

The Petrophysical and Petrologic Characteristics of the Magnetic Igneous Intrusion at Mt Derriwong, N.S.W.

D.W. Emerson¹, B.J.J. Embleton², D. Clark²

¹*Department of Geology & Geophysics, The University of Sydney*

²*Division of Mineral Physics, C.S.I.R.O.*

An isolated, complex, 3000 gamma magnetic anomaly, occurs on the Condobolin-Fifield road about 25 km from Condobolin. It lies in the Girilambone-Wagga Anticlinorial zone of the Lachlan Geosyncline. Poorly outcropping, mostly basic, rocks were sampled for laboratory determinations of susceptibility, density and magnetic remanence. The rocks associated with the anomaly are hornblende rich diorites and pyroxenites with a very variable magnetite content; non-titaniferous magnetite is the dominant iron oxide with minor hematite. The intrusion appears to occur over a 1000 × 1000 metre area; it is heterogeneous in a magnetic density and petrologic sense; the country rock is non magnetic Ordovician metasediment. The physical properties of the three main rock types recognised are: diorite with a density of about 2.80 and a susceptibility range of 0.001 to 0.004 cgs; pyroxene hornblendite with a density of about 3.14 and a susceptibility range of 0.0002 to 0.005 and hornblende pyroxenite with density of about 3.24 and a susceptibility of about 0.0065; the average Koenigsberger ratio is about 0.4. The data indicate a dense, variably magnetic body in which induction contributes the major part of the magnetic anomaly. It is considered that the body is a mafic pod having the form roughly of a cube with a side of about 1000 m. The body is thought to be the remnant of a dioritic stock.

1. Introduction

As part of research on magnetic intrusives in the Palaeozoic of central western New South Wales, the small intrusion at Mt Derriwong was studied (Figures 1, 2). In studying such bodies it was considered that petrological and petrophysical investigation on samples taken from the limited available outcrop could shed some light on the mineralogical, magnetic and geological features of the body causing the aeromagnetic anomaly. This is a much neglected aspect of magnetic

interpretation where unsatisfactory geometrical abstractions are usually invoked to account for causative bodies that are often geologically complex and physically variable. Whereas it may never be possible to obtain a complete and unambiguous picture of an anomalous body's characteristics, a better picture does result if geological and physical properties are taken into account. In addition, the publication of data on relations between the petrology and petrophysics of rock suites will lead to significant improvements in the overall quality of magnetic interpretation.

The aims of the study were twofold. The major and specific aims were: to identify the geological features contributing to the anomaly and to gauge their complexity; to establish the likely origin, mode of emplacement and geological setting of the intrusion; and to determine the rocks' magnetic properties. These factors are relevant to the geophysical interpretation — they provide control, constraints and guidelines for meaningful modelling. The secondary and general aim was to add to the meagre store of petrophysical knowledge. Although the likely causative body is adumbrated, the purpose of this paper was not to give a detailed interpretation of the Mt Derriwong magnetic data.

2. Geology & Geophysics

(a) Regional

Little is known of the detailed geology and geophysics of the Mt Derriwong area. However, the regional setting is fairly well established; this is shown in Figure 1 based on published maps and information from the Geological Survey of N.S.W. and the Bureau of Mineral Resources.

The area lies in the southern part of the Girilambone Anticlinorial Zone where Suppel (1974) describes Ordovician metasediments — largely chloritic quartz mica schists — occurring in an extensive meridional belt with patches of Silurian and Devonian sediments and volcanics. The Palaeozoic sequence has been intruded in a few places by lower Devonian intermediate to basic igneous rock complexes often showing cumulus texture and, being massive, lacking shear or stress textures. The intrusives are dioritic and monzonitic, often with a large component of

hornblende and are thought to have been emplaced during the Bowring tectonism in the late Silurian-early Devonian. Intrusions occur to the north near Fifeild (the Tout Complex) and near Tottenham (the Hylea Complex); further north (off Figure 1) lies the Honeybugle Hornblendite.

All these intrusions have prominent associated aeromagnetic anomalies; to the south at Wyalong a group of dioritic rocks have strong aeromagnetic anomalies too. These localised magnetically anomalous features all occur on the western side of the Girilambone Anticlinorial Zone just off the western edge of a huge, meridional, regional aeromagnetic anomaly over 300 km long, 50 km wide and several hundred gammas in amplitude. This broad belt awaits a study as to its

significance but it would appear to be a major shallow crustal feature probably related to andesitic volcanism. Emerson et al (1972) reported on the Ordovician andesites at Parkes 70 km east of Mt Derriwong. These volcanics have prominent aeromagnetic anomalies that appear to form the eastern edge of the major belt. A regional gravity high coincides approximately with, but is apparently wider than, the magnetic belt.

(b) Local

The Mt Derriwong geology and magnetic anomalies are depicted in Figure 2. Outcrop is poor but the salient features are an Ordovician metasedimentary mica schist basement intruded by a diorite – thought to be Lower Devonian (ca

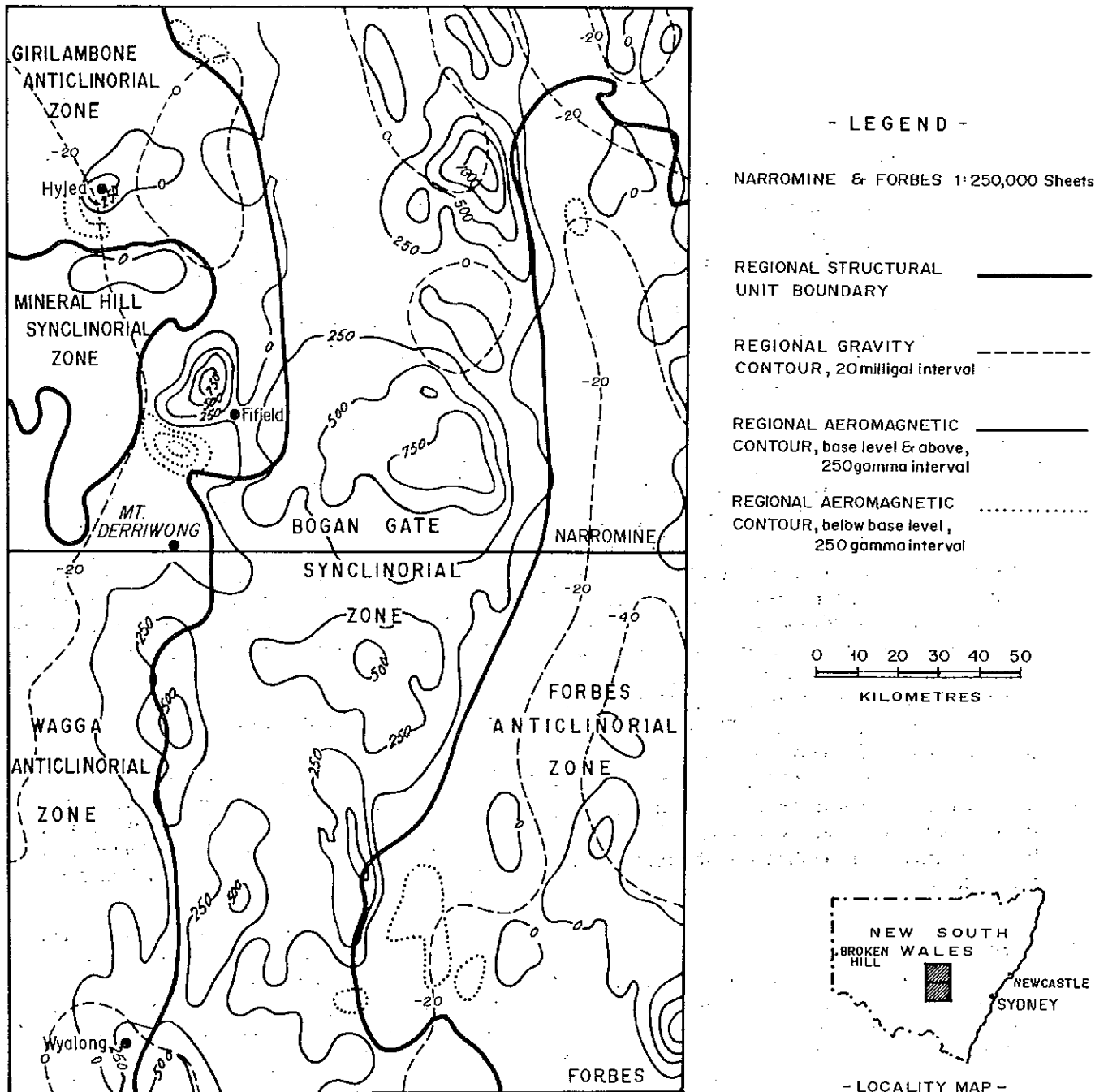


FIGURE 1
The regional setting of Mt Derriwong showing major structural and geophysical features.

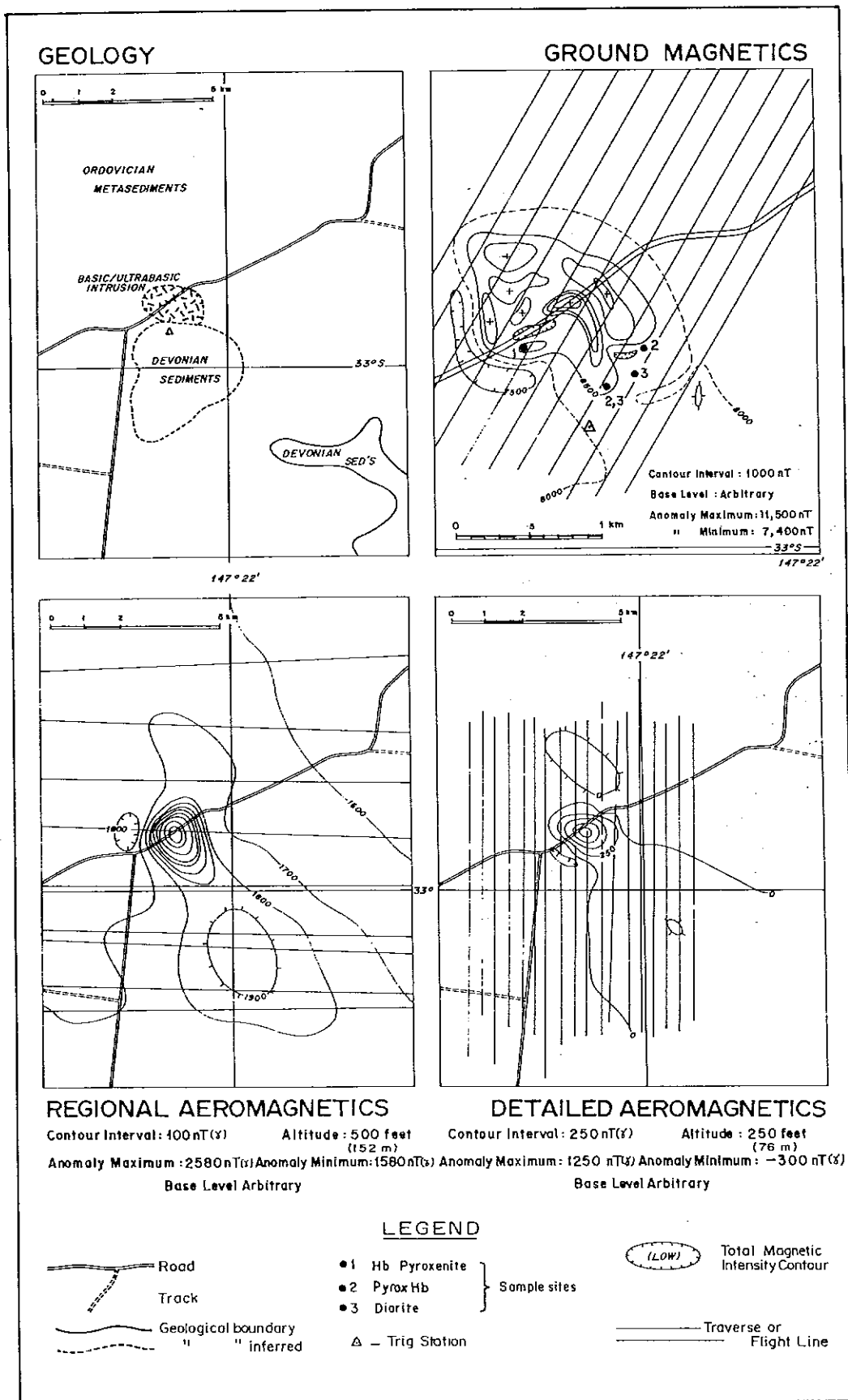


FIGURE 2 .
The Mt Derriwong geology and magnetic anomalies recorded on the ground and in the air.

380 m.y.) on regional relationships. Patches of flat lying later Devonian sediments unconformably overlie the older rocks. Total magnetic intensity contours for regional and detailed airborne surveys and for a ground survey illustrate the increasing complexity of the anomaly as the source is approached.

In sampling the intrusion the great bulk of the rock mass was not accessible and no drilling had been done. Knowledge of the intrusion depended therefore on samples taken from four sites. At Mt Derriwong where the area of good outcrop is limited the necessity of choosing specimens with minimum weathering and fracturing meant that sampling was purposeful and not random. Although the conditions and procedures of sampling were far from ideal, with perhaps one or more major rock types not being sampled, it is considered that sound subjective inferences can be made about the nature of the bulk of the rock mass — the target population. Oriented samples were collected and some oriented cores drilled from the eastern sample sites in excavated pits and a track cutting. Samples from the central area were not oriented as exposures were not good. Lithologies similar to those sampled have been noted in float material over the intrusion.

Some attention was paid to the soil encountered during the study. The soils appear to have been derived from the intrusion, they are about one metre thick and are quite magnetic with *in situ* susceptibilities varying between 200 and 2000×10^{-6} cgs — the average value being about 1000×10^{-6} . An idea of the weathering profile variation can be seen in Figure 3 which shows the susceptibilities measured with an Elliott portable bridge on the side of one of the eastern sampling pits. Soils developed over the sediments are very low in susceptibility.

3. Petrology and Chemistry

By studying many thin sections in transmitted light, three main rock types were recognized: diorite, pyroxene hornblendite and hornblende pyroxenite. The pyroxene hornblendite is somewhat similar to an appinite. The rocks are medium to coarse grained and have undergone only low greenschist facies metamorphism with no signs of major

TABLE 1

Petrology and Chemistry: Mt Derriwong Intrusion			
Rock Class:	Diorite (MD2/B)	Pyroxene Hornblendite (MD5)	Hornblende Pyroxenite (MD2S)
Basicity	increasing — — —>		
Relative Abundance: (Inferred)	minor phases	major (bulk of intrusion)	common (in central part)
Average Modal Proportions of Minerals (Volume percent)			
Plagioclase	60	tr	5
Olivine	—	—	—
Clinopyroxene	2	15	60
Orthopyroxene	1	5	—
Green Amphibole primary & secondary	20	70	30
Biotite	10	—	—
Alkali Felspar	5	5	—
Quartz	tr	—	—
Sphene	0.5	—	—
Apatite	tr	tr	tr
Epidote	tr	tr	—
Calcite	—	3	—
Iron oxides	1.5	2	3+
Sulphides	—	tr	—

Chemical Analyses (XRF LIBO₂ technique: Na₂O: AAS; Fe₂O₃, H₂O, CO₂: Classical)

SiO ₂	53.89	45.71	46.77
TiO ₂	0.78	1.20	0.87
Al ₂ O ₃	15.93	9.22	6.26
Fe ₂ O ₃	4.99	7.52	5.50
FeO	3.97	7.91	8.09
MnO	0.20	0.25	0.22
MgO	4.67	10.61	12.34
CaO	8.01	13.05	17.09
Na ₂ O	3.71	1.20	1.12
K ₂ O	2.80	1.05	0.59
H ₂ O+	1.34	2.00	1.36
H ₂ O-	0.15	0.18	—
P ₂ O ₅	0.42	0.63	0.07
CO ₂	—	—	—
Total	100.86	100.53	100.28

CIPW, Weight percent, Normative Calculations

Calcite	0.00	0.00	0.00
Apatite	1.01	1.48	0.17
Pyrite	0.00	0.00	0.00
Ilmenite	1.49	2.28	1.63
Orthoclase	16.53	6.18	3.51
Albite	31.42	10.17	5.64
Anorthite	18.56	16.66	10.29
Corundum	0.00	0.00	0.00
Magnetite	7.22	10.91	7.97
Diopside	14.58	35.06	59.18
Hypersthene	6.97	13.39	0.00
Quartz	1.61	0.00	0.00
Olivine	0.00	2.24	8.43
Nepheline	0.00	0.00	2.09

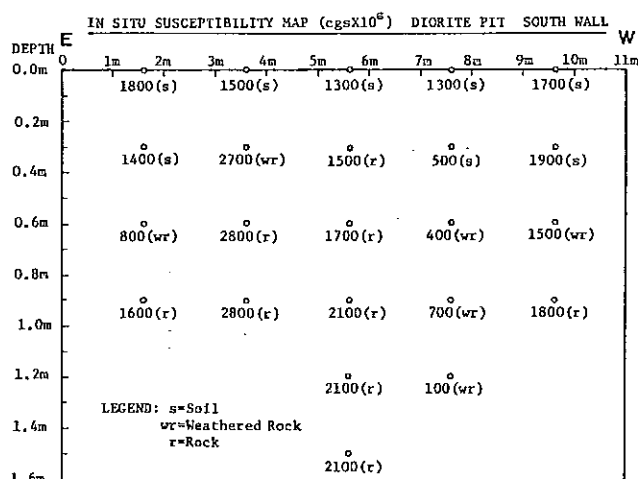


FIGURE 3

Measured susceptibility values in the wall of a sampling pit — site No. 2

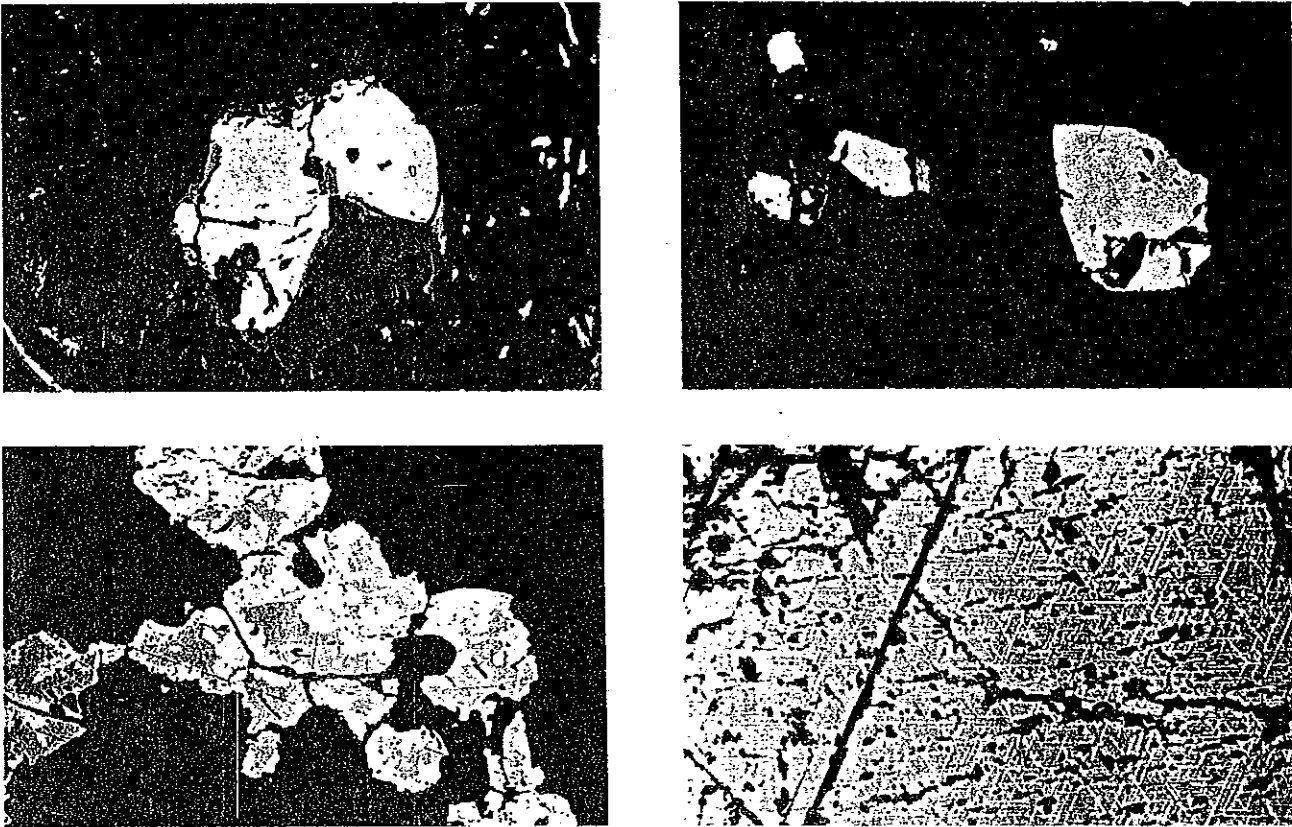


FIGURE 4

Reflected light views (0.36 X 0.25 mm) of magnetites in diorite (t. & b. left), pyroxene hornblendite (top right), diorite (bottom right). Hematite is the white phase in all the magnetite grains (grey); oxidation (martitization) has taken place along the 111 spinel planes in the first three plates with extensive mottling apparent in the third; exsolution intergrowths comprising evenly distributed hematite lamellae are visible in the fourth plate with some oxidation mottling near grain edges.

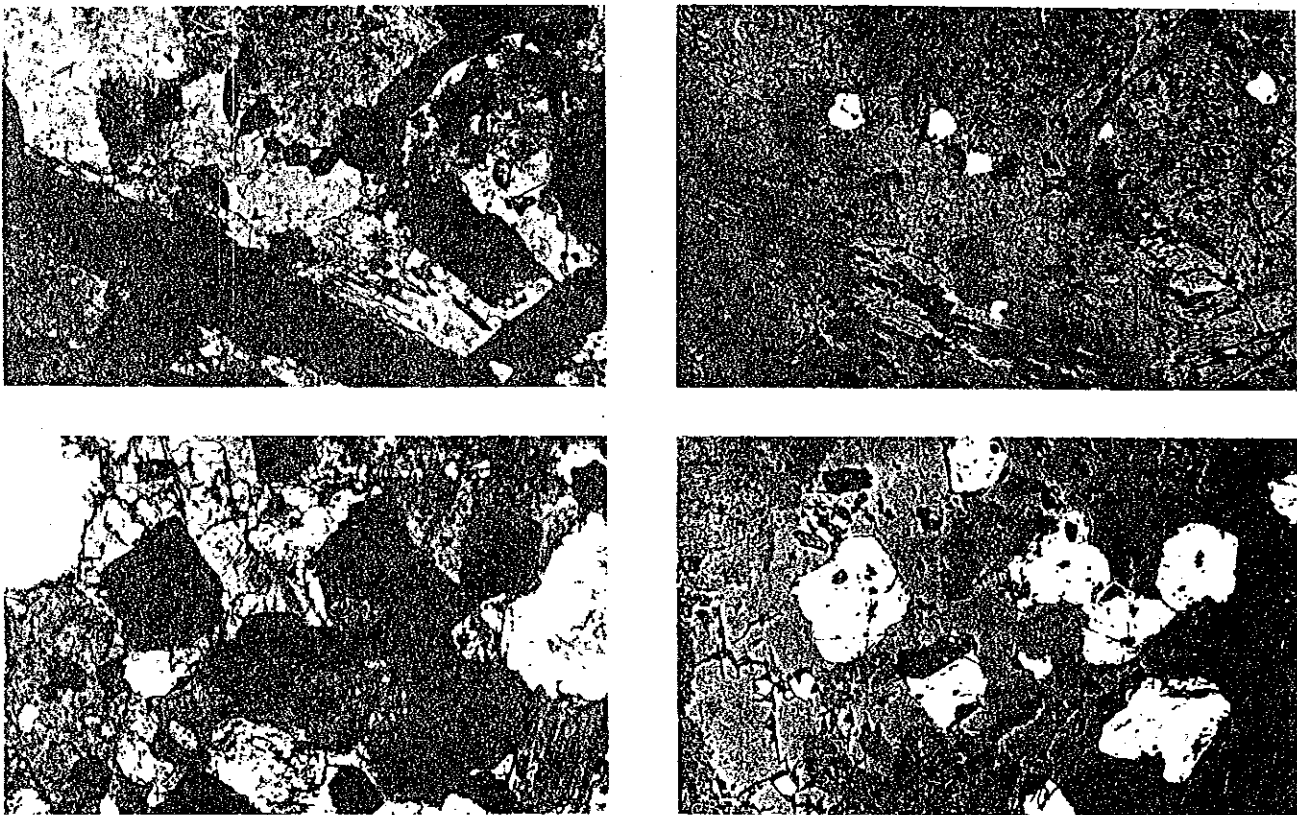


FIGURE 5

Transmitted (LHS) and reflected (RHS) light views (0.73 X 0.5 mm) of magnetites in diorite rock. The equant magnetites are black in transmitted light and grey-white in reflected light. The patchy occurrence of magnetite in these and other plates is typical of that seen in many sections.

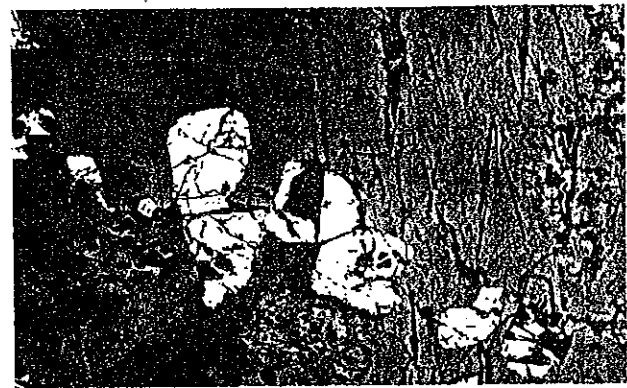


FIGURE 6

Transmitted and reflected light views (0.73 X 0.5 mm) of magnetites in pyroxene hornblendite rock.

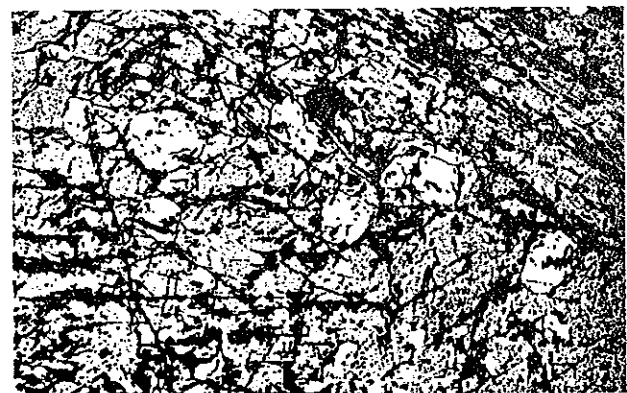
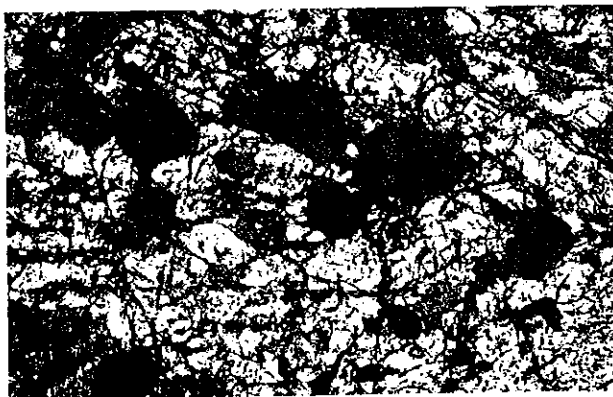


FIGURE 7

Bleb of magnetite in hornblende pyroxenite in transmitted and reflected light (11 X 7.5 mm) — top left and right. Bottom left and right show transmitted and reflected light views (1.5 X 1 mm) of magnetite grains as typically seen in the pyroxenite.

shearing or penetrative deformation. Modal, chemical and normative data are presented in Table 1 where the felsic nature of the diorite is in sharp contrast with the mafic nature of the more basic phases.

4. Opaque Mineralogy

The opaques were virtually all magnetites; studied in reflected and transmitted light they were observed as slightly fractured, partly oxidised, equant grains of primary magnetite. Hematite was noted in two forms; firstly, as ex-solution intergrowths with lamellae due to unmixing of a magnetite-hematite high temperature solid solution on slow cooling; and secondly, as oxidation mottling on the margins of the magnetites. The hematite is minor — perhaps a few percent; the magnetite is non titaniferous and maghemite was not observed. Figures 4 to 7 illustrate the features of the magnetites of the three main rock types.

A range of magnetite content was noted; the diorite, pyroxene hornblendite and hornblende pyroxenite having up to 1.5, 2 and 3 per cent by volume magnetite (visual estimates) respectively, suggesting medium to high susceptibilities. The magnetite occurs in a very variable way. It is not uniformly disseminated but is present as clusters, blebs, veinlets, clumps and irregular disseminations roughly 1 mm apart. Some portions of the rocks have very sparse occurrences. The magnetites generally occur in and around hornblende grains and are usually about 0.1 mm in diameter. Occasional larger magnetites were noted — one bleb in the pyroxenite was 10 mm long (Figure 7). Smaller magnetites were common and the presence of submicroscopic grains was suspected too.

Commonly in most basic rocks titaniferous magnetite is observed with ilmenite intergrowths as a result of subsolidus reorganization of an originally homogeneous member in the high temperature magnetite — ulvospinel solid solution. To verify the non-titaniferous nature of the magnetites, two specimens were analysed by electron microprobe, the results are presented in Table 2. Some difference in the TiO₂ and Cr₂O₃ concentrations are evident but the magnetites are quite similar chemically; both are very low in TiO₂, and thus are pure magnetites that would oxidise along the Fe₃O₄ — Fe₂O₃ join of the FeO — TiO₂ — Fe₂O₃ ternary system. Cubic maghemite may result from low temperature (150-250°C) oxidation but it is metastable and converts irreversibly to trigonal hematite above about 350°C. Maghemite resulting from recent weathering and oxidation is present in only very small amounts if it is present at all. It is thought here that the magnetites have undergone high temperature magmatic oxidation. Low (and high) temperature oxidation of titanium poor magnetite typically yields hematite (Haggerty, 1976). Although magnetites from the pyroxenite were not analysed, their optical similarity to the others also suggests a very low TiO₂ content.

X-Ray powder photographs of the magnetic fraction of the soils indicate that magnetite with minor hematite and no maghemite is the magnetic mineral. Thus the magnetites in the soils and rocks are very similar; the former certainly being derived from the latter.

5. Discussion — Geological Model

The data so far adduced facilitates the formulation of a reasonable geological model for the Mt Derriwong intrusion.

TABLE 2
Microprobe Analyses of Magnetites, Mt Derriwong

Components (Weight %)	Diorite (MD — 2/B)						Pyroxene Hornblendite (MD — 5)							
	Location 1		Location 2		Location 3		Location 1		Location 2		Location 3			
	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 3	
MgO	—	0.13	0.06	0.04	0.05	0.09	0.04	0.03	0.07	0.03	0.02	0.07	0.04	0.32*
Al ₂ O ₃	0.05	0.09	0.07	0.10	0.03	0.07	0.11	0.09	0.05	0.09	0.32	0.12	0.09	0.38*
SiO ₂	0.12	0.11	0.11	0.10	0.19	0.15	0.15	0.15	0.14	0.13	0.15	0.10	0.11	0.66*
TiO ₂	0.06	0.05	0.04	0.04	0.01	0.03	0.06	0.02	0.06	0.09	0.14	0.10	0.06	0.10
Cr ₂ O ₃	0.16	0.16	0.08	0.09	0.12	0.10	0.08	0.10	0.22	0.20	0.27	0.42	0.42	0.41
MnO	0.05	0.08	0.04	0.06	0.05	0.08	0.03	0.07	0.01	0.06	0.06	0.05	0.04	0.05
Fe ₃ O ₄	99.75	99.96	99.10	99.15	98.78	100.50	99.95	99.81	98.76	98.07	97.65	99.66	99.53	97.83
Total	100.19	100.58	99.50	99.58	99.23	101.02	100.42	100.27	99.46	98.67	98.61	100.52	100.29	99.75

Note: Total Fe expressed as Fe₃O₄, *possible slight silicate contamination, "location" refers to different clusters of magnetite grains in the one thin section, "site" refers to two or three different points in the same cluster of grains.

On the basis of the normative calculations it would be tempting to propose a volcanic feeder pipe-like body of great depth extent and belonging to the tholeiitic association derived from the partial fusion of mantle material. But the norms reflect the abundance of hornblende and are not reliable for inferring magma types especially for plutonic

TABLE 3 — Physical Properties

Mt Derriwong intrusion, Narromine 1:250,000 sheet N.S.W.; lat. 32°59'S, long. 147°21'E; earth's magnetic field: 0.58 oersted, inclination -64°, declination 10°E.

Physical Properties	Diorite	Rock Type Pyroxene Hornblende	Hornblende Pyroxenite
Number of specimens	20	20	7
Density, dry, gms cm ⁻³ , average value	2.80	3.14	3.24
Density range of values	2.75 - 2.92	3.10 - 3.19	3.20 - 3.29
Magnetic volume susceptibility, cgs X 10 ⁶ , average **	3288	2755	6483
Susceptibility, range	1000 - 4420	200 - 5000	6250 - 6750
Intensity of magnetization (I) emu/cm ⁻³ X 10 ⁶ , average	1908	1598	3760
Susceptibility anisotropy, major/minor axis, average	1.11	1.13	1.10
Susceptibility anisotropy, range	1.04 - 1.14	1.05 - 1.22	1.05 - 1.20
Natural remanent magnetization NRM, 'microgauss', average ***	287	675*	2550
NRM range	10 - 580	96 - 1997*	610 - 4440
Koenigsberger ratio, NRM/I, average	0.15	0.57*	0.71
Koenigsberger ratio, range	0.02 - 0.41	0.15 - 0.95*	0.41 - 1.13
Initial directions NRM	scattered, but mostly north and northeast directions with low negative inclinations		N.A.
Final directions NRM after AF cleaning	scattered, but generally east directions with low negative inclinations		N.A.

Note: Units used are cgs for convenience and practicality, to convert to SI multiply cgs values by following factors: density kg m⁻³ = 1000 gm cm⁻³; susceptibility dimensionless but SI value = 4π cgs; intensity of magnetization Amp. metre⁻¹ = 10⁻³ cgs (gauss or emu cm⁻³).

* The hornblende diorite remanence values do not include four specimens from one site with very high NRM: average 30740, range 12200 - 59430; Koenigsberger ratio: average 13.2, range 4.4 - 21.1. This spot might have a large IRM due to lightning.

** On a semi log frequency plot of all susceptibility values a bimodal curve results with peaks at 750 and 4300 X 10⁻⁶.

*** A plot of all the NRM values is log normally distributed with a peak at 250 microgauss.

Country Rock: The measured susceptibilities of the Ordovician schist and Devonian sediment are very low; the dry densities of these country rocks are 2.75 (schist) and 2.61 (sed.).

Soils: In situ and laboratory susceptibility measurements indicated a range of 200 to 2000 with an average of 1000 X 10⁻⁶ cgs; the NRM is very low - about 30 microgauss.

TABLE 4

Mt Derriwong Remanence Data

Raw in situ directions

	Average Direction — Mean-Declination Inclination (Azimuth) (Dip)		Fisherian Statistics accuracy scatter, c.s.d.	
	α ₉₅	θ _{α3}	α ₉₅	θ _{α3}
Diorite	17.5°	-32.8°	26.6°	33.0°
Hornblende Diorite	42.9°	-32.8°	45.7°	41.8°
All	27.5°	-33.4°	21.7°	36.3°

Directions after AF cleaning

Diorite	61.0°	-34.1°	26.4°	32.5°
Hornblende Diorite	70.4°	-9.8°	27.5°	27.5°
All	65.5°	-27.7°	18.4°	31.8°

Palaeolatitude 15°

Virtual Geomagnetic Pole: 27°S, 54°E (27°N, 234°E)

Earth's field at Mt Derriwong: Decl. 10°E Incl. -64° Intensity 0.58 oe.

rocks. Important evidence is provided by the magnetites. Typically, titanomagnetites occur in dry, high-temperature (1000°C) tholeiitic basaltic magmas but usually magnetites are titanium poor in hydrous, relatively low temperature (800°C) calc-alkaline magmas (e.g. see data: Buddington & Lindsley, 1964). Indeed the abundance of primary hornblende suggests a wet (5% water) magma, and the hornblende/plagioclase/orthoclase mineralogy fits into the calc-alkaline category. It is thought on the basis of mineralogy, texture and character that the three rock types are comagmatic. The existence of the three rock types points to a heterogeneous, complex intrusion.

A felsic magma is proposed to have been generated in the lower crust from where it rose as a diapir to crystallise over a period of perhaps a million or more years of continual or periodic injection into tensional openings in the upper crust. Continuing magma pulses during crystallization would mean that earlier mafic rock phases would be distributed in a chaotic way as the magma convected. Clinopyroxene crystallises first so it would accumulate as pyroxenite agglomerate that would tend to settle towards the bottom of the magma pod. Hornblende and magnetite then crystallise out with ferric iron available and oxygen fugacity high. Feldspars are the last to crystallise. It should be noted that the low alumina and lack of biotite are not usual for a calc-alkaline magma, it is possible that the Mt Derriwong magma type is in an indefinite area between the calc-alkaline and tholeiitic categories. Nevertheless this does not vitiate the model, the main element of which is the felsic nature of the magma that would, in gross terms, be expected to crystallise out at least half as leucocratic components i.e. diorite. These, being lighter, would rise towards the top of the magma pod or stock; the mafic and ultramafic parts would tend to settle towards the bottom with overlap and gradations between the various phases and they would have a random or chaotic arrangement. Erosion would be expected to remove the higher, mainly dioritic, part of the chamber leaving a multi-phase rock complex as a remnant.

The model proposed implies that the body is depth limited with only a narrow neck, if anything, connecting the body to the lower crust. The nature of the rocks suggests that the intrusion is post tectonic so it is probably related to a Palaeozoic cratonization process. It is possible that the magma was generated in the lower part of the thickened continental crust where raised geotherms led to local melting. On the other hand, isostatic adjustment between two crustal blocks might have depressed crustal material to a level where local melting occurred.

It is considered that the whole region would be likely to contain many such heterogeneous intrusions at a variety of vertical levels. Such intrusions would be expected to be quite dense in their lower parts and variably magnetic overall.

6. Physical Properties

Measurements of density, magnetic volume susceptibility and anisotropy of susceptibility were made on samples collected. The densities of dry specimens were determined on an Ohaus balance; the saturated (wet) densities of igneous rocks such as these, with extremely low porosities, should not be very different (e.g. cf. Gupta and Burke, 1977). Magnetic property measurements, were carried on a Digico susceptibil-

ity bridge and a Digico anisotropy delineator. The results are presented in Table 3. There is no correlation between susceptibility and density, as the plots in Figure 8 make clear; the coefficient of correlation is 0.2. The rock types, both felsic and mafic, manifest medium to high susceptibilities; the pyroxenite has a large susceptibility while the pyroxene hornblendite has some quite small values. Overall the susceptibilities reflect the visual estimates of magnetite content in the thin sections — along the lines of the simple equation relating susceptibility to magnetite content as given by: Nettleton & Elkins (1944), Mooney & Bleifuss (1953) and Balsley & Buddington (1958).

In considering the susceptibilities of the Mt Derriwong rocks the only recognisable independent variable is the amount of magnetite. The individual susceptibilities of the magnetite grains are not that important because geometric and demagnetization effects result in an effective grain susceptibility of about 0.25 cgs — not the laboratory measured value of around unity. The relative basicity of the rocks does not seem to be so important as shown by the overlap of values for diorite, hornblende diorite and pyroxenite. However when maximum measured values of susceptibility (and density) are considered then they increase with ascending basicity.

The anisotropy of susceptibility measurements are given as ratios of the major to minor axis of the ellipsoid. Anisotropy is only minor (about 10%) indicating a lack of magnetic fabric; the intrusion is probably unstressed. As the rocks are virtually isotropic in a magnetic sense corrections for deviation of magnetization (induced and remanent) from the geomagnetic field are not necessary — the maximum deflection of 10% anisotropy is less than three degrees (McElhinny, 1973).

7. Rock Magnetism

Magnetic anomalies of rocks are due to the magnetization resulting from the vector addition of a component induced by the earth's field and the natural remanent magnetism (NRM). Remanence measurements were made on a Digico spinner magnetometer to determine intensity (\bar{J}) and direction. The stability of NRM was tested on a Schonstedt alternating field demagnetization apparatus. The induced component of magnetization (\bar{I}) was calculated as the product of the susceptibility (k) and the magnetizing force of the earth's field \bar{H} . The relative magnitude of both components is Q the Koenigsberger ratio $Q = J/kH$. The NRM has considerable influence on the nature of observed magnetic anomalies unless Q is small.

A summary of the results is given in Tables 3 (lower part), 4 and Figures 8b, 9. The mafic rock types exhibit considerably more remanence than the diorite. Generally Q is less than one but the pyroxene hornblendite and pyroxenite values indicate that remanence will be a significant influence on the magnetic anomalies' shape and magnitude. Correlation overall between the induced and remanent magnetization is fair with a coefficient of 0.6. This is to be expected as both depend on the occurrence of magnetite, the induced component varying directly with the amount of magnetite and the remanent component being a complex function of domain structure, amount and history of the magnetite.

Typical plots of the raw remanent directions show considerable scatter although generally the northeast quadrant and a

low negative inclination are favoured. The scatter exhibited by the directions is typical of Palaeozoic igneous rocks; it could be due to magnetic "creep" over time as partial thermoremanent magnetizations are acquired over successive temperature intervals to give the total TRM. Progressive alternating field demagnetization rotated the NRM directly to an easterly setting as shown in Figure 9; the generally low negative inclinations and the scatter still obtain. Initially the directions have a planar great circle distribution; on cleaning this planar tendency is reduced and the directions have moved away from the present or dipole field. If the intrusion had been remagnetized by the present or dipole field it would be expected that the planar distribution would pass through these points on the stereographic projection. The magnetizations appear to be genuinely ancient (tectonic stability has obtained in the area), and the virtual geomagnetic pole (Table 4) is consistent with Siluro-Devonian results believed to refer to the main Australian platform.

The typical demagnetization curves are shown in Figure 9 where a degree of moderate instability is indicated showing that a proportion of the NRM is of secondary origin with isothermal and viscous components. The magnetic behaviour suggests the presence of single, pseudo-single and multidomain grains of magnetite in the rocks.

The calculations and statistics in Table 4 quantify the directional scatter. An F test demonstrates that the diorite and hornblende diorite directions are not significantly different but the large α and Θ parameters mean that no definite direction and inclination can be ascribed to the remanence in situ. All that can be inferred from the data is that a northeasterly azimuth and a low negative inclination might approximate the bulk of the intrusion's remanence. It should be noted that this is suggested on the basis of limited surface sampling in which oriented samples of the hornblende pyroxenite could not be collected.

8. Discussion

The data show ranges of susceptibility and density that reflect the intermediate — basic nature of the rock types tested. Poor outcrop and imperfect sampling mean that the data cannot be regarded as definitive in a petrophysical sense especially as there appears to be a quite magnetic rock unit that was not accessible — none of the sample sites was near a major magnetic peak. Nevertheless the data are invaluable in outlining the properties of parts of an intrusion that appears to be in gross terms quite magnetic, with medium to high susceptibilities; with generally high densities; but heterogeneous in a petrophysical and petrological sense. The remanence results show that the directions are not random and the magnitudes are not small; so the remanence is significant and important in understanding the magnetic anomalies. It is considered that the petrophysical measurements do suggest likely "average" properties of the bulk of the intrusive mass; however there are too many unknowns and too few data to solve the magnetics in a detailed way. It would be possible to present a detailed solution of internal features, however, its merits would be more geometric than geologic in the absence of adequate control.

9. Gravity Data

The density measurements suggest a density contrast of

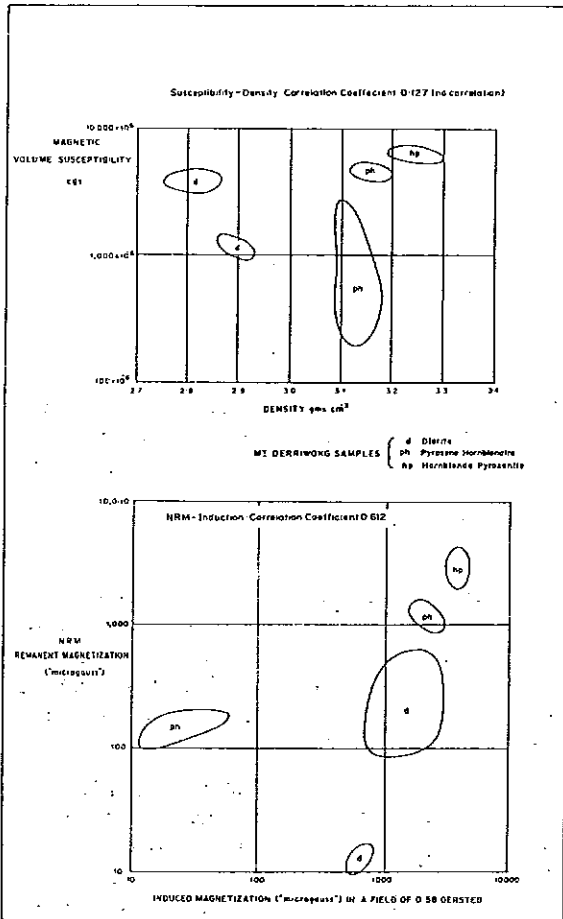


FIGURE 8
Plots of susceptibility – density and induced magnetism – remanence for the sampled suites of Mt Darrivong rocks. Boundaries shown encompass scattered prints

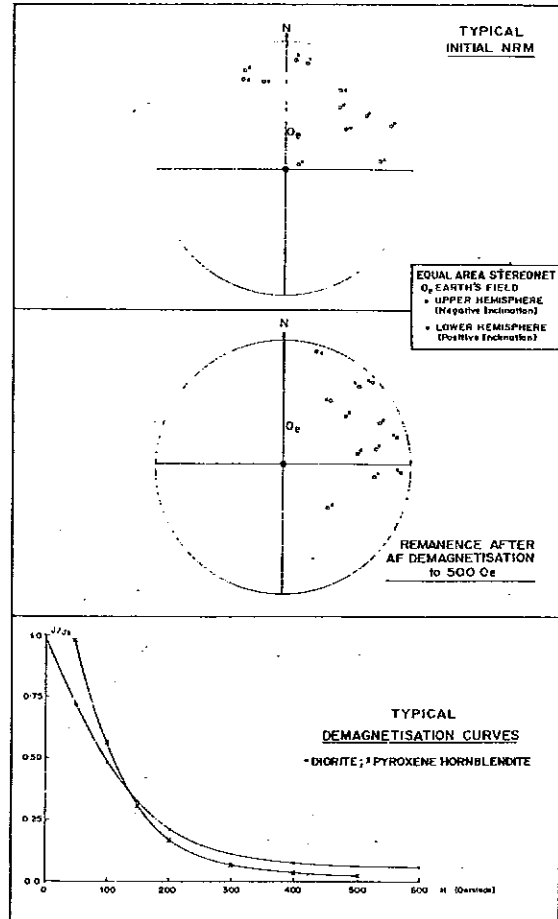


FIGURE 9
Equal area projections of some initial and final remanence directions; typical alternating field demagnetization curves.

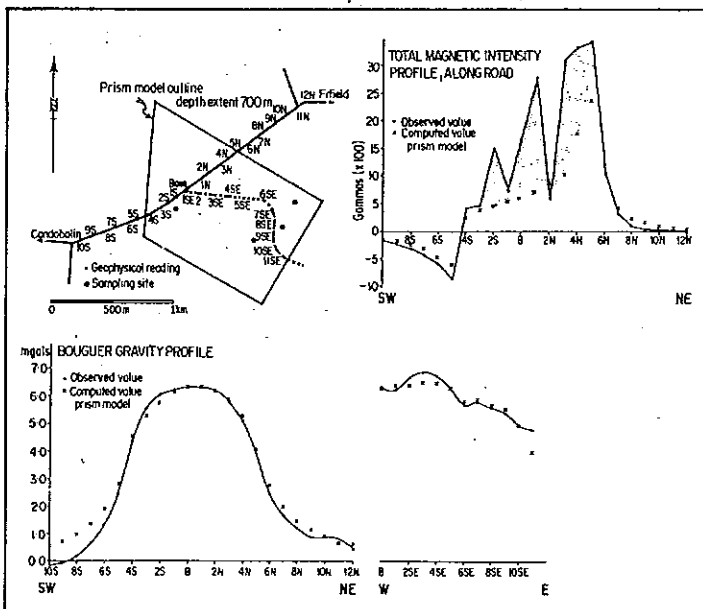


FIGURE 10
Magnetic and gravity modelling of an outcropping prismatic body (depth extent 700 m) with trapezoidal section in plan view to account for the gravity anomaly and the gross features of the magnetic anomaly. The stippled portion of the observed magnetic anomaly is due to local irregular magnetic features in the intrusion. The density contrast used was 0.4 gms/cc and the susceptibility contrast was 3000×10^{-6} with a Koenigsberger ratio of 0.5.

about 0.4 gms cm^{-3} for the intrusion if it is dominantly mafic in composition, as is thought likely on the basis of the lithologies observed in outcrop and noted in float. To assist in the magnetic interpretation gravity profiles were run through and across the body by establishing 36 gravity stations on the main road and side tracks. The accuracy of an individual reading was estimated to be 0.05 milligals (0.5 micro Galileos). The symmetrical anomaly observed on the main profile, northeast to southwest, was 6.35 milligals with a half width of one km. This profile traverses to the west of the intrusive's centre (Figure 10).

10. Magnetic Anomalies

The magnetic anomalies associated with the intrusion are shown in Figures 2 and 10. The ground magnetics show an intense and complex anomaly. The simplicity of the airborne anomalies and their lack of resolution contrasts with the complexity of the ground anomaly. The regional aeromagnetics give a misleading picture owing to line spacing and direction effects.

It is commonly thought the depth extent of a magnetic body can be gauged from the field fall off with height. For example, a compact body shows a $1/r^3$ fall off where r is the distance from the source; a body greatly extended in one dimension, such as pipe, shows a $1/r^2$ fall off. But these relations only hold for the far field — they do not obtain close to the source. Within say 300 m, in the near field, the fall off rate for cubes and pipes is about $1/r^{0.3}$. Thus the Mt Derriwong data are not diagnostic in estimating the form of the source. Magnetic modelling of prismatic bodies shows that the computed results are insensitive to the depth extent of the magnetic body. Thus it is generally not possible to determine the base of a prismatic body from magnetics alone; in this case the gravity data were used to corroborate the magnetic analysis.

11. Interpretation

To model the gross form of the intrusion a prismatic body was chosen with a bulk susceptibility of 3000×10^{-6} c.g.s., a Q value of 0.5, a remanence azimuth of 65°E and an inclination of -20° . These variables are within the range of those measured, the remanence chosen is close to the average direction after cleaning of all specimens tested, and a fair contour match is obtained especially for the observed and computed lows to the south west of the body. The inference then is that for this intrusion its bulk is characterised by a stable remanence direction relatively unaffected by viscous components and that surface samples need magnetic cleaning to give a good estimate of the *in situ* remanence.

The plan view of the gross body is a trapezoid with largest side 1600 m as shown in Figure 10. The body has vertical sides and extends to 700 m depth. The magnetic field of this body gives a reasonable match to the ground and airborne contours in outline but not in magnitude over the high. However if the computed field is subtracted from the observed ground field then several sharp "local" anomalies are left. These spiky anomalies (shown stippled in Figure 10) are due to local igneous phases within the intrusion (their shape cannot be estimated nor can the width or depth extent). But as a hypothetical example, noting that the susceptibility-thickness product is the controlling factor, if a susceptibility of $6,000 \times 10^{-6}$ is assumed, then regular bodies can be

used to approximate the sharp anomalies. The calculated fields give the right order of magnitude at the level of the airborne anomalies too. It should be clearly understood that such bodies are not claimed to exist; rather it is thought that random or quasi random occurrences of high susceptibility pyroxenitic bodies add to the field of the gross body producing the complex anomaly observed. These randomly occurring bodies may have the form of blocks, pods, bands, dykes or pipes with varying attitudes. They probably represent magnetite concentrations like those, and in excess of those, noted in the three recognised rock types. For instance, late stage hydrothermal alteration could generate magnetite rich zones in shears as a result of the oxidation of ferrous iron contained in silicates. To test this point, a prism containing a random arrangement of high susceptibility spheres — representing igneous pods — was modelled. The results showed a remarkable similarity in amplitude and character to the internal, complex part of the anomaly.

As noted previously the magnetic model is not very sensitive to changes in depth extent. To check this uncertainty a density contrast of 0.4 was applied to the 700 m deep trapezoid model. Its computed gravity field (Figure 10) gives a very good match to the observed gravity values and credence is given to the magnetic interpretation. On the basis of the magnetic and gravity interpretations it cannot be asserted definitely that the body has this gross form. But it can be said that if the country rock at depth is schist and if the body has vertical sides, a not unreasonable assumption for an igneous intrusion, then it is depth limited. Furthermore its overall composition is mafic as indicated by the density contrast because other combinations of depth extent and density contrast do give the correct anomaly amplitude but not the correct anomaly shape. For similar reasons upright or inverted truncated pyramidal bodies are inappropriate. Of course a variety of bodies with quite irregular shape could account for the magnetic and gravity anomalies but these can be rejected on general geological grounds as being implausible.

Through the Poisson Theorem relating the gravity and magnetic potentials it should be possible to derive physical property relationships without knowing the shape of the source body (Cordell and Taylor, 1971). If physical properties are known then the source body shape can be better estimated. However such an approach is based on the existence of an homogeneous causative body which clearly is not the case at Mt Derriwong. Here the body outline has been estimated by assuming a background uniformity of physical properties. (These produce the main part of the potential field anomalies; the inhomogeneities (positive or negative in contrast) give the remainder of the field and are responsible for the anomaly complexity.) It is not possible to interpret confidently the sources of these superimposed magnetic anomalies without additional surface and subsurface control. Although the gravity field could only be measured on the available road and tracks the good match and absence of complexity suggest a fairly homogeneous, high density intrusion. Given the range of measured densities this suggests that the diorite is a minor phase.

12. Concluding Remarks

A multi-phase dioritic intrusion is clearly associated with the complex magnetic anomaly; the petrology and chemistry

of the intrusion suggest a calc-alkaline affinity i.e. a hydrous magma generated in the lower crust and rising to form an intermediate-basic composite pluton; the physical properties measured indicate a dense and quite magnetic body in bulk; in detail the magnetization is variable in magnitude owing to a range of susceptibilities, with overlap between rock types, but the directions of resultant magnetization are confined to the northeast quadrant. The data presented are new and thus augment the background information to which interpreters continually refer.

Where an anomalously magnetic igneous rock is accessible for sampling, petrological and petrophysical studies afford insight into the nature of magnetic anomalies; such work is essential in understanding the characteristics of magnetic bodies and their signatures. Any magnetic interpretation involves the formulation of a geological hypothesis, however naive or simple. Preliminary laboratory studies help in the framing of a meaningful geological model with accurate, if not definitive, physical properties assigned to it. At Mt Derriwong the weight of geophysical evidence tends to corroborate the geological hypothesis advanced.

In this study the misleading simplicity of the aeromagnetics is noteworthy. It contrasts with the complexity of the ground magnetics where the composite nature of the anomaly is clearly apparent. This heterogeneity precluded a detailed interpretation but even the broad interpretation is in debt to the gravity and laboratory measurements. It is considered that the results of detailed magnetic interpretations in local hard rock investigations should be treated with reserve in the absence of auxiliary control. The comment is especially applicable to aeromagnetics where often little attention is paid to problems of anomaly resolution.

13. Acknowledgements

It is a pleasure to acknowledge the help of many colleagues in discussions on the petrology of the intrusion: Dr R.A. Binns, of the CSIRO Mineral Chemistry Division, was particularly helpful as was Dr W. Ryall; Dr K.L. Williams was of considerable assistance with the mineragraphy and photography. R. Beck did the chemical analyses, R. Sealy prepared the plates, L. Hay drafted the figures and Mrs D. Garbler typed the manuscript. The magnetic and gravity modelling was done with computer programs written by B.E. Long whose help and advice were much appreciated. The laboratory work was carried out using the facilities of the CSIRO Division of Mineral Physics, the analysis and interpretation were done in the Dept. of Geology and Geophysics, University of Sydney. The magnetic data are available on open file at the Geological Survey of N.S.W. — GS 1973/197,389.

References

- BALSLEY, J.R. and BUDDINGTON, A.F., 1958. Iron-titanium oxide minerals, rocks and aeromagnetic anomalies of the Adirondack area, New York. *Bull. Soc. Econ. Geol.*, V. 53, pp. 777-805
- BUDDINGTON, A.F., and LINDSLEY, D.H., 1964. Iron-titanium oxide minerals and synthetic equivalents. *Jour. Petrology*, V. 5, pp. 310-357
- CORDELL, L., and TAYLOR, P.T., 1971. Investigation of magnetization and density of a North Atlantic seamount using Poisson's theorem. *Geophysics*, V. 36, pp. 919-937
- EMERSON, D.W., SMITH, M.J., and TEMPLETON, R.J., 1972. Aeromagnetic survey over lower Palaeozoic andesites in the Parkes-Daroolbaigie area, N.S.W. *Bull. Aust. Soc. Explor. Geophys.* V. 3, No. 2, pp. 1-12
- GUPTA, V.K., and BURKE, K.B.S., 1977. Density and magnetic susceptibility measurements in southeastern New Brunswick. *Can. Jour. Earth Sci.*, V. 14, pp. 128-132
- HAGGERTY, S.E., 1976. Opaque minerals oxide in terrestrial igneous rocks. Mineralogical Society America Short Course Notes, Vol. 3 Oxide Minerals, ed. D. Rumble; ch. 8
- McELHINNY, M.W., 1973. *Palaeomagnetism and plate tectonics*. Cambridge Uni. Press, 358 pp.
- MOONEY, H.M., and BLEIFUSS, R., 1953. Magnetic susceptibility measurements in Minnesota. Part 2: analysis of field results. *Geophysics*, V. 18, pp. 383-393
- NETTLETON, L.L., and ELKINS, T.A., 1944. Association of magnetic and density contrasts with igneous rock classifications. *Geophysics*, V. 9, pp. 60-78
- SUPPEL, D.W., 1974. Girilambone anticlinorial zone. *The Mineral Deposits of New South Wales*, eds. N.L. Markham & H. Basden, pp. 118-131. Geol. Surv. N.S.W., Sydney