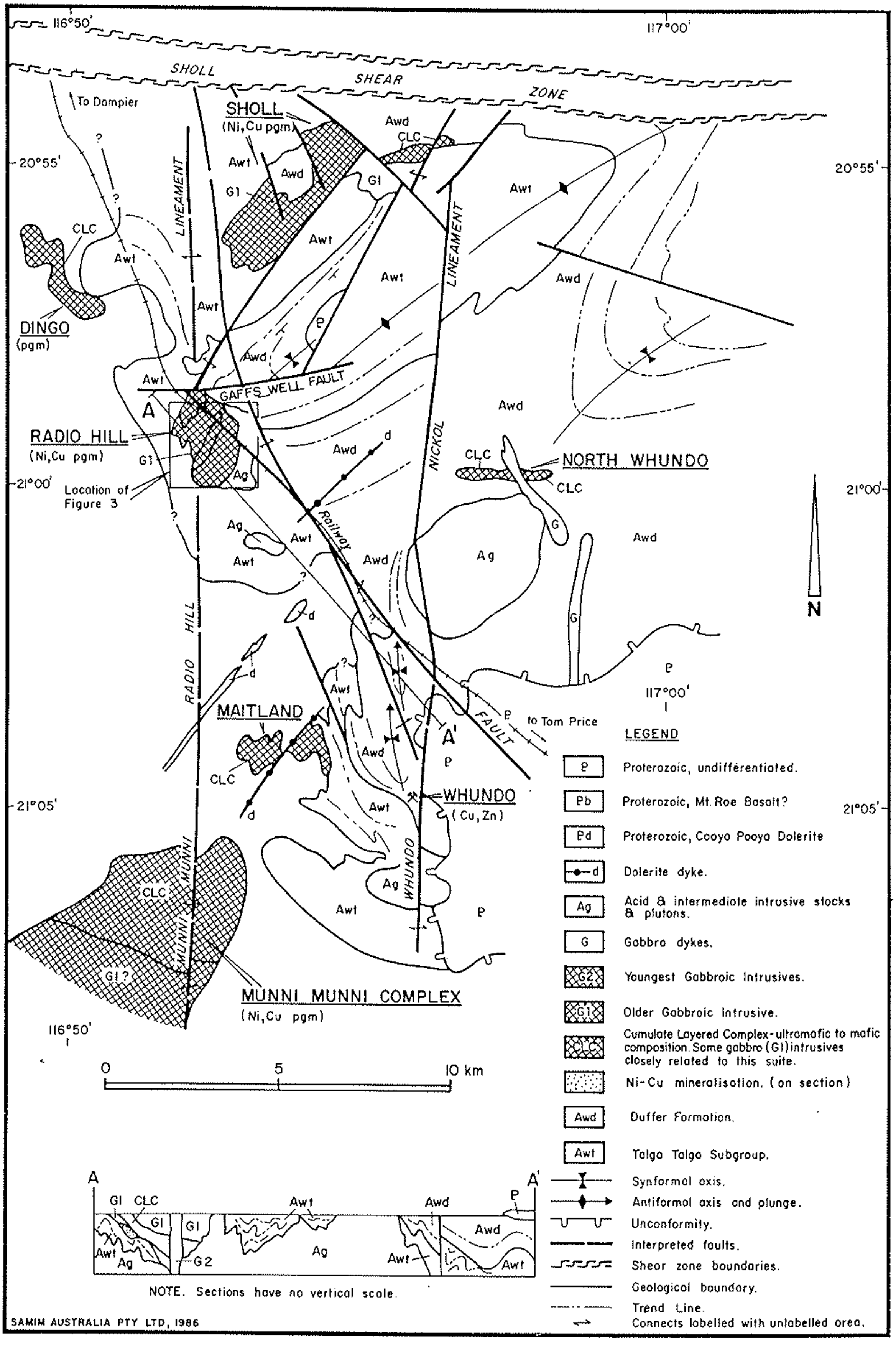

FIG. 2—Geology of the KJV area.

the presence of an uplifted and strongly denuded block to the south-west of the Railway Fault and also explain the greater exposure of coarse basal crystalline phases of basic igneous intrusives observed in the Munni Munni, Dingo and Maitland areas. The southward tilting of the Munni Munni gabbros suggests the denuded block to be tilted south-westward, a suggestion strengthened by thick Proterozoic cover development in that direction. Such tilting would enhance exposure of basal phases in the Munni Munni, Maitland, Dingo (?) and Radio Hill intrusives. The Railway Fault may be the hinge for such south-west flexuring.

The cumulate layered complex at Dingo is rafted in underlying granite gneiss. Unfolded cumulate layered gabbro dykes in the Maitland complex are intensely thermally metamorphosed and could be part of the feeder dykes of an eroded overlying layered complex. Thermal metamorphism is attributed to the event responsible for the granitization of the unit Agn. Thus Maitland has the aspect of a partial feeder zone of the layered complexes in that area.

Three periods of granitic intrusion span the basic intrusive activity: a basement granitization with development of acid ortho- and paragneiss; a second, well-foliated, porphyritic biotite adamellite which has thermally metamorphosed pre-existing basic complexes and intruded in turn the Radio Hill gabbros; and a third ·ase represented by post-tectonic biotite granite stocks, intrue into the N. Whundo and Ruth Well layered complexes and granite dykes and plugs intruding the Sholl gabbros. Several late dolerite dykes, trending NE-SW, cut across the Archean sequences.

Stratigraphic Succession

A brief description of the stratigraphic divisions used in this report follows (see Table 1).

Talga Talga Subgroup

This succession is dominated in the KJV tenement areas by strongly deformed pillowed metabasalts and basic agglomerates having intimately interlayered metadolerite phases.

Minor intercalations of acid to intermediate volcanics are known in the Radio Hill area and also form useful structural markers outlining small-scale fold patterns in the area adjacent to the Railway Fault. Where it is juxtaposed to the cumulate layered complex, it is hornfelsed, brecciated and strongly veined with quartz and calcite. Hornfels development is more pronounced and extensive in coarser crystalline phases. The basalts mostly appear to be tholeiitic in nature and nothing suggesting a komatiitic tex- e or composition has been noted.

Duffer Formation

The Duffer Formation is typified by acid to intermediate lavas and fragmentals with a lesser expression of basaltic volcanism. Impersistent cherts are intercalated with this sequence in the mapped area. Volcanism is tholeiitic or calc-alkaline intermediate in character.

Metamorphic deformation and alteration appear to be less intense than within the Talga Talga Subgroup, perhaps because the Duffer Formation lies higher in the sequence. The Duffer Formation attains its greatest development in the central-eastern part of the KJV area (Fig. 2).

Salgash Subgroup

No Salgash Subgroup beds have been recognized south of the Sholl Shear Zone. The mapped sequence of acid and basic volcanics, peridotites, exhalative sediments and basaltic komatiites in the Ruth Well/Mt. Princeps synform are here assigned to the Salgash Subgroup, as defined by Hickman (*op. cit.*).

Mount Roe Basalt

Resting with a strong basal unconformity on the Archean sequence 3km NE of Radio Hill, a mass of fresh, chloritic, undeformed, amygdular, pillowed and fragmental basalts occurs that is interpreted to be the equivalent of the Proterozoic Mount Roe basalt.

THE RADIO HILL INTRUSION

Geology

Regional and local geological mapping conducted during the course of the KJV programmes have led to a viewpoint revised from that advanced in earlier works (Richardson, unpublished data, 1976) on the geology of the Radio Hill intrusion.

Richardson believed the Radio Hill intrusion to represent a cumulative layered basic-ultrabasic basin of some 5 km² in the area with an inward dipping periphery, occupied centrally by dioritic and granophyric differentiates of the primary magma. Recent work invalidates this view, especially the areal extent of the intrusion and its geometric configuration. As shown in Fig. 3, it is now seen as a cumulate layered basic-ultrabasic intrusion occupying an area of approximately 3 km² comprising a basal ultrabasic-basic sequence (CLC) overlain by a layered melagabbro/gabbro sequence (G1), having a shallow southerly dip of approximately 25 to 40 degrees. A late major felspathic gabbro dyke (G2), near vertical in attitude, has transected the layered complex to form the NE trending backbone of Radio Hill. The dyke is occupied in the central part by a leucocratic pegmatoidal phase, conformable in dip and strike to the main dyke. The entire mass is viewed as an elongated lopolithic body comprising shallow-dipping basic igneous layers cut by a late sub-vertical gabbro feeder dyke.

The Radio Hill Intrusion is bounded to the east and west by hornfelsed metabasaltic basement rocks, with which it sometimes intertongues, and to the south by foliated granites with which it has thermally interacted.

The attitude of most of the contacts between the Radio Hill Intrusion and the country rock is not known. However, detailed drilling has established a strongly and irregularly flexured north-western margin having southerly dips varying from shallow to sub-vertical and in places apparently overturned towards the north-west. In some northern sections, the basal mineralized gabbros dip westward and probably represent intrusive wedges of gabbro into the basement.

Major cross-cutting faults are suspected of having displaced the north-eastern portions of the complex north-westward (see Figs. 4, 5 and 6). In particular, the Railway Fault appears to have displaced the northern-most tip some 1.3 km northward to occupy the site previously referred to as the RH4 Ni-Cu prospect. In this locality, drilling has also confirmed a smaller westward displacement by the Gaffs Well Fault.

A northeast-southwest trending fault can be observed in basement outcrops located to the north and south of the Radio Hill deposit and, due to the lack of rock exposure in the Radio Hill area, this fault is inferred to continue through the deposit. In fact, evidence of faulting has been observed in some drill cores. Magnetic data contribute as well to support the presence of faults (Fig. 7), although the degree and nature of faulting remain unclear at this stage.

Petrology

Drilling of part of the unexposed lower sequence has intersected a finely layered sequence of cumulate-textured peridotites and clino-pyroxenites, with gabbroic pyroxenites and gabbros developed in the basal section.

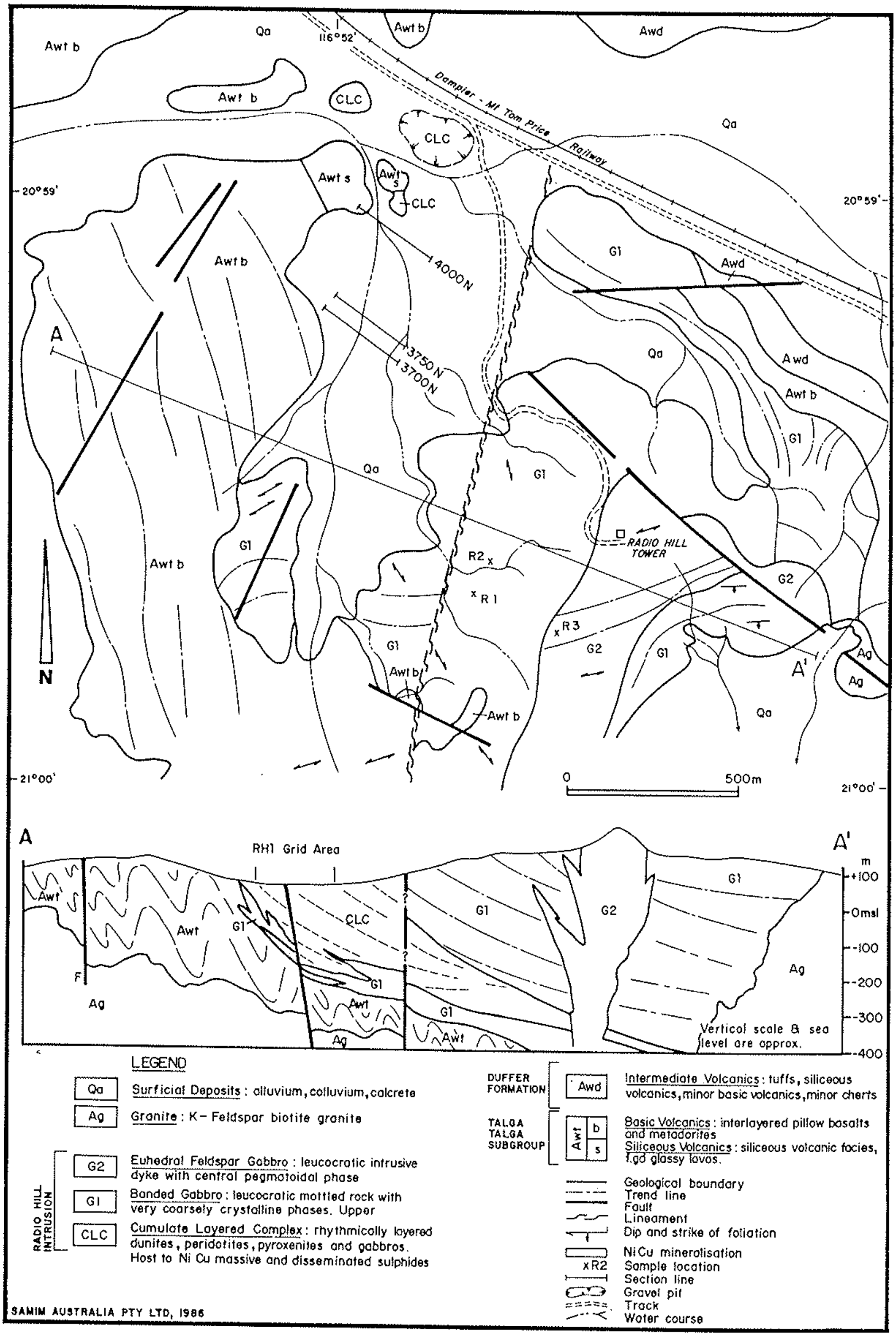

FIG. 3 — Geology of the Radio Hill Prospect.

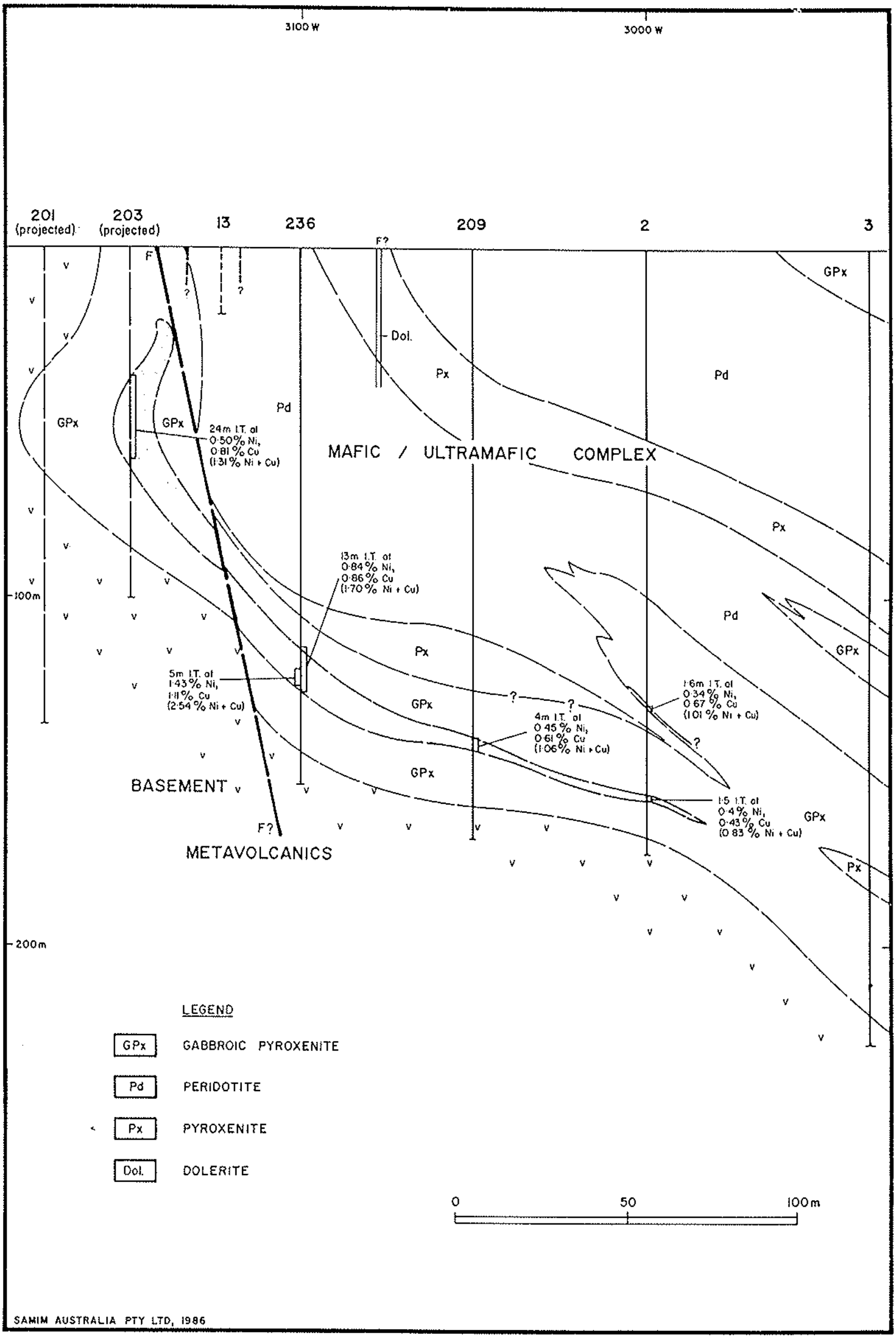

FIG. 4 – 4000N economic drill section.

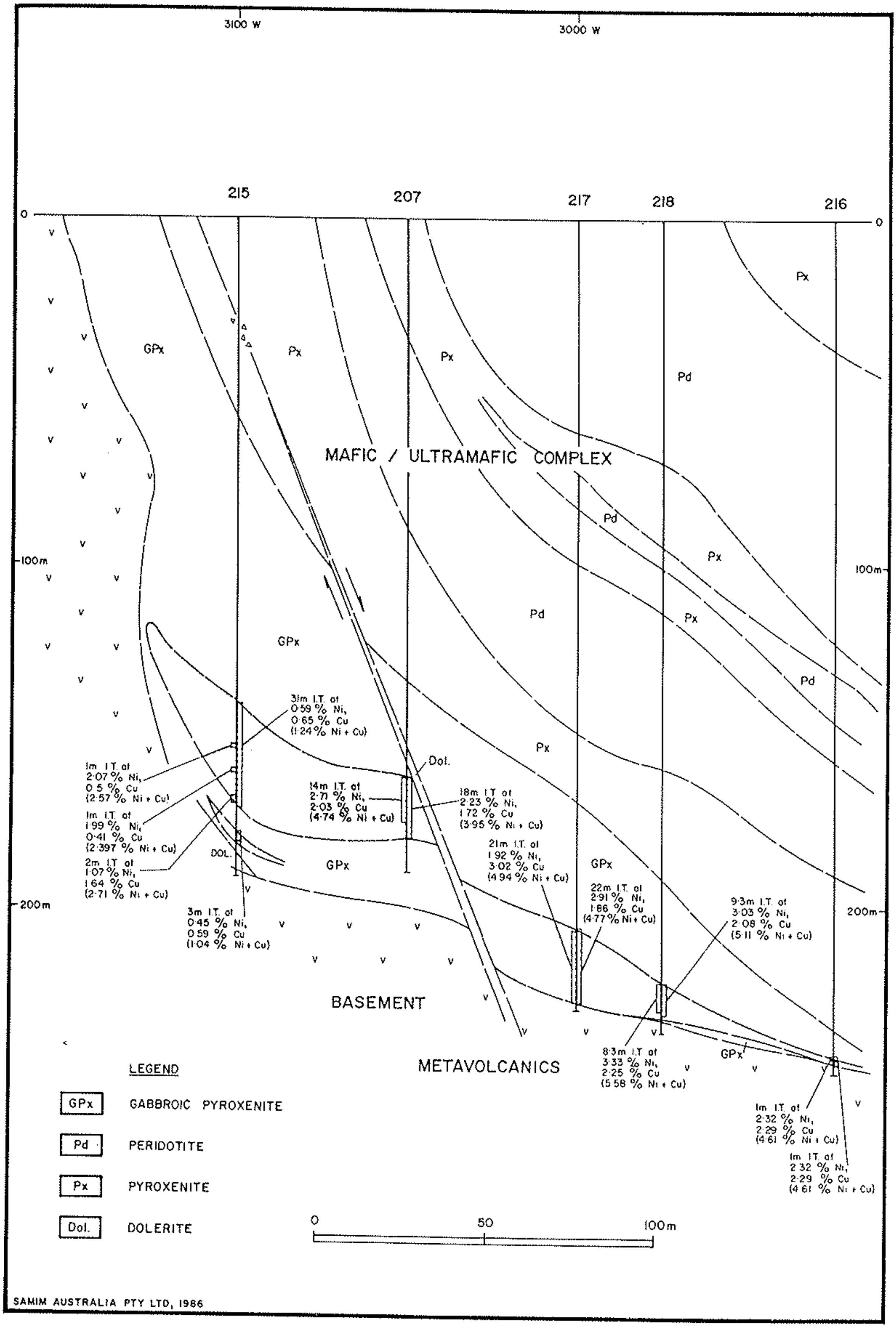

FIG. 5—3750N economic drill section.

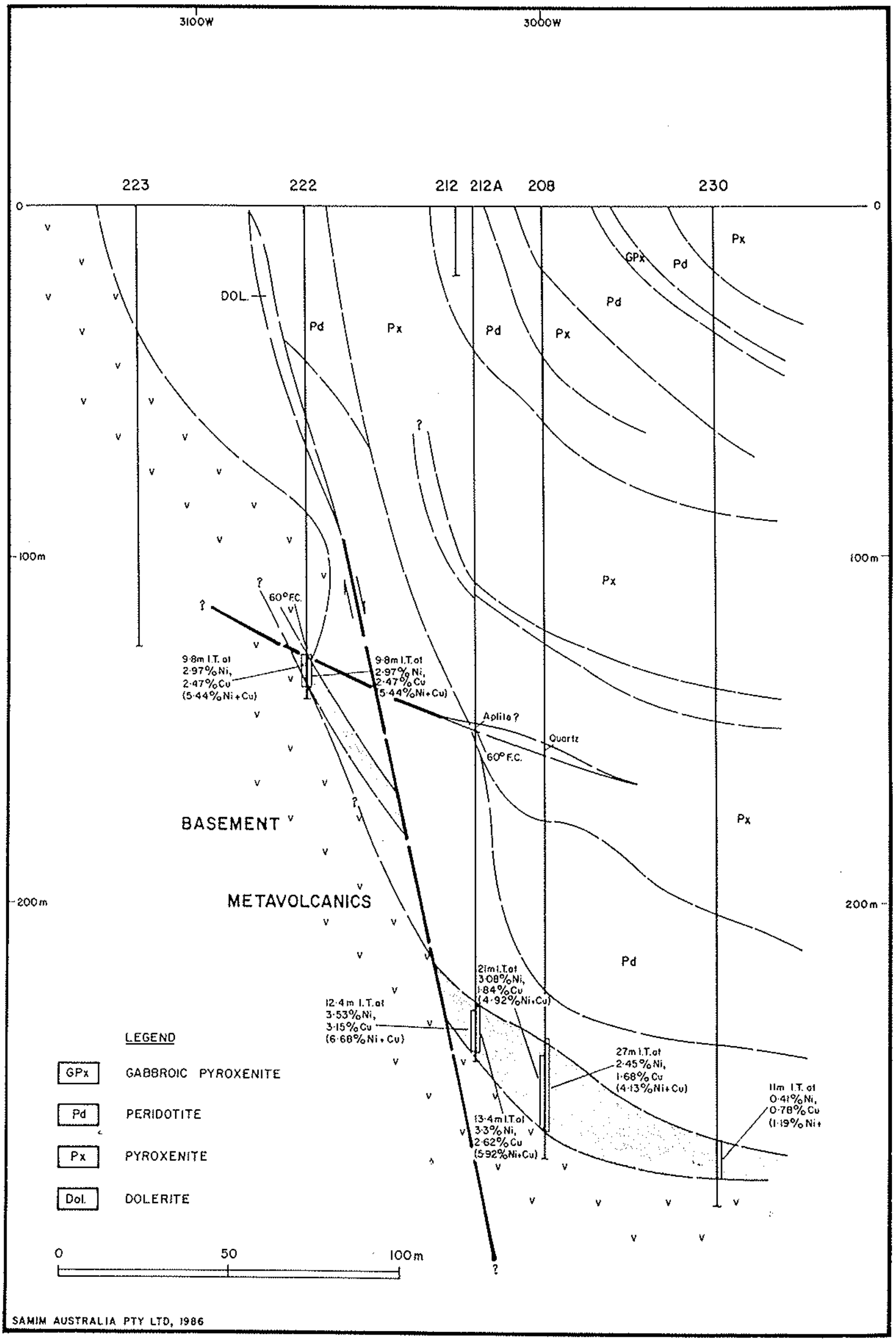

FIG. 6—3700N economic drill section.

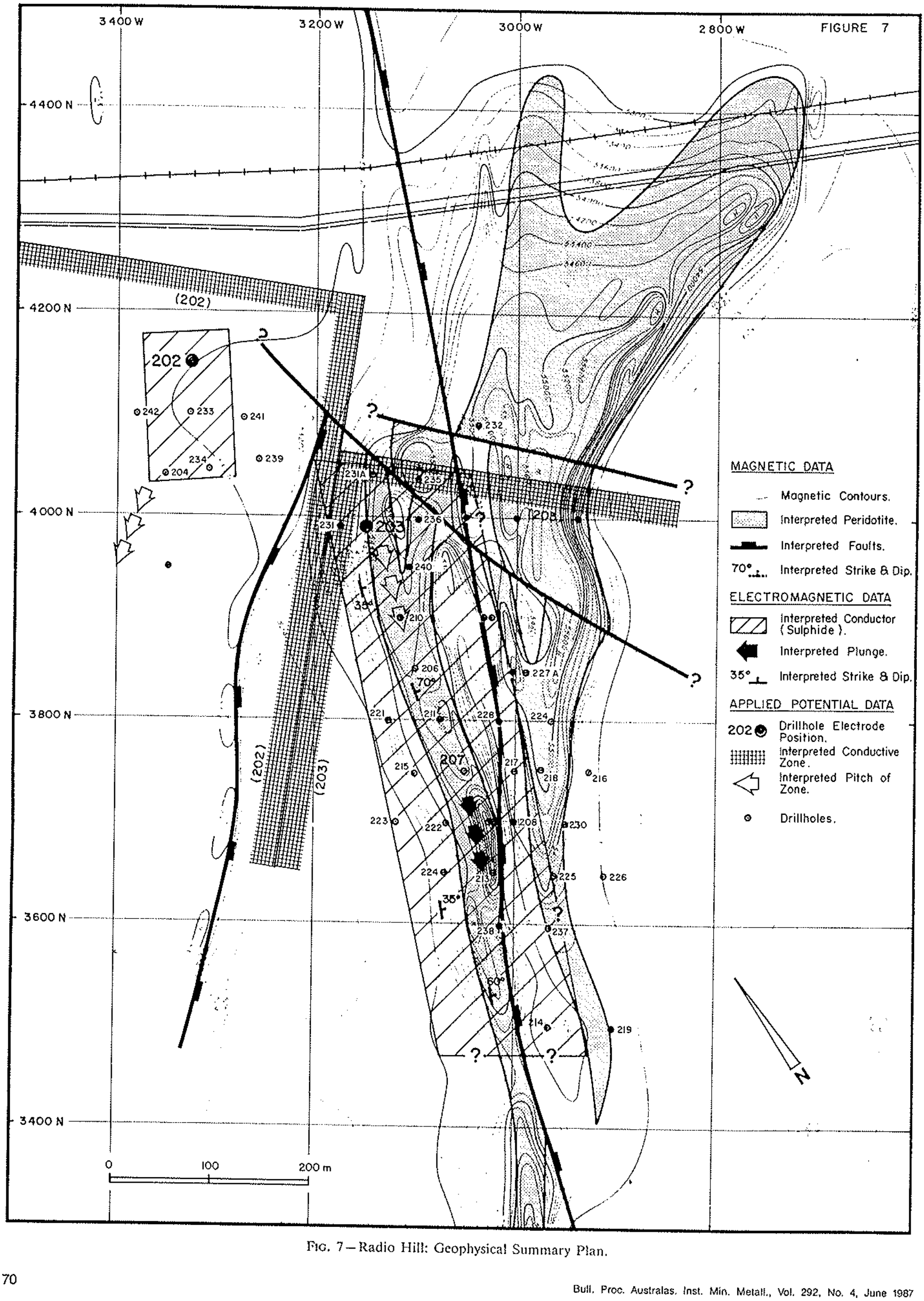

FIG. 7—Radio Hill: Geophysical Summary Plan.

Rhythmic banding on a scale ranging from metres to centimetres is present within the peridotite-clinopyroxenite suites. The peridotite unit tends to exhibit sharp basal contacts with its upper phases being transitional to pyroxenite. The layering and rhythmic banding have presented difficult correlation problems to date, especially when logging the cuttings from percussion drilled intervals.

The basal gabbros and gabbroic pyroxenites have been found to be a locus of good Ni-Cu sulphide mineralisation, and excellent massive sulphide mineralisation is commonly present at, or juxtaposed with, the basal contact with hornfelsed metabasaltic volcanics. Higher in the layered ultramafic sequence, finely disseminated primary and metasomatic Ni-Cu sulphide mineralisation is present in peridotite.

Petrological studies on drill samples and surface rock samples from unit G1 show a marked compositional affinity with those derived from the Mt. Sholl cumulate layered complex, and typically contain a limited (5 to 15 per cent) content of orthopyroxene. Rocks classed as G2 gabbro are petrologically and petrochemically distinct from the G1 unit.

Petrochemistry

Whole rock chemistry of two samples of G1 (R1 and R2) and one of G2 (R3) at Radio Hill is shown in Table 2.

TABLE 2
Whole rock geochemistry of G1 and G2 gabbros.

Rock No.	SiO_2	Al_2O_3	MgO	CaO	K_2O	Na_2O	FeO	Fe_2O_3	TiO_2
R1	51.6	8.50	11.6	11.3	0.529	1.78	7.71	7.71	0.565
R2	50.3	8.88	11.6	11.9	0.492	1.74	8.14	8.14	0.613
R3	52.3	16.80	5.90	8.65	1.15	2.82	6.33	6.33	0.597

The location of the samples is shown on Fig. 3.

The composition of the G2 sample borders on dioritic and is regarded as an advanced differentiation of the G1 gabbro. The latter has higher CaO and MgO, and lower K_2O and Al_2O_3 values.

The similarity of these rocks to those associated with the mineralized drilled sequence is evident from the averaged whole rock analyses shown in Table 3.

TABLE 3
Average whole rock geochemistry in the Radio Hill area.

	Rock Types	SiO_2	Al_2O_3	MgO	CaO	K_2O	TiO_2
	Gabbros	50.77	8.18	11.08	11.79	0.25 −0.48	0.64
2	Pyroxenites	48.29	5.61	19.96	11.72		0.50
3	Peridotites	43.8	3.76	12.8	6.54		0.30
4	Mineralized Px	44.22	3.87	14.61	14.0		0.42

Late stage dolerite and gabbroic dykes, some of Proterozoic age, cut the mineralized sequence. The identification of these by whole rock chemistry is also readily possible.

Mineralization

Three styles of sulphide mineralization have been observed and are listed, from remobilized to primary, as follows.

i) Massive pyrrhotite-chalcopyrite-pentlandite pyrite magnetite at, or in juxtaposition to, the basement contact. Often the latter is strongly brecciated with quartz-carbonate-chlorite veining. Sulphides replace and envelop country rock fragments. Approximately 90 per cent of the pyrrhotite present is the non-magnetic hexagonal variety.

ii) Disseminated, blebby and stringer/gash vein pyrrhotite-chalcopyrite-pentlandite associated with tremolite-actinolite- chlorite alteration and minor carbonate veining. Mineralization sometimes rims chloritised phenocrysts or occurs as patchy impregnations of fine to medium grained sulphides within the rock matrix. Occasional massive pyrrhotite (pentlandite, chalcopyrite) veins occur in lieu of a wider massive sulphide intersection.

iii) Disseminated (matrix?) sulphides. These are usually represented by fine grained pyrrhotite (pentlandite, chalcopyrite) in interstitial sites between serpentinised olivine crystals in peridotite/dunite host rock. The disseminated mineralization appears to represent primary sulphide content and has undergone no apparent remobilization.

Pyrite is present in most rock types in varying degrees either as disseminations or as "paint" pyrite coating chloritic and serpentine joint planes. Framboidal paint pyrite on joints appears to represent the final sulphide phase.

Mineralogy

Investigations on several samples, some from barren rock but most derived from drill cores of the mineralized zones, were conducted to ascertain the nature and interrelationship of sulphide assemblages, determine sulphide-silicate relationships, and attempt to formulate a mineragenetic sequence. The specimens were examined by different specialists using a variety of techniques, viz. optical microscopy (reflected and transmitted light), chemical and microchemical analyses, scanning electron microscopy and diffractometric analysis. Generally, a good agreement was achieved in the description of the material and this also agreed with geological concepts deduced from field observations.

In summary, the sulphides comprise fine and coarse grained aggregates of pyrrhotite, chalcopyrite and pentlandite and discrete particles of the individual minerals. Pyrrhotite contains only minor (less than 2 per cent) flame pentlandite and no nickel was located in solid solution within pyrrhotite. No secondary millerite, marcasite or pyrite have been detected to date. Usually, magnetite is closely associated with the massive sulphides. Scanning electron microprobe work did not identify platinum in the sulphide samples but did locate tellurides of Pd, Bi and Pb within pyrrhotite. Cobalt was detected in rock and concentrate assays to levels up to 0.47 per cent and was identified, replacing some Ni in gersdorffite. Other trace metals present include Au, Zn and native tin. The elemental association of Sn, Bi, Te, Pd and Co is also known at Sudbury (Canada), Monchegorsk (USSR), and Rustenburg (South Africa).

Grains of pentlandite and chalcopyrite commonly exceed 50 micron and range up to 2 mm diameter both individually and within composite aggregates. Flame pentlandite (2 to 200 micron) represents at most two per cent of the pyrrhotite bulk. Further work on a composite sample of pyrrhotite from the massive sulphide zone showed that only ten per cent of the monoclinic magnetic variety is represented, with the remainder being non-magnetic hexagonal pyrrhotite.

X-ray diffraction analysis of a powdered sample and investigation of distribution of magnetic domains in a polished section (magnetic colloid test) indicated that hexagonal pyrrhotite is 90 per cent of the total, with the monoclinic variety accounting for the remaining 10 per cent. Studies on other deposits indicate that monoclinic pyrrhotite is the main constituent of massive ores, whilst hexagonal pyrrhotite is typical of disseminated ores (Bennett *et al.*, 1972; Marston, 1984).

With regard to the mineragenic sequence, some preliminary conclusions are shown below.

(a) Nickel-copper sulphides occur in gabbro, pyroxenite and peridotite within the layered sequence, with the gabbro forming the most important economic host.

(b) remobilization and redeposition of sulphides have occurred.

(c) the majority of sulphides in low-grade material (e.g. in peridotites) is almost certainly of primary origin.

(d) massive sulphide concentrations are likely to represent reworked primary sulphides which underwent structurally controlled redeposition.
(e) primary sulphide remobilization took place during thermal metamorphism.
(f) a late-stage hydrothermal pyritic-gersdorffite overprint occurred and is tentatively equated with late stage aplitic-microgranodioritic veining.
(g) flame pentlandite in pyrrhotite represents only a small fraction of the pentlandite content.

The sulphide remobilization model is based on the observation that, in all significantly mineralized differentiates of the layered basic igneous intrusion, extensive amphibolitization of the primary constituents occurs intimately intergrown with the sulphide.

In addition, the amphibolitization process is more accentuated where massive and stringer sulphides are present and these are, in turn, spatially associated with the G1 gabbro.

An exception is present in the zone of drillholes RHPD 222 and 240, (see Figures 6 and 7), where sulphides are associated with a fresh, unmetamorphosed granophyre. The granophyre is considered to be a subsequent intrusion that further remobilized existing sulphides.

Copper and nickel geochemistry

Calculations of Cu/(Cu+Ni) have been made from assays of borehole samples, including ratios for individual rock types, individual boreholes, and weighted triangular ore blocks. Generally, in the Radio Hill deposit the range of Cu/(Cu+Ni) values is 0.32 to 0.73 and attains 0.75 to 0.79 in the northern part.

A high Cu/(Cu+Ni) zone tends to symmetrically envelop a zone of high Ni/(Cu+Ni) that is coincidental with the major volume of massive sulphide. The Ni/(Cu+Ni) ratio also increases slightly to the north of drill hole RHPD 210 (see Fig. 7). Where more than one zone of mineralization occurs in a borehole, the Cu/(Cu+Ni) ratio increases in the deeper zones.

The Cu/(Cu+Ni) ratios calculated for a variety of mineralized rocks using a cut-off grade of 0.8 per cent (Cu+Ni), are shown in Table 4.

TABLE 4
Cu/(Cu+Ni) ratio of the Radio Hill deposit.

Rock Type	Gabbro	Pyroxenite	Peridotite	Massive Sulphide
Ratio Cu/(Cu+Ni)	0.48-0.79	0.45-0.79	0.52-0.58	0.28-0.54

For moderate grades (less than 2.5 per cent Cu+Ni) of disseminated and stringer mineralization, the Ni/(Cu+Ni) is lower than for higher grade sulphide mineralization. A relative concentration of Ni with increasing combined grade is indicated.

The Cu:Ni ratio is often close to 1 and neither element is particularly enriched with respect to the other. The Ni/Cu or Cu/Ni ratio rarely exceeds 5:1, in contrast to higher ratios typical of volcanogenic deposits (Naldrett and Cabri, 1976; Naldrett, 1981).

Metallurgy

Metallurgical testwork was done on massive and disseminated mineralization from Radio Hill to establish the metallurgical parameters required for preliminary process design and to delineate a typical metallurgical performance. For massive sulphides, production of separate copper and nickel concentrates is feasible using differential flotation. Eighty per cent of the copper can be expected in the copper concentrate at a grade of 26 per cent Cu and 1.5 per cent Ni; 70 per cent of the nickel can be recovered to a nickel concentrate at 12 per cent Ni and 1 per cent Cu, with the remaining metal being contained in pyrrhotite. Flowsheet development for the separation of Ni and Cu in disseminated mineralization is still in progress. On experience gained from studies of disseminated ores from the Mt. Sholl deposit, the Radio Hill ores are expected to respond to a similar process, viz. a collective/selective scheme which, applied to a clean bulk nickel/copper concentrate, showed the possibility of good results.

The testwork performed on the disseminated sulphides indicate that overall recovery of copper and nickel into a clean bulk concentrate is very dependent on the head grade of the ore being processed. Work on this type of ore is continuing.

Assay results from concentrates of Radio Hill massive ore (drill hole 84RHPD 208, Fig. 6) show interesting values for cobalt and precious metals (Table 5).

TABLE 5
Chemical assays of Ni Cu concentrates from Radio Hill.

Sample	Cu%	Ni%	ppm Co	Pd	Pt	Ag	Au
Copper Concentrate	23.8	2.43	890	5.63	0.41	18	0.56
Nickel Concentrate	1.35	12.9	4700	1.67	0.11	5	0.05

GEOPHYSICS

A large number of geophysical techniques have been used over the deposit both in the early reconnaissance phase and also later in the detailing phase. At least two aeromagnetic surveys have been flown over the area and it was the first of these that led to initial target selection. This survey showed a discrete magnetic anomaly of several hundred nanoteslas west of Radio Hill in an area of overburden. A subsequent detailed aeromagnetic survey defined the anomaly more clearly.

Results from the main ground surveys are summarized in Fig. 7. Magnetic, electromagnetic, electrical and gravitational techniques have all been used over the deposit.

Two ground magnetic surveys have been completed over the area. The magnetic contours from the more recent survey are shown in Fig. 7 and show a well defined anomalous structure about 1,200 m long striking northeast and widening to the north. A number of faults have been interpreted including a north-south fault downthrown to the east, and coincident with a dolerite dyke bisecting the structure.

In the north, multiple narrow magnetic bands tend to form one composite main magnetic body with a strike swinging to the east, whereas in the south there are two distinct linear magnetic units striking northeast. The interpreted dips of the magnetic units are steeply east and the interpreted depths to top are shallow (ca. 30 m). This confirms that the magnetic units are magnetic peridotite layers overlying the mineralization and not the mineralization itself which is considerably deeper and shallow dipping. Magnetic susceptibility measurements on drill core have confirmed the strongly magnetic nature of the peridotite. The pyrrhotite in the massive sulphide mineralization is largely of the non-magnetic hexagonal variety which would explain its low magnetic response.

The first electromagnetic method used over the area was the TURAM large fixed loop frequency domain system in 1972. This produced several possible linear conductors which were mainly related to surficial features and contacts. Only one conductor in the north may have represented shallow mineralization.

In 1978 the Crone Pulse EM system was used on two lines and an excellent conductor detected over a shallow northern part of the mineralization. This area had been tested already by shallow percussion drilling which had stopped just short of the mineralization and no further drilling had been undertaken.

In 1981 SIROTEM surveying using 100 m square offset loops was completed over the entire magnetic anomaly. This detected a small conductor in the northwestern part of the grid and a larger conductor coincident with the western flank of the magnetic anomaly. Both conductors had excellent conductivities. The highest amplitude response was from the northern part of the main conductor and drilling of this zone resulted in a 24 m intersection of 0.86 per cent Ni+Cu. The interpretation showed this to be the shallow northern end of a conductor plunging to the south. An applied potential (*mise en la masse*) survey carried out in 1984 used the earlier sulphide intersections in drillholes RH 203 and RH 202 as downhole current electrodes.

This survey outlined two separate plate-like bodies plunging to the south with one dipping to the west and one to the east. Drilling of the eastern body resulted in the "discovery" hole (RH207) with 18 m of 3.95 per cent Ni+Cu at a depth of 160 m.

An EM37 fixed transmitter loop survey was carried out in order to detail the main conductor more accurately. This outlined a plate-like body with a strike length of 600 m dipping about 35° east and plunging at about 20° to the south with a depth ranging from 70 m in the north to 300 m in the south. The subsequent drilling programme that outlined the deposit was based upon this interpretation which proved to be substantially accurate.

Downhole SIROTEM surveying was carried out in 1985 using as many holes as possible but was severely hampered by blocked and inaccessible holes. The method did detect good responses in the few holes successfully logged and would be a considerable aid in exploration of similar deposits if holes were preserved.

Density and velocity measurements were carried out on drill core to establish the potential usefulness of gravity and seismic surveys for mapping the basement gabbro interface. The mean density of the basement volcanics was 3.10 g/cm^3 and the various gabbro units averaged about 3.30 g/cm^3. This relatively low contrast would give only a very marginal response at the depths of interest and the resolution would be poor. Modelling showed that the massive sulphide body itself may be just detectable (0.2 mgals) and two trial gravity lines (3300N, 3700N) were surveyed. No response was detected over the deposit. The velocity measurements showed that both the basement and gabbro units have similar velocities of about 6,000 m/sec. Seismic methods are therefore unlikely to be successful.

The Radio Hill deposit is a good example of a successful application of remote sensing techniques (regional and ground geophysical surveys) integrated with traditional exploration methods to discover a blind, potentially economic, massive sulphide deposit.

RESOURCE

The geological resource, in situ and based on 34 diamond and ? percussion drill holes, is up to 2.5 million tonnes at an average grade of 1.5 per cent Ni and 1.4 per cent Cu. This is calculated using a cut off grade of 0.8 per cent Ni+Cu, a 2 m minimum true thickness and a specific gravity of 3.5.

At a 2 per cent Ni+Cu cut off grade, a higher grade zone of mineralization has been delineated within the 0.8 per cent Ni+Cu cut-off grade, with the resource totalling 570 000 tonnes at an average grade of 2.5 per cent Ni and 2.3 per cent Cu.

CONCLUSIONS

The principal conclusions, based on the preliminary work done to date, are summarised in the following

1. The studies conducted on the Radio Hill deposit confirm that the mafic-ultramafic rocks of the West Pilbara region are part of a metallogenic province of economic significance (Barley and Groves, 1984).
2. The Radio Hill deposit has no surface expression of either host rocks or the mineralization. Its discovery was based on appropriate interfacing of exploration methods, particularly in the utilization of SIROTEM and EM37 systems to generate drill targets.
3. The Radio Hill deposit can be classified as a gabbroic associated type (Papunen and Koskinen, 1978; Thornett, 1981; Marston, op.cit.), occurring in a layered mafic-ultramafic sequence of Archean age. The layered sequence was probably intruded along zones of discontinuity developed within the upper crust (Anderson *et al.,* 1979).

   The intrusion is preferentially emplaced within the upper part of the Talga Talga Subgroup, possibly in the Mount Ada Basalt or at the unconformable contact between this unit and the overlying Duffer Formation.
4. Some mineralization is present as disseminated interstitial grains in peridotite-dunite host rock (cumulate layered sequence, clc of Fig. 2) and is considered to be of primary origin. Gabbros and pyroxenites host sulphides that have been locally remobilised and redeposited as stringer and massive concentrations. This is believed to be due to the intrusion of a gabbroic magma (Gl) of genetic affinity with the cumulate layered sequence (Moeskops, 1977).
5. Contrary to what is observed in other deposits, pyrrhotite in the Radio Hill massive sulphides is represented mainly by the non-magnetic, hexagonal variety.

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