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Exploration and Mining Report 436R

PHYSICAL PROPERTIES, MAGNETIC AND RADIOMETRIC SIGNATURES OF THE KIDSTON-LOCHABER AREA: IMPLICATIONS FOR EXPLORATION

D.A. Clark and B.L. Dickson

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Prepared for AMIRA Ltd (P426)

November 1997

CSIRO Exploration and Mining
PO Box 136, North Ryde, NSW, Australia

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Executive Summary

This report presents petrophysical data from the palaeomagnetic, rock magnetic and radiometric studies carried out in the Kidston-Lochaber area by D. Clark and B. Dickson as part of P425/426. The magnetic, density and radiometric properties of the samples collected for this study have been incorporated into petrophysical databases which have been supplied in various formats to all sponsors of P425. The petrophysical databases are essential tools for interpreting the geophysical signatures of the Kidston Breccia Pipe and the Lochaber-Bagstowe Ring Dyke Complex. Clear relationships between physical properties and lithology, alteration and rock age have been established, which add insights to the geological interpretations as well as constrain geophysical models.

In spite of their very felsic composition, the Lochaber and Bagstowe Granites have moderate susceptibilites due to their oxidised nature, which favours partitioning of some of the limited available iron into magnetite (up to 0.1 vol %). The Black Cap Diorite, which rims the Bagstowe Granite and represents an early stage in the magmatic evolution of the Lochaber-Bagstowe Complex, is the most magnetic rock type sampled, reflecting the oxidised nature of the magma, coupled with its larger iron content. Compositionally similar andesite dykes at Kidston have similar susceptibilities. Felsic dykes and porphyries are generally very weakly magnetic, but the magnetic properties of the breccia phases in the pipe are very variable, reflecting variability in clast lithology and degree and type of alteration. Gneisses and amphibolites of the Einasleigh Metamorphics have generally low to moderate susceptibilities, except where altered at Kidston.

The dominant alteration types at Kidston (phyllic and albitic) are magnetite-destructive. On the other hand, early potassic (biotite) alteration, of restricted occurrence, is associated with magnetite and locally enhances magnetisation. At shallow levels phyllic alteration is associated with pyrite, whereas higher temperature, deep phyllic alteration is associated with pyrrhotite, which is the main magnetic mineral in the pipe, as well as pyrite. Weak propylitic alteration is largely magnetite-stable, whereas more intensely developed propylitic alteration is partially magnetite-destructive.

The palaeomagnetic results from reliable samples indicate that the magmatic and hydrothermal evolution of the Kidston-Lochaber suite spanned several geomagnetic reversals in the Early Carboniferous, suggesting a duration of several million years. Remanence is subordinate to induced magnetisation in most rock units with the following exceptions:

- the deep phyllic, pyrrhotite-bearing zone in the Kidston Breccia Pipe, which carries relatively strong NRM of dual, but predominantly normal, polarity,
- moderately magnetic, potassically altered metamorphics adjacent to Macks Porphyry, which carry a reversed remanence, associated with moderate to high Koenigsberger ratios.

Densities of the rock types represented in the Kidston-Lochaber area vary predictably with the content of mafic minerals in the rocks. Some density changes seem to be produced by alteration, but the effects on the overall density contrast between the pipe and its host rocks appear to be minor. Phyllic and albitic alteration appear to reduce the density of affected rocks by ~0.02 g/cm^3 , whereas alteration associated with pyrrhotite (deep phyllic and potassic with pyrrhotite veins) increases the density by a comparable amount. The data suggest that Kidston Breccia Pipe exhibits a small negative density contrast with the surrounding rocks. Such a density contrast should produce a detectable gravity anomaly, with an amplitude of about

-10 g.u. (-1 mgal) over the pipe. Detailed gravity surveys over the inferred buried intrusions flanking the Kidston mine area might define the subsurface distribution of porphyry and breccia phases, which could be prospective for Kidston-type mineralisation.

Analyses of radioelements show that the Lochaber and Bagstowe Granites are particularly rich in radioelements, reflecting the felsic and fractionated nature of these intrusions. This enrichment is also seen in the quartz-feldspar porphyry dykes in the area between the granites and the Kidston complex. Two other porphyries (Wises and Macks Porphyry) and the Median Dyke, all associated with the complex, do not have the high eU and eTh contents found in the larger intrusions. Unaltered Oak River Granodiorite in the area has low abundances of the radioelements, especially eTh, relative to the Einasleigh Metamorphics. Alteration associated with mineralisation in brecciated granodiorite or polymictic breccia within the pipe is K-rich. Loss of K due to breakdown of feldspar during weathering is evident in soils developed over unaltered felsic rocks in the Kidston area. Potassium in muscovite tends to be less depleted by weathering, because muscovite is more resistant to weathering than feldspar.

Significant features of the aeromagnetic data include:

- zonation of the Lochaber Granite from a relatively magnetic margin to a less magnetic core, accompanied by a substantial increase in Th and U evident in the radiometrics,
- a prominent magnetic high rimming the western and southern margins of the Bagstowe Granite, which arises from the Black Cap Diorite,
- major magnetic lineaments corresponding to NE-trending structures, such as the Gilberton Fault and the Noel Fault, that appear to have influenced emplacement of the Lochaber-Bagstowe complex and, in the case of the Noel Fault, may have been a control on the Kidston pipe,
- a faintly discernible set of NNW-trending lineaments that passes through the Kidston area, parallel to the main trend of the Paddys Knob dyke swarm and coincides with the axis of the underlying batholith that has been interpreted from gravity data,
- structures that appear to be important in localising the Kidston Breccia Pipe are represented by truncations of narrow linear features in first vertical derivative images, or by changes in their trend,
- two diffuse highs, with superimposed local anomalies, immediately NW and SE of Kidston. These may represent stocks emanating from the underlying batholith, with apophyses that almost reach the present surface.

The zonation of the Lochaber Granite detected by the aeromagnetic data is contrary to that reflected in the susceptibility measurements of surface samples, which are affected to varying degrees by hydrothermal alteration. This indicates that the alteration is restricted to shallow depths and suggests that the presently exposed granite was near the roof of the intrusion.

Detailed examination of aeromagnetic profiles and magnetic modelling establish that a small (~15 nT), local, magnetic high, with narrow flanking bumps, occurs over the Kidston pipe. This magnetic high is largely attributable to the remanent magnetisation of the deep pyrrhotite zone. The anomaly associated with the Kidston pipe is largely masked by the numerous local anomalies of comparable, or greater, magnitude associated with susceptibility variations within the Oak River Granodiorite and Einasleigh Metamorphics. A local magnetic low near Macks Porphyry arises from reversely remanently magnetised potassically altered metamorphics.

Significant features of the airborne radiometric data include:

- At a regional scale, the rocks of the complex are quite radioelement poor compared to those in the adjacent Lochaber and Bagstowe Granites, which are felsic and fractionated intrusions. Zoning of the Lochaber Granite is evident in the radiometrics, particularly in the Th channel. Similar radioelement-rich dykes cut the complex but fail to contribute significantly to the aerial survey. The dyke swarm connecting the top (north) of the Lochaber Granite to the complex has also not been detected, due to their relatively insignificant exposure, despite the high radioelement contents of these rocks compared to the host Einasleigh Metamorphics. Proterozoic leucogranitoids in the area are also radioelement-rich and confuse the search for the Carboniferous dykes.
- Weathering effects exert an important influence on radiometric signatures around Kidston. The enhanced potassium signature associated with phyllic alteration in the Kidston pipe tends to be less depleted by weathering, because muscovite is more resistant than feldspar. Consequently weathering can enhance the contrast between the breccia pipe and equivalent unaltered lithologies outside the pipe.
- Kidston is a difficult target for an aerial gamma-ray survey. The rocks of the complex are, to a large extent, the same as those outside the complex with the addition of some K. In addition, one of those units (Einasleigh Metamorphics) ha a variable signature even when unaltered. As other felsic rocks of the area also have higher K contents, distinguishing the altered rocks from unaltered, K-rich rocks is difficult.

Although the Kidston pipe would not have been directly detectable from airborne magnetic/radiometric surveys, as its signature is neither strong nor very distinctive, the aerogeophysical data convey important geological information at all scales and therefore could assist exploration indirectly. Strong zoning of magnetite content, anticorrelated with Th and U concentrations, within the Lochaber and Bagstowe Granites is diagnostic of fractional crystallisation of oxidised, relatively felsic magmas, which is a necessary condition for development of intrusive-related Au(Cu, Mo) mineralisation. Related, minor mafic phases, which are suspected to be important for generation of economic Au mineralisation, via interaction with felsic magma in zoned magma chambers, are also evident in the magnetic and radiometric data. Major regional structures and local controlling structures at Kidston are prominent in the data, particularly in first vertical derivative magnetic images. The magnetic data also suggest the presence of buried intrusions, with apophyses reaching shallow levels, near Kidston. These bodies appear to link Kidston with the inferred underlying batholith and may be prospective for Kidston-type mineralisation.

1. Introduction

Extensive sampling of the Lochaber-Bagstowe Complexes, the Kidston Breccia Pipe, the Paddys Knob Dyke Swarm and the major country rocks to these phases was carried out in conjunction with field studies of AMIRA P425. Samples were analysed for magnetic properties, densities and radioelement contents. Petrophysical databases produced from these measurements are included on the floppy disc in the rear pocket. Airborne magnetic and radiometric data were provided by Placer Exploration Ltd and Kidston Gold Mines. This report discusses the petrophysics and geophysics of the Kidston-Lochaber region, relating the results to the findings of P425 and examining implications for exploration.

2. Geology of the Kidston-Lochaber Area

2.1 The Lochaber-Bagstowe Complex

Figure 1 shows the regional geology of the Lochaber-Bagstowe-Kidston area. The Lochaber and Bagstowe Ring Dyke Structures are two large, adjacent Carboniferous plutonic-volcanic complexes located south of the Kidston gold mine. Early mapping of the "Bagstowe Ring Dyke Complex" was described by Branch (1966). Significant progress in defining geological relationships and distribution of the Carboniferous igneous phases was presented in the Georgetown Special 1:250,000 scale geological map (Bain *et al.*, 1985). The Lochaber Ring Dyke Complex consists of the Lochaber Granite in the east and the Butlers Volcanic Group in the west. The Sues Creek Microgranite intrudes the Butlers Volcanics and is in turn intruded by the Noel Micromonzonite. Minor wolframite and molybdenite mineralisation is associated with the Lochaber Granite. Remapping of the Lochaber Granite by P. Blevin for P425 has shown:

- the Lochaber Granite becomes finer-grained and porphyritic towards its margins, with strong development of microgranitic textures along the northern and northeastern margins,
- textural variants of the granite, originally mapped as Sues Creek Microgranite and "rhyolites", are now considered to be facies of the Lochaber Granite, rather than separate ring dyke intrusions,
- the microgranites and, to a lesser extent, the porphyritic phases are brick red in colour due to haematisation, whereas the core granite is salmon pink,
- an extensive area of greisen-type sericitic and silicic alteration, which appears to post-date the haematisation, occurs as a patchy arcuate belt that straddles the transitional zone between the microgranitic and porphyritic facies of the Lochaber Granite.

The Lochaber-Bagstowe Complex forms a chemically coherent high-K calc-alkaline, I-type, oxidised suite (Lochaber Suite) ranging from diorites to syenogranites and aplites (Blevin, 1996). This suite is characterised by enrichment in large ion lithophile and high field strength elements and resembles the Ootann Supersuite of north Queensland, which is associated with Mo, W, Bi and Au mineralisation. The inferred source of the Lochaber Suite granitoids is an intermediate I-type underplate that formed during the Proterozoic. The Lochaber Granite is an oxidised, magnetite-series, felsic and fractionated I-type biotite syenogranite, close to minimum melt in composition, consisting of quartz, pink K-feldspar, sodic plagioclase and minor (~2 %) biotite, with accessory magnetite, zircon, allanite and xenotime. Airborne radiometric and magnetic data reflect the zoning of the intrusion, from a moderately magnetic microgranitic margin with relatively low U and Th, through a porphyritic medium-grained zone to a medium- to coarse-grained, mildly porphyritic core that is relatively weakly magnetic and rich in U and Th. Where the marginal phase is altered locally to brick-red granophyre, the susceptibility is very low, reflecting alteration of magnetite to haematite.

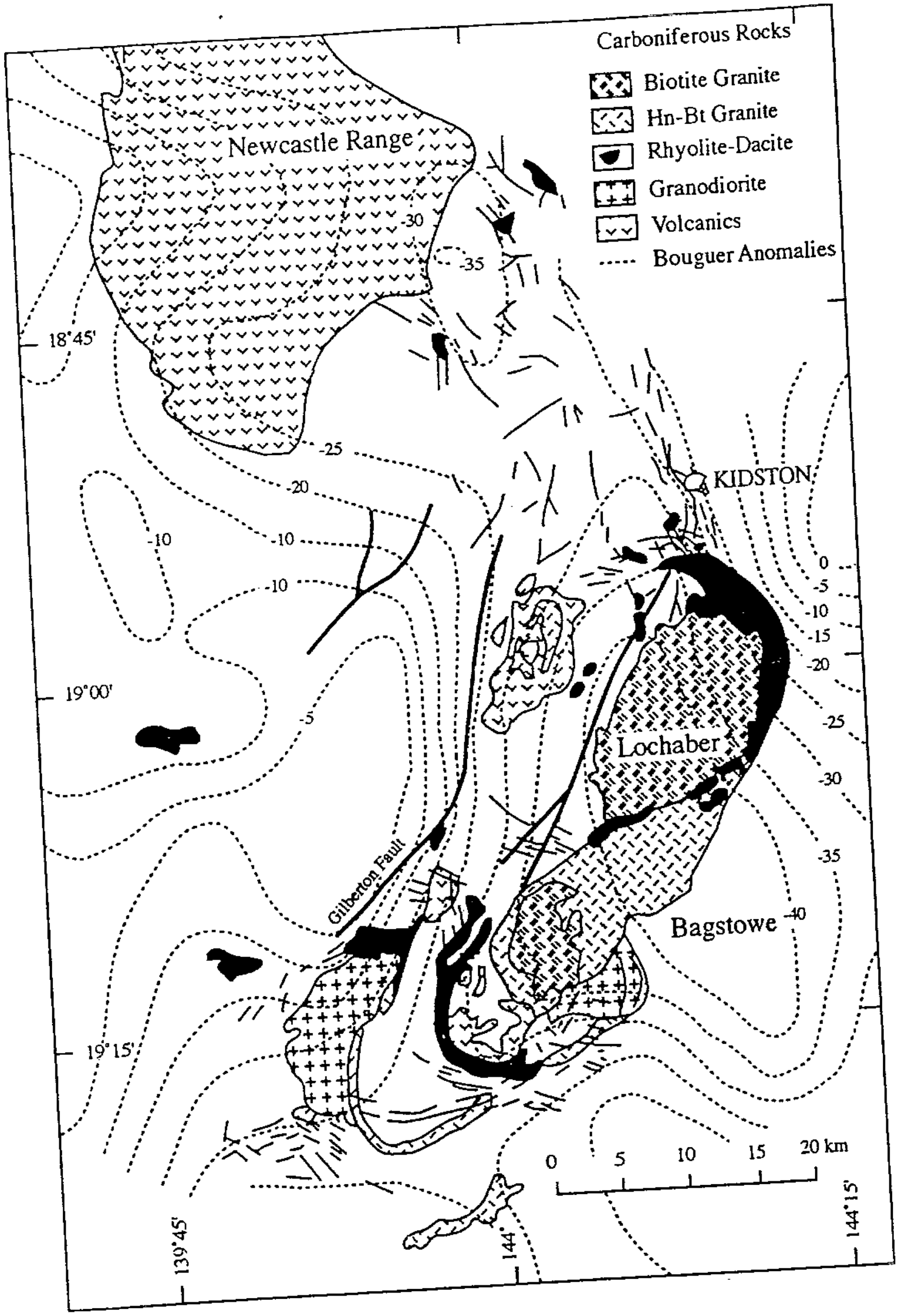


Fig. 1. Regional geology of the Kidston area showing the relationship of Kidston to centres of Carboniferous volcanism, the NW-trending rhyolite dyke swarm and the coincident gravity low, which suggests the presence of an underlying low density batholith (from Baker and Andrew, 1991).

2.2 The Kidston Breccia Pipe

Gold mineralisation at Kidston is hosted by the Kidston Breccia Pipe (Mustard, 1986; Baker, 1987; Baker and Tullemans, 1990), which is an intrusive breccia and porphyry complex, trapezoidal in plan, with surface dimensions of approximately 1100 m (NE-SW) by 900 m (NW-SE) and a depth extent of at least 1400 m. The breccia pipe margins are sharp and dip inwards at greater than 80°. The pipe boundaries are controlled by regional NE-trending faults and E-W trending intrusive-related fracture cone sheets that were active during pipe excavation. There is no evidence of extrusive volcanism at Kidston and the distribution of collapse breccia and large blocks in the upper part of the pipe suggest that it was enclosed by a roof of unbrecciated country rock.

The following summary of the geology of the Kidston mine is based on the synthesis produced for P425 by Blevin, Morrison and Chappell (1997). The Kidston Breccia Pipe comprises three generations of breccia, plus felsic porphyry plugs and felsic and intermediate dykes. The country rock stratigraphy is still largely preserved in the distibution of clast lithologies throughout the pipe. The pipe lies astride a steeply dipping contact between Middle Proterozoic, multiply deformed, gneiss, schist, amphibolite and granodiorite of the Einasleigh Metamorphics, to the NE, and granodiorite and tonalite of the ?Siluro-Devonian Oak River Granodiorite, to the SW (Fig.2). The NE half of the pipe contains mainly metamorphic clasts, whereas the SW half is dominated by granodiorite fragments. In the SW of the pipe, at Wises Hill, brecciated quartz-feldspar porphyry occurs.

The Wises Plug is largely within the pipe, and therefore brecciated, but is interpreted to connect with a porphyry body that extends outside the pipe at depth. It is zoned from a core of normal porphyry, outwards to a heterogeneous zone with locally developed brain rock, pegmatite, aplite, dendritic feldspar and micrographic zones, to a margin of sparse porphyry. Felsite dykes, similar in composition and texture to the marginal phases of the Wises and Macks porphyry plugs, occur as a NW-trending swarm cut by the breccia pipe and are interpreted as pre- to syn-porphyry plugs. The Median Dyke is a broad steep NW-trending dyke, interpreted as connecting with the core of the Wises Plug, that has steep radial arms and flat dish-like sills that cut the breccia, but do not extend outside the pipe margin. The Median Dyke has been phyllically altered (sericite-carbonate ± quartz, pyrite), but locally has relict quartz-albite-haematite alteration, generally in the core of the branches. Sheet veins and related secondary cavities with gold mineralisation cut the Median Dyke. The porphyry outside the pipe at Macks Knob appears in plan as a narrow NW-trending body, but is in fact a curved, shallow west-dipping sill. Figure 3 shows a schematic cross-section of the relationships between breccia and intrusive phases at Kidston. Overall the Kidston Breccia Pipe is interpreted as a single multi-phase intrusive centre with a mother intrusion at depth beneath Wises Hill.

The felsic dykes and plugs are extensively phyllically altered, with patchy remnants of quartz-albite-haematite or propylitic (sericite-chlorite-carbonate ± epidote) alteration, particularly in the deeper portions of the pipe. The main body of intrusive hydrothermal breccia in the centre of the pipe and permeable zones within the overlying collapse breccia have pervasive phyllic (quartz-sericite-pyrite-carbonate ± chlorite, fluorite) alteration. The phyllic alteration is associated with quartz-carbonate-fluorite-pyrite-pyrrhotite matrix replacement and infill mineralisation. This weak polymetallic porphyry-related mineralisation has an element association of (W, Mo, Bi, As, Cu, Zn, Pb, Sb) and exhibits vertical zonation over 1 km from W at depth to basemetals in the upper portions. The iron sulphides are zoned from pyrite-dominant at shallow levels to pyrrhotite-dominant in the deeper portions of the pipe, reflecting higher temperatures of deposition at depth (Baker and Andrew, 1991). Local zones of early potassic (biotite and K-feldspar) alteration preserved in and around the pipe are associated with networks of quartz-magnetite and quartz-molybdenite veins. However the quantity of secondary magnetite is probably insufficient to produce significant magnetic anomalies, except very locally.

The main phase of gold mineralisation is best developed at shallow levels and occurs in primary cavities that replace the matrix of the breccia and sheet veins that cut the breccia and the Median Dyke. The high grade assemblage is quartz-ankerite with phyllic alteration and free gold associated with base metal sulphides and Bi, Te, As and Sb accessories. The currently defined orebodies are hosted predominantly in the collapse breccia, above a flat sill-like arm of the Median Dyke. Morrison *et al.* (1996) explain the genesis of the Au mineralisation as follows:

- a parent magma chamber supplied multiple batches of magma to subvolcanic levels,
- each magma batch fractionates and chills to differing degrees, giving rise to primary textural variations,
- the intrusive phases may concentrate magmatic fluid, causing pervasive alteration, trap it beneath a crystallised cap to produce local stockworks and breccias, or become sufficiently overpressured that any perturbation leads to extensive hydrothermal brecciation in the country rock,
- phase separation (boiling) of magmatic fluid gave rise to metal and alteration zoning,
- attenuated boiling of an already refined fluid trapped in the breccia pipe and driven by valve action of sills within the pipe produced ore grade Au mineralisation.

Figure 4 summarises relationships between intrusive, brecciation, alteration and mineralisation events at Kidston, constrained by geological, geochemical and geochronological data. Absolute ages on this chart represent SHRIMP dating of the Lochaber Granite and Kidston intrusives, carried out for P425 (Fanning, 1996). Figure 5 illustrates the model for magmatic and hydrothermal evolution of the Kidston Breccia Pipe.

2.3 The Paddys Knob Dyke Swarm

A swarm of intermediate to felsic dykes, the Paddys Knob Dyke Swarm (Blevin, 1996), extends from the northern portion of the Lochaber Ring Dyke Structure to the Kidston mine and beyond, appearing to link the Lochaber-Bagstowe complexes to the Newcastle Range Volcanic Complex in the north. Regional BMR gravity data suggests that the Paddys Knob Dyke Swarm and the Kidston Breccia Pipe lie above a buried, low density batholith that represents a subsurface extension of the deeper portions of the Lochaber-Bagstowe structures (Fig.6). M. Seed of Kidston Gold Mines subdivided the swarm into six groups and defined timing relationships with respect to intrusive events at Kidston. The six dyke groups recognised are (interpreted from oldest to youngest):

Group	**Field Terms**	**Petrographic Summary**
PKD1	Dacite	grey, hornblende-plagioclase dacite porphyry with rare quartz phenocrysts
PKD2	Rhyodacite	buff plagioclase-quartz porphyry, sparse
PKD3	CQFHP	green (buff where altered), *coarse* crowded *quartz-feldspar hornblende porphyry*, with biotite
PKD4	QFP	yellow to white, sparse to mod. crowded, massive to flow-laminated, quartz porphyry & *quartz-feldspar porphyry* (incl. felsite)
PKD5	CQFP	*crowded*, mostly pink to red, often spherulitic *quartz-feldspar porphyry* and miarolitic porphyritic microgranites
PKD6	Andesite	green-grey pyroxene-bearing porphyritic andesites to micromonzodiorites

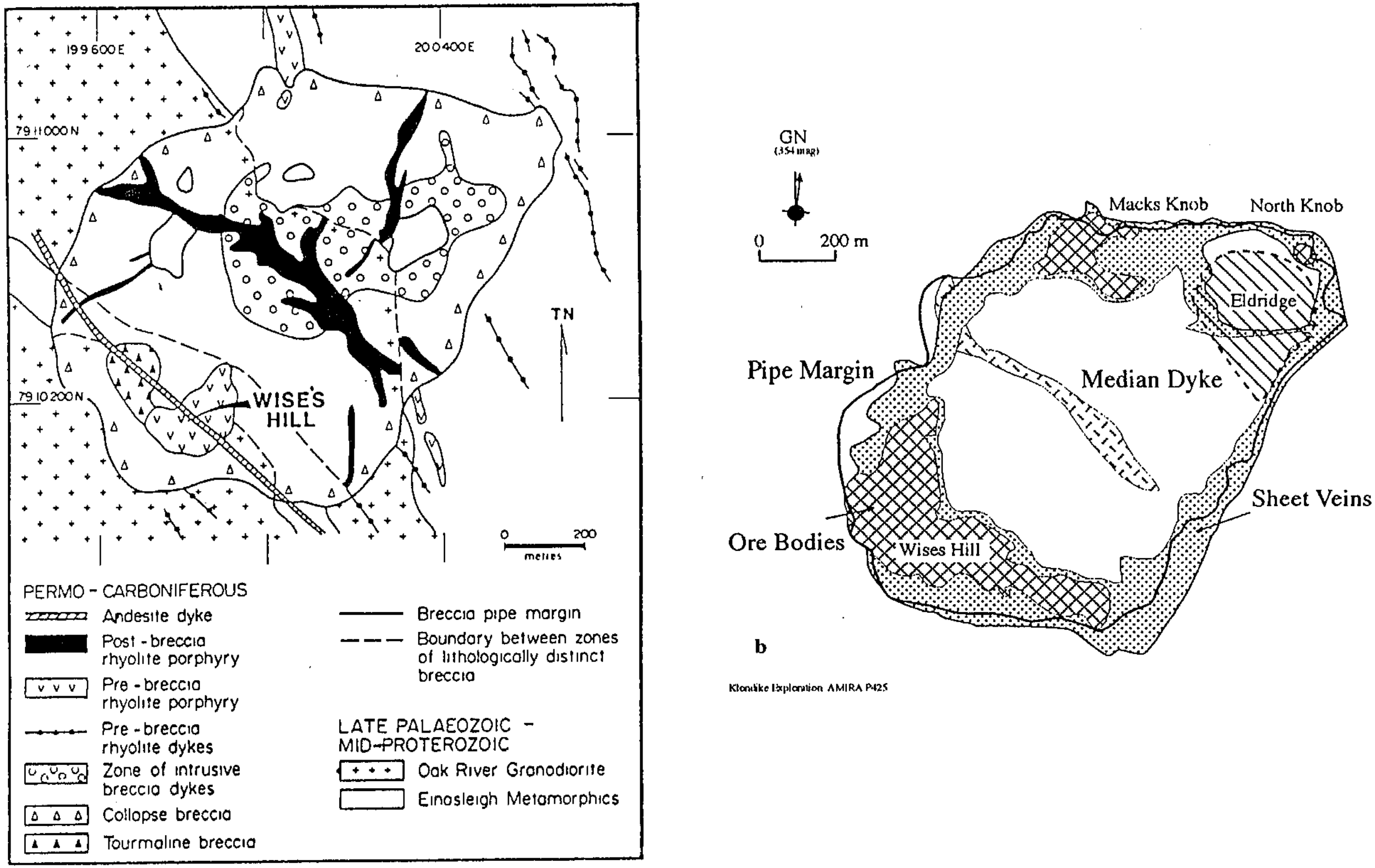


Fig.2.(a) Surface geology of the Kidston mine area (after Baker and Tullemans, 1990). (b) Sheet vein zones and orebodies in the Kidston Breccia Pipe (Blevin, Morrison and Chappell, 1997).

KIDSTON INTRUSIVE EVOLUTION

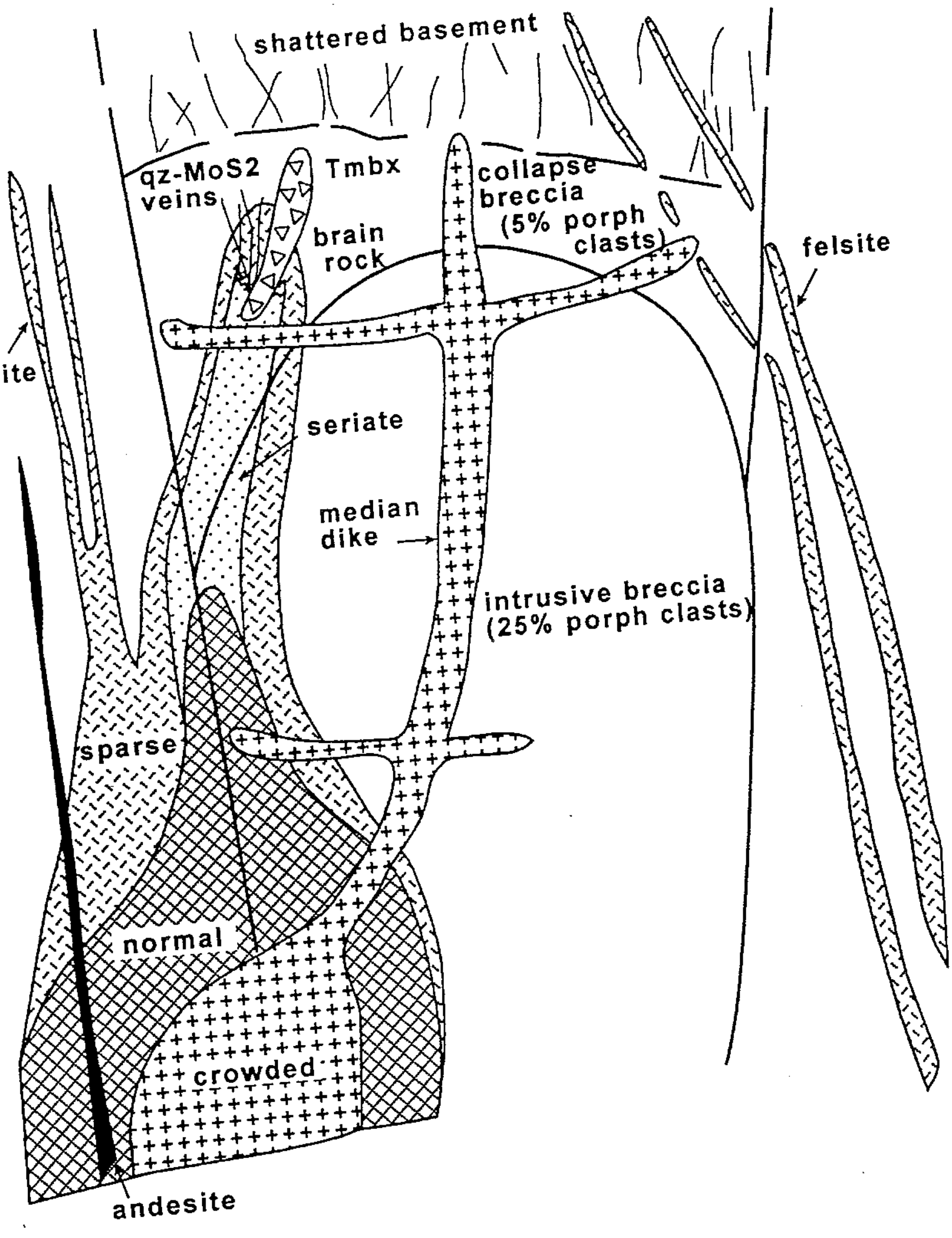


Fig.3. Schematic relationships between breccia and intrusive phases in the Kidston Breccia Pipe based on cross-cutting relationships and clast distribution in breccias. Approximate scale 1500 m vertical (Blevin, Morrison and Chappell, 1997).

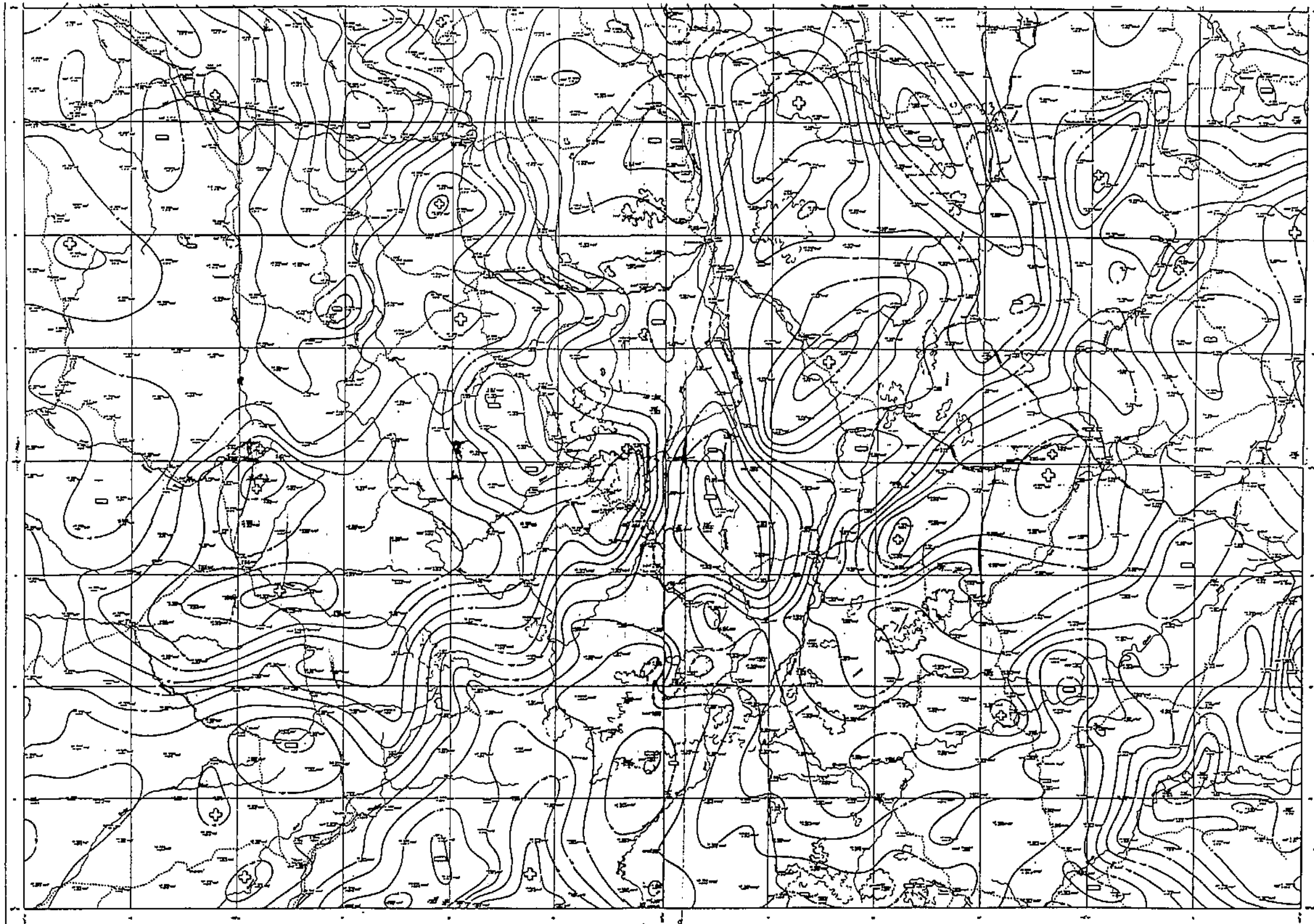


Fig.6. Compilation of regional (~11 km grid) BMR gravity data from the Georgetown, Einasleigh, Gilberton and Clarke River 1:250,000 Sheets. The prominent gravity low with an amplitude of about -40 mgal is interpreted to represent a buried batholith between the Lochaber Granite and the Newcastle Ranges.

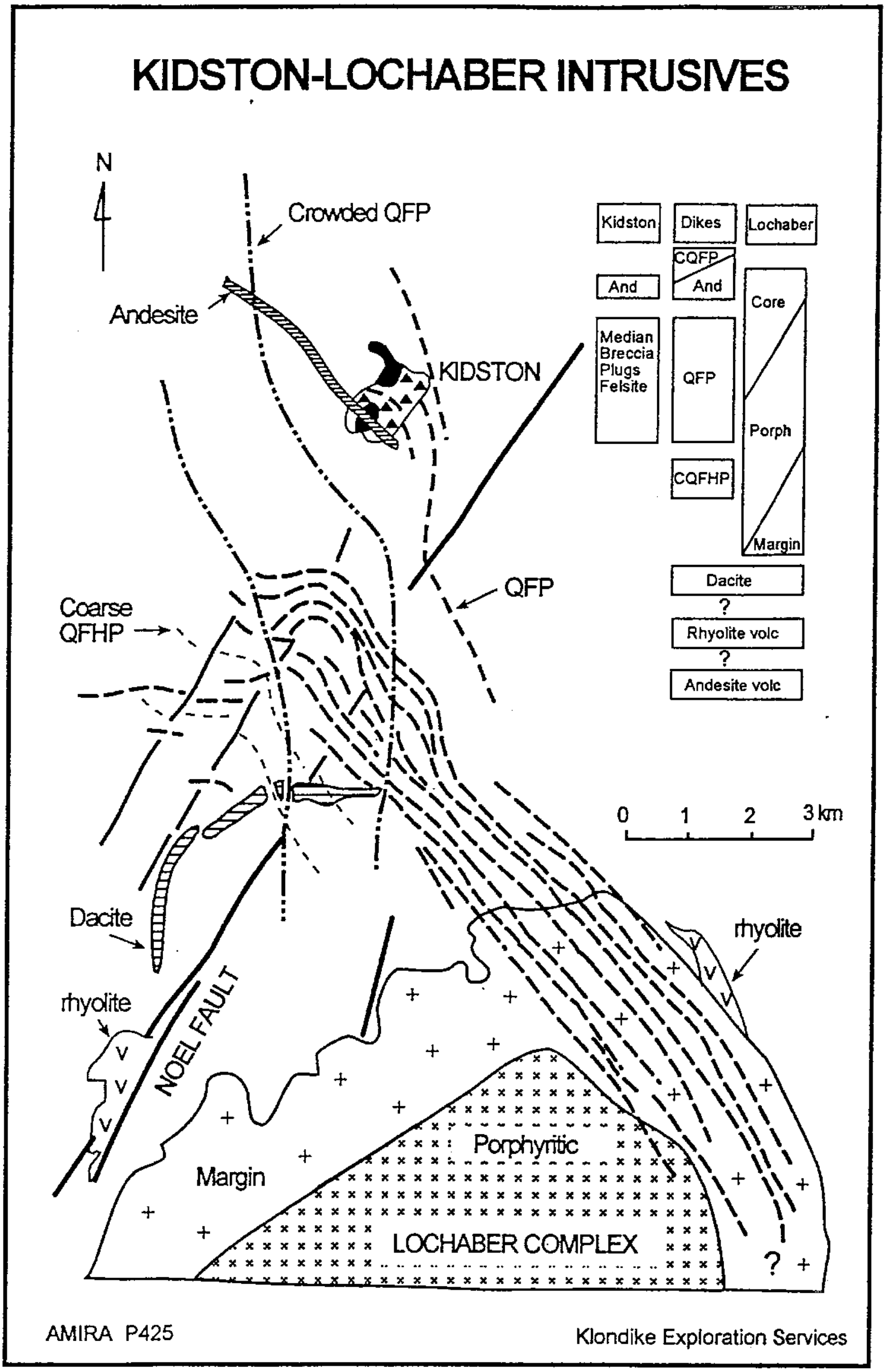


Fig.7. Corrrelation Chart for the Lochaber Complex, Paddys Knob Dyke Swarm and Kidston Intrusives.

Further work by G. Morrison and P. Blevin during P425 has refined the classification of the dykes and the interpreted relationships with the intrusive phases within the Kidston pipe. P. Blevin's mapping of the northern portion of the Lochaber Granite and the southern portion of the Paddys Knob Swarm established the critical field relationships required to link the Lochaber Granite to Kidston. Groups 1 and 2 are distinctly older than the other members of the swarm, are extensively altered and broken and are now interpreted as representing parts of an older failed ring dyke structure, now intruded and broken up by faulting and intrusion of the later dykes and the Lochaber Granite. Groups 3,4 and 5 intrude the NE margin of the Lochaber Granite and post-date reddening alteration and greisen veining within the granite. The Group 6 andesite dyke in the mine cuts all intrusive phases in the Kidston pipe and is post-mineralisation, but is affected by lower temperature late-stage alteration. In the mine area the Group 6 dykes have now been shown to be post-Group 4 and essentially syn-Group 5, whereas near the northern edge of the Lochaber Granite the andesite is cut by Group 5 dykes.

Geochemical investigations carried out for P425 have also demonstrated the close affinities between the Kidston Breccia Pipe, the Lochaber-Bagstowe Ring Complex and the younger members of the Paddys Knob Dyke Swarm. Taken together, the new geological and geochemical data show that the various phases of the Lochaber-Bagstowe Complex are comagmatic and essentially coeval with the Group 3 - Group 6 dykes and with the porphyry plugs and dykes within the Kidston Breccia Pipe. All intrusive phases are inferred to be derived from an underlying batholith in the Early Carboniferous (~330-340 Ma). Figure 7 shows the correlations established between the Lochaber Complex, the dyke swarm and the Kidston intrusives.

There is an increase in fractionation from Group 3 to 4 to 5 dykes. The Group 5 dykes are the most fractionated intrusives in the region. The felsic intrusives at Kidston are essentially indistinguishable from each other and are very close in composition to the Group 4 dykes. The Kidston intrusives therefore were emplaced immediately prior to the onset of intense fractional crystallisation that produced the Group 5 dykes. Mineralisation occurred in the interval between the Group 4 and Group 5 dykes and is clearly linked to the fractional crystallisation process. The near synchroneity of the Group 5 and Group 6 dykes in the Kidston mine area also suggests that injection of mafic magma into the fractionating felsic magma chamber beneath the Kidston pipe may have been involved in the generation of mineralising fluids. The Group 6 dykes are very similar in composition to the Black Cap Diorite, which rims, and is partially engulfed by, the Bagstowe Granite. These andesitic rocks belong to the same high-K calc-alkaline suite as the felsic intrusives and are of crustal origin. They are too evolved in composition to represent direct products of an island arc or continental margin setting.

3. Magnetic Properties and Densities

3.1 Introduction

Experimental procedures are described in Clark and Dickson (1996). Table 1 gives estimated average susceptibilities, Koenigsberger ratios (Q) and densities of the various phases of the Lochaber-Bagstowe Complex and its country rocks. Table 2 summarises these properties for various dyke suites of the Paddys Knob dyke swarm and Tables 3-5 give, respectively, susceptibilities, Koenigsberger ratios and densities for the lithologies of the Kidston pipe and its environs, as a function of alteration. The Koenigsberger ratio of each sample defines the relative importance of remanent and induced magnetisation for that sample. The Q value for the corresponding rock unit depends on the consistency of remanence direction, as well as the typical Q for samples of that rock type.

3.1 Susceptibilities of the Lochaber-Bagstowe Complex

The distribution of susceptibilities for the core Lochaber Granite, altered marginal ("Sues Creek") microgranite, the Bagstowe Granite and the associated Black Cap Diorite are shown in Fig.8(a). The magnetic properties of these phases can be summarised as follows:

- The core phase of the Lochaber Granite has a moderate susceptibility, averaging 350 μG/Oe (4.4 $\times 10^{-3}$ SI), which corresponds to about 0.1 % magnetite by volume,
- The Bagstowe Granite has a somewhat lower susceptibility, averaging 160 μG/Oe (2.0 $\times 10^{-3}$ SI),
- Some exposed portions of the altered marginal microgranite phase of the Lochaber Complex that is cut by dykes of the Paddys Knob swarm have very low susceptibilities (< 30 μG/Oe = 0.38 $\times 10^{-3}$ SI), due to replacement of magnetite by haematite,
- The regional aeromagnetics indicates that overall, including at depth, the Lochaber Granite is magnetically zoned, with susceptibility decreasing inwards,
- The Black Cap Diorite is the most magnetic rock type sampled, with an average susceptibility of ~2600 μG/Oe (33 $\times 10^{-3}$ SI).

3.2. Susceptibilities of Dykes, Porphyries and Breccias in the Kidston Area

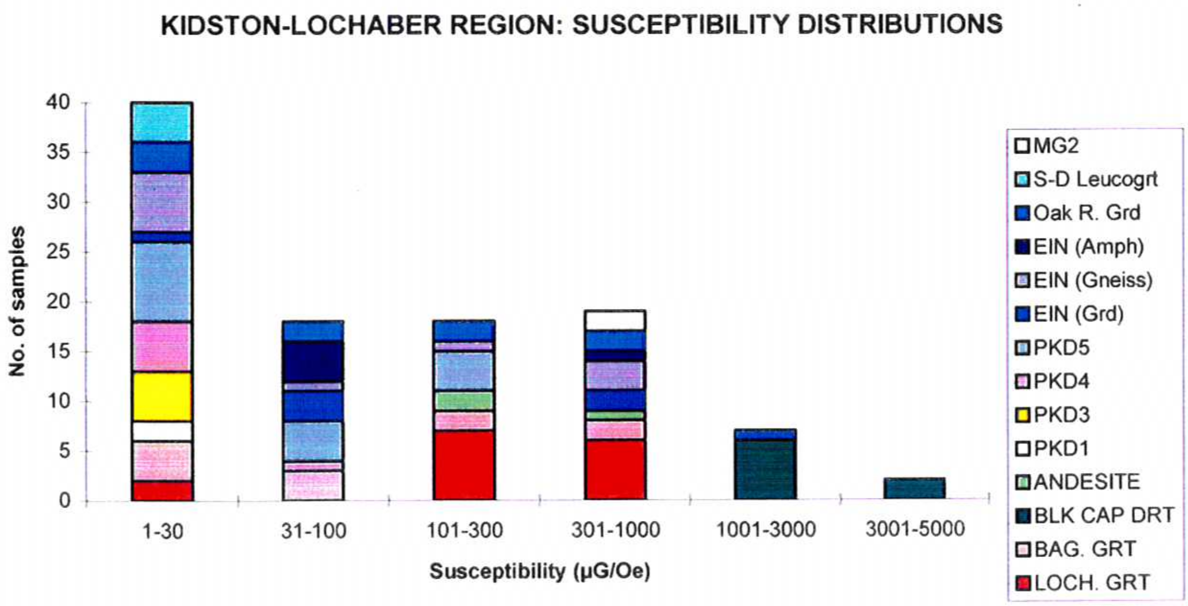
Figure 8(b) shows the distribution of susceptibilities for the lithologies represented in the Kidston mine area. A similar pattern of susceptibilities was found for the intrusive phases in the Kidston mine and for the dyke swarm:

- Felsic dykes and porphyries are very weakly magnetic, with susceptibilities usually less than 10 μG/Oe (0.13 $\times 10^{-3}$ SI). Their average susceptibility is 35 μG/Oe (0.44 $\times 10^{-3}$ SI).
- Andesite dykes are much more magnetic (k ~ 800 μG/Oe = 10 $\times 10^{-3}$ SI).
- The magnetic properties of the breccia phases in the pipe are very variable, reflecting variability in clast lithology and degree and type of alteration. Susceptibilities range from 1-1000 μG/Oe (0.01-13 $\times 10^{-3}$ SI), but are generally low, except in the pyrrhotitic deep phyllic zone.

3.3 Susceptibilities of Country Rocks

- Gneisses, granodiorites and amphibolites of the Einasleigh Metamorphics have generally low to moderate susceptibilities (80-900 μG/Oe = 1-11 $\times 10^{-3}$ SI), except where altered at Kidston,
- Unaltered gneisses have average k ~ 170 ± 120 μG/Oe (2.1 ± 1.5 $\times 10^{-3}$ SI),
- Unaltered Proterozoic granodiorites have average k ~ 280 ± 190 μG/Oe (3.5 ± 2.4 $\times 10^{-3}$ SI),
- Unaltered amphibolites have an average k of 200 ± 100 μG/Oe (2.5 ± 1.3 $\times 10^{-3}$ SI),
- Siluro-Devonian Oak River Granodiorite and Proterozoic granodiorite have similar susceptibilities to each other and to the Lochaber and Bagstowe Granites (200-300 μG/Oe = 2.5-3.8 $\times 10^{-3}$ SI).

(a)



(b)

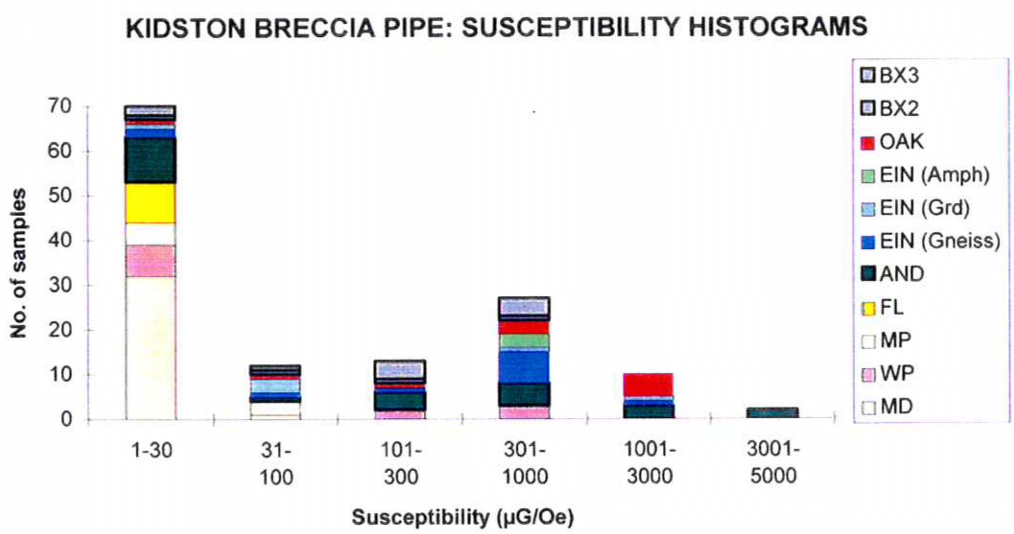


Fig.8(a). Histogram of susceptibilities of lithologies from the Lochaber-Bagstowe Complex and country rocks. (b) Histogram of susceptibilities of lithologies from the Kidston Breccia Pipe.

3.4 Remanence Properties

The magnetic signatures in the Kidston-Lochaber area are predominantly due to induced magnetisation, for several reasons:

- Remanence makes only a subordinate contribution to the the total magnetisation of most of these rocks, as Koenigsberger ratios are generally less than unity.
- Furthermore the NRM is usually dominated by a viscous magnetisation acquired in the recent field, and is therefore subparallel to the induced magnetisation. Thus effect of remanence is to slightly increase the effective susceptibility of the rocks above the values indicated by susceptibility meters.
- Where stable remanence is present it is generally of dual polarity, reflecting frequent reversals of the geomagnetic field in the Early Carboniferous. This tends to lead to cancellation of the contribution of remanence to the total magnetisation of large volumes of rock.
- One exception to the general pattern of weak remanent magnetisation is afforded by the pyrrhotite zone at depth in the Kidston Breccia Pipe. Relatively strong NRM, with accordingly high Koenigsberger ratios, is carried by the pyrrhotite. This remanence is of dual polarity, partially cancelling its contribution to the bulk magnetisation of this zone. However the high to very high Koenigsberger ratios, generally in the range 2-10 and sometimes greater suggests that remanence may contribute to the magnetic anomaly associated with this zone.
- Effects of remanence appear to be detectable locally. Drill hole KM496 was drilled to test a magnetic low near Macks Porphyry. Results from three samples of moderately magnetic, potassically altered metamorphics and a single weakly magnetic sample of Macks Porphyry indicate a consistently reversed remanence, associated with moderate to high Koenigsberger ratios ($Q = 0.6 - 5.2$ for the metamorphics, $Q = 30$ for the Macks Porphyry sample).

It should be noted that the Q values given in Tables 1,2 and 4, which are averages of values for individual *samples*, are only indicative of the relative contribution of remanence to the total magnetisation for the corresponding *rock units*. This is partly because the consistency of remanence directions is a major control on the net remanent magnetisation of each rock unit, as mentioned above. In addition, the sample average Q ignores the differing contributions of strongly magnetic and weakly magnetic samples to the overall magnetisation. Clearly, samples with high susceptibility and moderate Koenigsberger ratios can have stronger remanence than very low susceptibility samples that have much higher Q. Thus the susceptibility and Koenigsberger ratio data should be considered together when assessing the possible contribution of remanence to total magnetisation.

When k and Q are considered together the magnetic properties fall into three main categories, which reflect the dominant remanence carrier in the rocks:

- samples with moderate to high susceptibility and $Q < 1$, representing magnetite-bearing rocks,
- samples with very low susceptibility and $Q >> 1$, representing haematite-bearing rocks with negligible magnetite or pyrrhotite,
- samples with moderate susceptibility and $Q >> 1$, representing pyrrhotite-bearing rocks.

The only significant exception to these generalisations is for magnetite-bearing Einasleigh Metamorphics, potassically altered in part, adjacent to Macks Porphyry, which have $Q > 1$. Remanence is usually only a significant contributor to the magnetic response for rocks in the third category. The only substantial volume of rock to which this applies is the pyrrhotite-dominant deep phyllic zone of the breccia pipe.

3.5 Magnetic Effects of Alteration at Kidston

Even very felsic rocks, such as the Lochaber Granite, contain sufficient iron to form small amounts of magnetite, provided the oxidation state is favourable. Oxidised melts contain significant ferric iron, which combines with ferrous iron to form magnetite, whereas reduced melts contain iron mainly in the ferrous form, which partitions preferentially into paramagnetic silicate phases. Even 0.03 % magnetite by volume increases the susceptibility of a rock substantially above paramagnetic levels. Reduced melts produce weakly magnetic rocks with susceptibilities in the paramagnetic range that are essentially proportional to the total iron content of the rock. Extremely oxidised melts and alteration by very oxidised fluids precipitate haematite instead of magnetite and also produce weakly magnetic rocks. The reddening alteration of the marginal microgranite accounts for the low susceptibility of this phase. The magnetic signatures of the Lochaber-Bagstowe Complex reflect the oxidised nature of the parental magmas, which produced magnetite-series granitic rocks. The felsic phases contain small amounts of magnetite, whereas the mafic (diorite/andesite) phases contain up to ~1% magnetite by volume, reflecting their greater iron contents.

- The bulk of the Kidston pipe is affected by phyllic (sericite-quartz-carbonate-pyrite) alteration, which is magnetite-destructive. The very low susceptibilities of the porphyries and dikes in the mine (significantly lower than the similarly felsic phases of the Lochaber-Bagstowe Complex) are attributable to the pervasive phyllic alteration.
- Within the phyllic alteration there are patchy remnants of earlier quartz-albite-haematite alteration, which is also magnetite-destructive.
- The earliest stage of alteration is the quartz-magnetite stockwork stage, accompanied by potassic (biotite-K feldspar-epidote-chlorite-muscovite-calcite) alteration. Locally, the secondary biotite associated with early potassic alteration of the more mafic country rocks is accompanied by significant magnetite, greatly increasing the susceptibility. There is less potential for precipitation of secondary magnetite in more felsic host rocks, because of their lower iron contents.
- Biotite-altered amphibolite at Kidston has higher susceptibility (~450 μG/Oe = 5.7×10^{-3} SI) than unaltered amphibolite (~200 μG/Oe = 2.5×10^{-3} SI).
- Similarly, biotite-altered gneiss at Kidston has greater susceptibility (~800 μG/Oe = 10×10^{-3} SI) than unaltered gneiss (~200 μG/Oe = 2.5×10^{-3} SI).
- The andesite dykes in the mine post-date the mineralisation and are weakly altered. Their relatively high primary magnetite content is therefore preserved and is reflected in their high susceptibilities. Although compositionally very similar to the Black Cap Diorite, they have susceptibilities that are about 30 % lower, probably reflecting the late stage propylitic alteration that affects the andesites in the mine area. Weak propylitic alteration is largely magnetite-stable, whereas more intensely developed propylitic alteration is partially magnetite-destructive.

Iron sulphides are associated with all broad alteration types (potassic, phyllic and propylitic). Relative proportions of pyrite and pyrrhotite vary through the Kidston pipe, with pyrrhotite becoming more prominent at depth. Some, perhaps all, of the pyrrhotite is the ferromagnetic monoclinic variety. Baker and Andrew (1988) report a typical composition of 47 atomic % Fe for pyrrhotite in sheeted veins within the deep phyllic zone. This is close to the average composition of monoclinic pyrrhotite (~ Fe_7S_8; 46.7 atomic % Fe). The effect on the magnetic properties of variations in iron sulphide species is profound: pyrite is almost non-magnetic, whereas monoclinic pyrrhotite has fairly high susceptibility and can carry strong and stable remanence. Hexagonal pyrrhotite (~ Fe_9S_{10} - $Fe_{11}S_{12}$: 47.4 - 47.8 atomic % Fe), on the other hand, is paramagnetic and would make little contribution to the magnetisation. The average composition of pyrrhotite suggests that some hexagonal pyrhhotite may be intergrown with monoclinic pyrhhotite in the deep phyllic zone.

3.6 Palaeomagnetism of the Early Carboniferous Kidston-Lochaber Suite

The Kidston-Lochaber Suite is of Visean age (~335 Ma), which clearly predates the Permo-Carboniferous Reverse Superchron (PCRS). The most recent estimates of the duration of the PCRS suggest that the geomagnetic field was continuously reversed, except possibly for some very brief excursions, from ~315 Ma to ~260 Ma. Prior to the onset of the PCRS the geomagnetic field was reversing frequently, with little preference for normal or reversed polarity. Thus the magmatic and hydrothermal evolution of of the Kidston-Lochaber Suite, which probably took several million years, could be expected to span several reversals of the geomagnetic field. Australia, which represented part of the Gonwanaland supercontinent at this time, moved rapidly from low latitudes in the Early Carboniferous to high latitudes in the Late Carboniferous (Clark, 1996). Remanence acquired in the Early Carboniferous is characterised by low to moderate inclination and dual polarity, whereas the Late Carboniferous-Early Permian reference field direction for this area is steep and has reversed polarity (directed approximately south and steep down).

Samples from many sites sampled for this study exhibit scattered NRM directions, indicating the presence of multiple remanence components. These components may either reflect a complex magnetisation history or represent palaeomagnetic noise superimposed on geologically meaningful remanence. Palaeomagnetic demagnetisation techniques indicate the remanence is often unstable and it is therefore difficult in many cases to isolate characteristic components of remanence that may record an ancient palaeofield. However, sufficient samples exhibit interpretable demagnetisation behaviour that useful conclusions can be drawn from the palaeomagnetic analysis. In many cases drill core samples appear to exhibit more reliable behaviour than surface samples. The drill core samples are azimuthally unoriented, but differing drill hole attitudes allow directions to be constrained.

Well-defined stable remanence components isolated by palaeomagnetic cleaning techniques are interpreted as primary thermoremanence, if the rocks are unaltered or weakly altered, or as thermochemical remanence acquired during alteration, if the rocks are strongly altered. In some cases two stable components, interpretable as an alteration overprint on a primary magnetisation, can be defined in a single specimen. This case is particularly clear if the two components are of opposite polarity. In that case the two events recorded by the specimen are separated by at least one geomagnetic reversal. When different samples from a single rapidly cooled intrusion record opposite polarities of remanence, indicating acquisition of remanence over a substantial interval, this is good evidence of local overprinting, either due to alteration or to baking by a later adjacent intrusion. The palaeomagnetic results from reliable samples indicate:

- the magmatic and hydrothermal evolution of the Kidston-Lochaber suite spanned several geomagnetic reversals, suggesting a duration of several million years,
- the palaeofield directions recorded are NE with shallow to moderate negative (upward) inclination or SW with shallow to moderate positive inclination, the corresponding palaeopole is consistent with other reliable Early Carboniferous poles from Australia (Bathurst Granite in the Lachlan Fold Belt; Mt Eclipse Sandstone and Brewer Conglomerate in central Australia).

The remanent magnetisation of pyrrhotite is easily reset by relatively low grade thermal events, but is quite stable at ambient temperatures (Clark, 1983). The NRM of the pyrrhotitic zone at Kidston should therefore date from the final cooling of the deeper portions of the pipe. Given that the magmatic-hydrothermal evolution of the Kidston-Lochaber suite spanned ~10 Ma (Fig.4), the remanent magnetisation carried by pyrrhotite probably records the geomagnetic field c.325-330 Ma, shortly after emplacement of the youngest dykes.

Table 1. Properties of Kidston-Lochaber Region Samples

ROCK UNIT	LITHOLOGY	SUSCEPTIBILITY (μG/Oe)	Q	DENSITY (g/cm^3)
Lochaber Granite (core)	Biotite syenogranite	350 ± 50	0.09 ± 0.01	2.616 ± 0.006
Lochaber Granite (porphyritic)	Biotite syenogranite	125 ± 60	0.45 ± 0.03	2.576 ± 0.013
Lochaber Granite (microgranitic margin)	Biotite syenogranite	310 ± 90	0.1	2.601
Bagstowe Granite	Granite	160 ± 60	0.82 ± 0.10	2.587 ± 0.005
Black Cap Diorite	Diorite	2610 ± 230	0.33 ± 0.13	2.779 ± 0.017
Einasleigh Metamorphics	Amphibolite	140 ± 70	0.12 ± 0.08	2.949 ± 0.058
Einasleigh Metamorphics	Granodiorite	280 ± 190	0.15 ± 0.06	2.678 ± 0.026
Einasleigh Metamorphics	Mafelsic gneiss	155 ±75	1.4 ± 0.7	2.698 ± 0.016
Einasleigh Metamorphics (Mt Borium area)	Adamellite (unaltered)	580 ± 260	0.38 ± 0.19	2.700 ± 0.031
Mt Borium Complex	Andesite	3050	0.52	2.855
Mt Borium Complex	Rhyolite (propylitic)	120	0.69	2.640
Mt Borium Complex	Qfp (potassic alteration)	780 ± 370	0.55 ± 0.15	2.652 ± 0.019
Mt Borium Complex	Qfp (phyllic alteration)	5.4 ± 3.7	0.49	2.655
Oak River Granodiorite	Granodiorite	310 ± 140	0.41 ± 0.28	2.719 ± 0.018
Oak River Granodiorite	Pegmatite	6	0.23	2.623
Oak River Granodiorite	Leucogranite	13 ± 3	0.21 ± 0.06	2.608 ± 0.014
MG2 (Proterozoic)	Microgranite	810 ± 50	0.64 ± 0.21	2.617 ± 0.004

See Table 2 for explanation

Table 2. Properties of Paddys Knob Dyke Swarm Samples

ROCK UNIT	LITHOLOGY	SUSCEPTIBILITY (μG/Oe)	Q	DENSITY (g/cm^3)
PKD1	Dacite	22 ± 1	0.64 ± 0.36	2.678 ± 0.010
PKD3	Coarse QFP	8.5 ± 2.2	0.12 ± 0.03	2.611 ± 0.008
PKD4	Felsite	84	0.93	2.557
PKD4	QFP	2.1 ± 0.1	0.62 ± 0.08	2.493 ± 0.010
PKD5	Crowded QFP	46 ± 18	0.95 ± 0.17	2.523 ± 0.011
PKD5	QFP	160 ± 20		2.574 ± 0.011
PKD6	Andesite	780 (260-1300)	0.6	2.745 ± 0.005

1 μG/Oe = $4\pi \times 10^{-6}$ SI

Q = Koenigsberger ratio = NRM intensity/ (susceptibility × geomagnetic field intensity)

Values are given as arithmetic means ± 1 standard error

Table 3. Susceptibilities of Kidston Mine Area Samples as a Function of Rock Unit And Alteration

ALTERATION ROCK UNIT (Lithology)	**Unaltered**	**Propylitic**	**Potassic**	**Albitic**	**Phyllic (pyritic)**	**Deep Phyllic (pyrrhotitic)**	**Mean Of All Samples**
(All QFP)	33	3 [prop/phyllic]	320 ± 180 [pot+po vns]	10 ± 7	7 ± 5	150 ± 70	70 ± 40
Felsite (QFP)					2.5 ± 0.7		2.5 ± 0.7
Macks Porphyry (QFP)	33	3 [prop/phyllic]			0.8 ± 0.1	50 ± 30	29
Wises Porphyry (QFP)			320 ± 180 [pot+po vns]	4.5 ± 1.5	1.4 ± 0.3	345	230
Median Dyke (QFP)				13 ± 10	2.1 ± 0.5		5.4 ± 3.0
Mine Andesite	1310	230 ± 80	3800 ± 630	800 ± 520			770
Breccia2 (amph, gneiss, grd, qfp)			480 ± 240		45 (5-85)		260
Breccia 3 (amph, gneiss, grd, qfp)	34 ± 26					350 ± 60	240

Table 3. Susceptibilities of Kidston Mine Area Samples as a Function of Rock Unit And Alteration (continued)

ALTERATION ROCK UNIT (Lithology)	**Unaltered**	**Propylitic**	**Potassic**	**Albitic**	**Phyllic (pyritic)**	**Deep Phyllic (pyrrhotitic)**	**Mean Of All Samples**
Einasleigh Metamorphics (gneiss)	720 ± 200		800			270 ± 90	420 ± 120
Einasleigh Metamorphics (amphibolite)	565		450			320	450 ± 70
Einasleigh Metamorphics (anatectic granite)	40						40
Einasleigh Metamorphics (granodiorite)			650 ± 510			1230 ± 800	940
Oak River Granodiorite	660 ± 230		1610 ± 420 [(phyll.)/pot.]				1090

1 $\mu G/Oe = 4\pi \times 10^{-6}$ SI

Values given are arithmetic means ± 1 standard error

Table 4. Q Values of Kidston Mine Area Samples as a Function of Rock Unit And Alteration

ALTERATION ROCK UNIT (Lithology)	UNALTERED	PROPYLITIC	POTASSIC	ALBITIC	PHYLLIC (pyritic)	DEEP PHYLLIC (pyrrhotitic)
(All QFP)	0.37	30 [prop/phyllic]	17 ± 3 [pot+po vns]	3.4 ± 1.1	3 ± 1	12 ± 7
Felsite (QFP)					1.6 ± 0.9	
Macks Porphyry (QFP)	0.37	30 [prop/phyllic]			3 ± 1	7 ± 4
Wises Porphyry (QFP)			17 ± 3 [pot+po vns]	6.1 ± 1.1	7.0 ± 2.5	52
Median Dyke (QFP)				2.2 ± 0.6	2.2 ± 0.7	
Mine Andesite	0.63	0.55 ± 0.13	0.31 ± 0.08	0.71 ± 0.18		
Breccia2 (amph, gneiss, grd, qfp)			0.8 ± 0.2		0.8 ± 0.2	
Breccia 3 (amph, gneiss, grd, qfp)	0.8 ± 0.7					4.2 ± 1.3

Table 4. Q Values of Kidston Mine Area Samples as a Function of Rock Unit And Alteration (Continued)

ALTERATION ROCK UNIT (Lithology)	UNALTERED	PROPYLITIC	POTASSIC	ALBITIC	PHYLLIC (pyritic)	DEEP PHYLLIC (pyrrhotitic)
Einasleigh Metamorphics (gneiss)	1.5 (0.3-3.6)		3.3			36 ± 10
Einasleigh Metamorphics (amphibolite)	0.55		0.49			8.8
Einasleigh Metamorphics (anatectic granite)	0.02					
Einasleigh Metamorphics (granodiorite)			0.65 ± 0.32			30 ± 25
Oak River Granodiorite	4 ± 2.5		0.75 ± 0.14 [(phyll.)/pot.]			

Q = Koenigsberger ratio = NRM intensity/ (susceptibility × geomagnetic field intensity)

Values given are arithmetic means ± 1 standard error

4.2 Radiometric Properties

The results of the analyses are summarised in Table 6. Radioelements in Australian rocks show a wide distribution with potassium being evenly distributed over the range 0 - 4 %, with fewer samples ranging up to 7 %. Uranium is normally distributed about a mean of ~ 2 ppm, with a standard deviation of around 1.3 ppm. Few samples have U contents above 5 ppm. Thorium shows a log-normal distribution with many rocks that have low Th and a few with >30 ppm. Thus in the discussion to follow the following ranges are used:

	Low	Medium	High	Very high
K	<1.0 %	1 - 3 %	3 - 5 %	>5 %
U	<1 ppm	1 - 3 ppm	3 - 5 ppm	>5 ppm
Th	<8 ppm	8 - 20 ppm	20 - 35 ppm	>35 ppm

4.3 Regional Intrusives

The Carboniferous Lochaber Granite and Bagstowe Granite have similar high radioelement contents (3.8 % K, 5.0 ppm eU and 32.8 ppm eTh) and are essentially indistinguishable. Soil samples collected over both granites also had high radioelement contents. The marginal microgranitic phase of the Lochaber granite (formerly mapped as "Sues Creek Microgranite") also has high radioelement contents, similar to those of the main portions of the two granites.

The Black Cap Diorite occurs marginal to the Bagstowe Granite. Three samples of this porphyritic hornblende-biotite microdiorite contained on average 1.7 % K, 2.9 ppm eU and 14.0 ppm eTh.

4.4 Rock types in or around the Kidston pipe

The Oak River Granodiorite is the major rock unit to the north and west of Kidston and is included as fragments in the breccias of the pipe. A total of 48 samples of granodiorite were analysed, allowing the changes which take place with proximity to the breccia pipe and alteration/mineralisation within the pipe to be assessed. Background granodiorite >400 m from the breccia pipe contains 1.8 % K, 0.6 ppm eU and 4.3 ppm eTh, a medium K but low eU and eTh content. Within the pipe, unmineralised granodiorite is often brecciated and brown coloured. Its radiometric signature of 1.8 % K, 0.8 ppm eU and 6.0 ppm eTh is similar to that of unbrecciated granodiorite outside the pipe. Fifteen samples of highly brecciated and mineralised granodiorite had an average 3.3 % K, 0.9 ppm eU and 5.5 ppm eTh, showing these rocks to be more K-rich than other granodiorite samples. Three samples of mafic inclusions in the Oak River Granodiorite had an average 1.9 % K, 2.5 ppm eU and 10.2 ppm eTh, considerably richer in eU and eTh than the granodiorite itself.

Nine soils overlying granodiorite remote from the breccia pipe were brown-khaki in colour and generally contained angular quartz granules. These had an average 0.8 % K, 0.4 ppm eU and 2.0 ppm Th, indicating losses of all 3 radioelements during pedogenesis or introduction of low-radioelement material into the soils, but still reflecting the low radioelement content character of the granodiorite .

Table 6 : Summary of Radioelement Contents of Rocks and Soils of the Kidston Study Area.

Unit	Rock					Soil			
	#	K %	eU ppm	eTh ppm	eTh/eU	#	K %	U ppm	Th ppm
Lochaber Granite (main phase)	6	3.77	5.01	32.75	6.53	5	3.91	5.35	37.87
Lochaber Granite (microgranitic margin)	6	4.10	5.05	29.06	5.75				
Bagstowe Granite	4	3.68	5.60	31.52	5.63	1	4.04	3.79	30.00
Black Cap Diorite	3	1.73	2.86	13.97	4.88				
Oak River Granodiorite outside breccia pipe	22	1.84	0.60	4.31	7.18	9	0.76	0.44	2.02
Oak R. Grd in breccia pipe	8	1.77	0.77	6.02	7.82				
Oak R. Grd, mineralised	15	3.33	0.90	5.53	6.14				
Oak R. Grd, mafic enclaves	3	1.89	2.48	10.23	4.13				
Einasleigh Metamorphics - inside breccia pipe	5	2.91	1.18	6.68	5.66	4	2.28	1.60	11.35
Einasleigh Metamorphics - outside breccia pipe	5	2.14	1.98	18.20	9.19	12	1.60	1.30	10.23
Granodiorite gneiss	6	2.52	1.69	12.58	7.44				
Leucogranitoids	3	3.71	7.66	40.29	5.26				
Einasleigh M. (amphibolite)	3	0.92	1.25	4.10	3.28				
Wises Porphyry	2	3.76	3.91	20.88	5.34				
Rhyolite dykes -outside breccia pipe	6	3.05	1.45	18.78	13.3	1	1.70	1.63	10.03
QFP -inside breccia pipe	8	2.78	1.45	19.83	13.7	1	1.84	1.02	10.79
QFP - silicified	1	0.83	0.55	7.73	14.0				
Pegmatite - outside pipe	4	2.65	0.60	4.42	7.37				
Pegmatite - in breccia pipe	1	3.35	0.41	-0.19	-				
Macks Porphyry	3	1.29	1.79	10.2	5.70				
Felsite dykes	2	3.64	4.21	27.67	6.57				
Green CQFP dykes (gp3)	3	3.86	3.91	29.80	7.62				
Yellow QFP dykes (gp4)	7	3.43	3.29	29.18	8.87	1	3.2	2.8	19.9
Late red QFP dykes (gp5)	4	3.51	5.63	35.51	6.30	2	2.4	1.6	10.7
Breccia 2	4	2.52	1.30	6.13	4.72				
Breccia undiff.	9	3.18	1.67	8.20	4.91				
Median Dyke	3	4.85	3.66	23.57	6.44				
Sheeted veins	2	2.68	3.74	9.77	2.61				
Andesite	8	1.40	1.46	11.48	7.86				
Gossanous ironstone	8	0.44	3.06	4.53	1.48				
No. of samples	167					36			

The Einasleigh Metamorphics consist of felsic (gneiss, schist, phyllite) and mafic (amphibolite) rocks. Five samples of undifferentiated metamorphics from outside the pipe contained 2.1 % K, 2.0 ppm eU and 18.2 ppm eTh whereas 12 soil samples had 1.6 % K, 1.3 ppm eU and 10.2 ppm eTh. Six samples of granodiorite - gneiss country rock contained 2.5 % K, 1.7 ppm eU and 12.6 ppm eTh.

Felsic metamorphics from within the pipe are greyish phyllites cut by 1.5 cm-thick quartz veins. Five samples contained 2.9 % K, 1.2 ppm eU and 6.7 ppm eTh, i.e. a higher K content but lower eTh than equivalent rocks outside the pipe. Four soils contained 2.3 % K, 1.6 ppm eU and 11.4 ppm eTh showing retention of K with weathering, although the higher eTh could suggest soil mixing is occurring.

Leucogranites occur commonly in the country rock surrounding the Kidston pipe of age varying from Proterozoic to Siluro-Devonian. Three samples of uncertain age showed high radioelement contents with an average 3.7 % K, 7.7 ppm eU and 40.3 ppm eTh.

Three samples of amphibolites of uncertain age were measured; these have low radioelement contents.

Two samples of Wises Porphyry intruding country rocks contained 3.8 % K, 3.9 ppm eU and 20.9 ppm eTh. Another 14 samples collected in the earlier studies and described variously as volcanic and quartz-feldspar porphyry rocks had similar high K and eTh contents but lower eU giving a high eTh/eU ratio of ~14. Six of these "volcanics" from outside the breccia pipe but generally within 150 m of it had an average 3.0 % K, 1.4 ppm eU and 19 ppm eTh. Seven from within the pipe and one from adjacent to mineralisation at Paddys Knob (considered with the within-pipe samples with which it is similar both mineralogically and radiometrically) had an average 2.8 % K, 1.5 ppm eU and 19.8 ppm eTh. These radioelement contents seem similar to those of the Wises Porphyry samples apart from a lower eU content and suggest that these "volcanics" were samples of Wises Porphyry.

A detailed examination of the 14 results for the "volcanics" show that the eU contents of these samples divide the samples into two groups, a low eU/eTh group (6 samples averaging 2.1 % K, 0.6 eU ppm and 12.2 eTh ppm) and a high eU group (8 samples, averaging 3.0 % K, 2.0 eU ppm and 21.7 eTh ppm) (Table 7). Examination of the mineralogy of these samples which had been previously determined (Scott and Dickson, 1991 - Table 7) did not show any identifiable causes for this variation in eU and eTh content of these samples. However it is clear that surface weathering and/or hydrothermal alteration effects have changed the radiometric character of these rocks to give very unusually high eTh/eU ratios of approximately 14.

Two samples of soil developed above the porphyry rocks contained an average 1.8 % K, 1.3 ppm eU and 10.3 ppm eTh, reflecting loss of K and eTh as the feldspar-rich parent rock weathers.

Five samples of pegmatite were sampled in the local area of the pipe. Four from outside the pipe had 2.6 % K, 0.6 ppm eU and 4.4 ppm eTh whereas one sample from within the pipe contained 3.3 % K, 0.4 ppm eU and -0.2 ppm eTh. These are typical radioelement contents for pegmatites, being K-rich but eU and eTh -poor.

Another rhyolitic porphyry plug occurs at Macks Hill (Macks Porphyry) and is considered to be similar age to the earlier intrusions of Wises Porphyry (Morrison and Blevin, 1995). Three samples of Macks Porphyry were obtained as clasts in the Main Stage Breccia. These had 1.3 % K, 1.8 ppm eU and variable eTh (3 - 20 ppm) and are thus quite different radiometrically from Wises Porphyry.

4.5 Minor Intrusives and Breccia Phases

Two samples from a felsic dyke (equivalent to Butlers Volcanics) had an average 3.6 % K, 4.2 ppm eU and 27.7 ppm eTh, indicating high radioelement contents in these Carboniferous intrusives. Three samples of CQFHP (Group 3) dykes intruding the marginal micrograniitic phase of the Lochaber Granite had a similar average of 3.9 % K, 3.9 ppm eU and 29.8 ppm eTh. Seven samples of Group 4 QFP dykes were sampled and gave an average 3.43 % K, 3.3 ppm eU and 29.2 ppm eTh. Four samples of Group 5 CQFP dykes (post-mineralisation) had an average 3.5 % K, 5.6 ppm eU and 35.5 ppm eTh. Three samples of the Median Dyke cutting NW across the centre of the pipe were analysed and gave an average 4.8 % K, 3.7 ppm eU and 23.6 ppm eTh. Two samples of sheet veins gave an average 2.7 % K, 3.7 ppm eU and 9.8 ppm eTh, giving these veins quite a low eTh/eU ratio of 2.6 (Table 6). Eight samples of the NW-trending porphyritic andesite through Wises Hill, was the last intrusive event in the Complex, have an average 1.4 % K, 1.5 ppm eU and 11.5 ppm eTh.

Four samples of main stage breccia (Breccia 2) have an average 2.5 % K, 1.3 ppm eU and 6.1 ppm eTh. Nine samples of polymictic breccia from earlier sampling had an average 3.2 % K, 1.7 ppm eU and 8.2 ppm eTh. In outcrop they are white to grey to pink-buff and red-brown silicified breccias often with gossanous fragments.

4.6 Miscellaneous Rock types

Red-brown silicified and generally gossanous ironstones were sampled over volcanics at Wises Hill and at Paddys Knob to the south of the Kidston breccia pipe. They consist of quartz and Fe oxides, with traces of muscovite, plagioclase, kaolinite and jarosite, i.e. they are dominated by Fe oxides with the other components of the felsic intrusives correspondingly depleted . Eight samples were analysed and these contain an average 0.44 % K, 3.1 ppm eU, 4.5 ppm eTh giving them a very low eTh/U ratio of 1.5.

4.7 Discussion of Radiometric Properties

The rocks collected in the Kidston-Lochaber area show a wide range of radioelement contents. A comparison of the average radioelement contents of the rocks is shown in Fig.10. Most of the rocks have eU and eTh contents which are closely correlated (Fig.10(a)), with contents ranging from the low values in the amphibolites to highest values in the leucogranites. Samples with unusual eTh/eU ratios include the gossans and sheet veins which tend to be eU-rich relative to their eTh contents. The "volcanics" (surface weathered Wises Porphyry) have anomalously low eU contents.

The K versus eTh plot (Fig.10(b)) shows a wide scatter of values. The Lochaber and Bagstowe Granites form a group of high K and eTh contents with the leucogranite having higher eTh and the Median dyke, a higher K content. The country rocks form a group with K ranging from 1 % to 3.2 % and eTh from 5 to 15 ppm. Outlying rock types include the amphibolite (high K, low eTh) and the gossan (low in both K and eTh). The "volcanics" and the Wises Porphyry fall in a group between the radioelement-rich igneous rocks.

4.8 Radiometric Properties - conclusions

A total of 203 rocks and soils from the Kidston breccia pipe and region have been analysed for their radioelement contents. The results show that the felsic Carboniferous intrusives (Lochaber and Bagstowe Granites) are particularly rich in radioelements. This enrichment is also seen in the quartz-feldspar porphyry dykes in the area between the granites and the Kidston complex. Two other porphyries (Wises and Macks) and the Median and sheet dykes, associated with the complex, do not have the high eU and eTh contents found with the intrusives. Unaltered Oak River Granodiorite in the area has low abundances of the radioelements, especially eTh, relative to the Einasleigh Metamorphics. Alteration associated with mineralisation in brecciated granodiorite or polymictic breccia within the pipe is K-rich. Scott and Dickson (1991) concluded that as this K was present as muscovite it was not severely depleted during weathering processes.

5. Interpretation and Modelling of Magnetics of the Kidston-Lochaber Region

5.1 Regional Aeromagnetic Data

The aeromagnetic data available to this project comprised a large regional compilation of a number of regional surveys covering a wide area south, west and north of Kidston. The detailed survey over Kidston was flown post-mining and cultural effects are prominent in the data. Figures 11-21 are presentations of the TMI and various derived magnetic datasets (RTP, first vertical derivative) over the Lochaber-Bagstowe Complex, north to the Kidston area. In this area magnetics and radiometrics are excellent regional mapping tools. Lithological variations and major structures are clearly evident in the magnetic images, including some features that are not shown in regional mapping.

Significant features of the magnetic data include:

- zonation of the Lochaber and Bagstowe Granites from a relatively magnetic margin to a less magnetic core, accompanied by a substantial increase in Th and U evident in the radiometrics,
- a prominent magnetic high rimming the western and southern margins of the Bagstowe Granite, which arises from the Black Cap Diorite,
- major magnetic lineaments corresponding to NE-trending structures, such as the Gilberton Fault and the Noel Fault, that appear to have influenced emplacement of the Lochaber-Bagstowe complex and, in the case of the Noel Fault, may have been a control on the Kidston pipe,
- a faintly discernible set of NNW-trending lineaments that passes through the Kidston area, parallel to the main trend of the Paddys Knob dyke swarm and coincides roughly with the axis of the underlying batholith that has been interpreted from gravity data (Baker and Andrew, 1991),
- structures that appear to be important in localising the Kidston Breccia Pipe are represented by truncations of narrow linear features in first vertical derivative images, or by changes in their trend,
- two diffuse highs, with superimposed local anomalies, immediately NW and SE of Kidston. These may represent stocks emanating from the underlying batholith, with apophyses that almost reach the present surface.

The zonation of the Lochaber Granite detected by the aeromagnetic data is contrary to that reflected in some of the susceptibility measurements of surface samples, which are affected to varying degrees by hydrothermal alteration. Reddened portions of the exposed marginal facies of the granite have the lowest susceptibility, the core phase has the highest measured susceptibility and the intervening, patchily altered, porphyritic facies has intermediate susceptibility. The difference between the surface expression of susceptibility variation and the aeromagnetic pattern, which reflects the average susceptibility of substantial volumes of rock beneath the surface, indicates that the alteration is restricted to shallow depths and suggests that the presently exposed granite was near the roof of the intrusion.

The decrease in susceptibility from the margin to the core that is evident from the magnetics is consistent with normal zoning of a large intrusion from a more mafic margin to a relatively felsic core. The magnetite content of rocks crystallising from an oxidised felsic melt is constrained by the availability of iron, which decreases with continuing fractionation, until no magnetite is able to form in the most felsic differentiates. Such prominent magnetic zoning, particularly when accompanied by build-up of Th and U, suggests that fractional crystallisation, which is a prerequisite for concentration of ore-forming elements in intrusive-related systems, is the cause of compositional variation in the Lochaber and Bagstowe Granites. Thus the airborne geophysical data suggest that the magmatic evolution of the Lochaber and Bagstowe complexes has potential for development of associated mineralising hydrothermal systems, given other favourable circumstances.

The association of comagmatic mafic rocks, such as the Black Cap Diorite and the andesite dykes, with the felsic granitic rocks may also be of significance for the type of mineralisation that may be associated with such intrusive complexes. Intrusive-related gold mineralisation appears to be associated with felsic magmas that have evolved from a relatively mafic, oxidised composition. Some interaction between mafic and felsic melts within the underlying magma chamber is also implicated in generation of gold mineralisation in such systems (Blevin, Morrison and Chappell, 1997). Mafic rocks in such an environment are strongly magnetic and produce a substantial magnetic response, unless their occurrence is restricted to volumetrically insignificant levels.

The structural features that may be significant controls on the formation of the Kidston pipe and its mineralisation are much more evident in first vertical derivative images than in TMI maps (Figs.14, 16, 17, 20). Some significant features emphasised by the derivative images include:

- The NW trend of the Paddys Knob Dyke Swarm is prominent through the Kidston mine area.
- NE trends are dominant throughout most areas of the Einasleigh Metamorphics, except immediately around Kidston.
- The Kidston mine area is enclosed by magnetic boundaries that define distinct changes in structural grain.
- The extension of the mapped Noel Fault appears as "tram line" magnetic anomalies that truncate the NW margin of the inferred stock SW of Kidston.
- The SE margin of the Kidston pipe is controlled by a fault, which has a faint magnetic expression, that is parallel to the nearby Noel Fault.

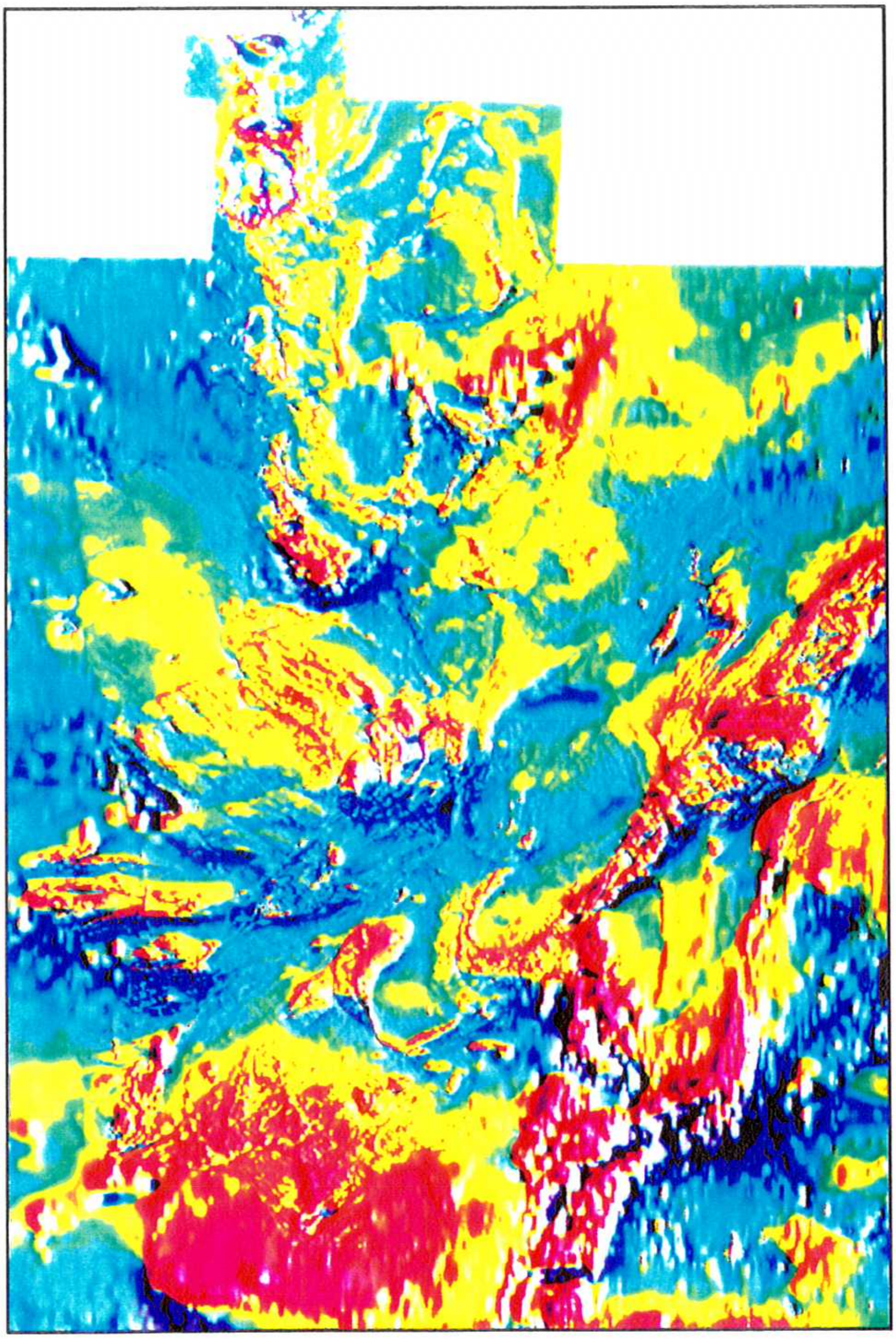


Fig.11. Regional colour TMI image for the Kidston-Lochaber-Bagstowe-Newcastle Ranges area (data courtesy of Kidston Gold Mines and Placer Exploration). Nested structures from SW to NE: the Glenmore Batholith, the Bagstowe Ring Dyke Structure and the Lochaber Ring Dyke Structures are prominent in the southern portion of the image. The Lochaber and Bagstowe Granites exhibit distinct zoning from relatively magnetic margins to weakly magnetic cores. The Black Cap Diorite corresponds to the pronounced narrow magnetic high rimming the SW end of the Bagstowe Granite. The Gilberton Fault and its NNE-trending extension, the Ballynure Fault, are represented by distinct magnetic lineaments, as is the Noel Fault. The Noel Micromonzonite within the Butlers Volcanic Complex is associated with a magnetic high to the west of the Lochaber Granite. Kidston is sandwiched between two relatively subdued magnetic highs, interpreted to represent stocks emanating from the inferred batholith beneath the Paddys Knob Dyke Swarm. Cauldron structures within the Newcastle Range Volcanics are prominent in the northern part of the image.

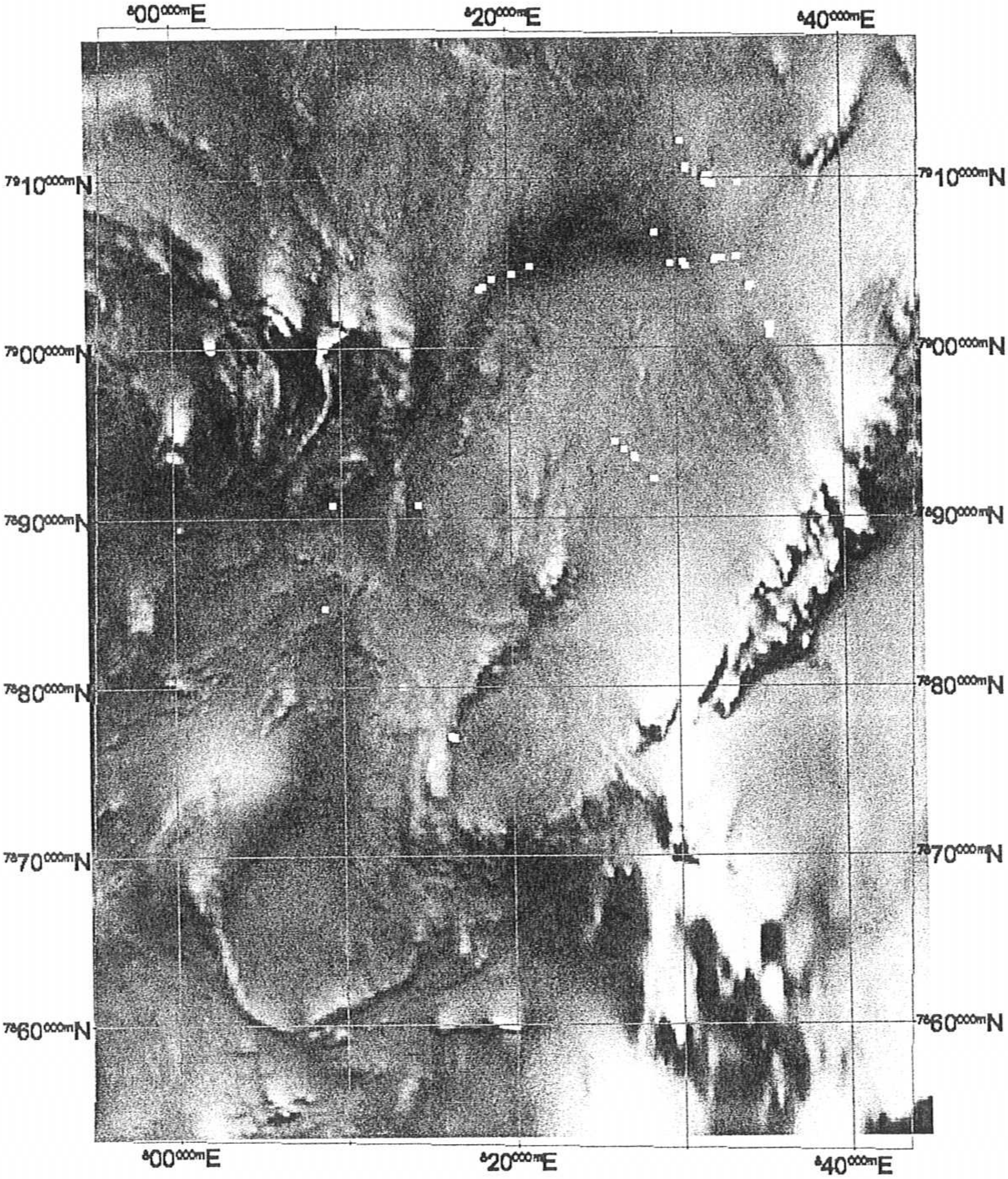


Fig.12. Regional greyscale reduced-to-the-pole TMI image for the Kidston-Lochaber-Bagstowe area. Locations of magnetic petrophysical sampling sites are shown as small white squares. The nested ring structures that show up clearly as smooth zones over the felsic granitic rocks, rimmed by more magnetic rocks, are (from SW to NE): the Glenmore Batholith, the Bagstowe Ring Dyke Structure and the Lochaber Ring Dyke Structure. Kidston is indicated by the dense sampling in the NE portion of the image. AMG co-ordinates are Zone 54.

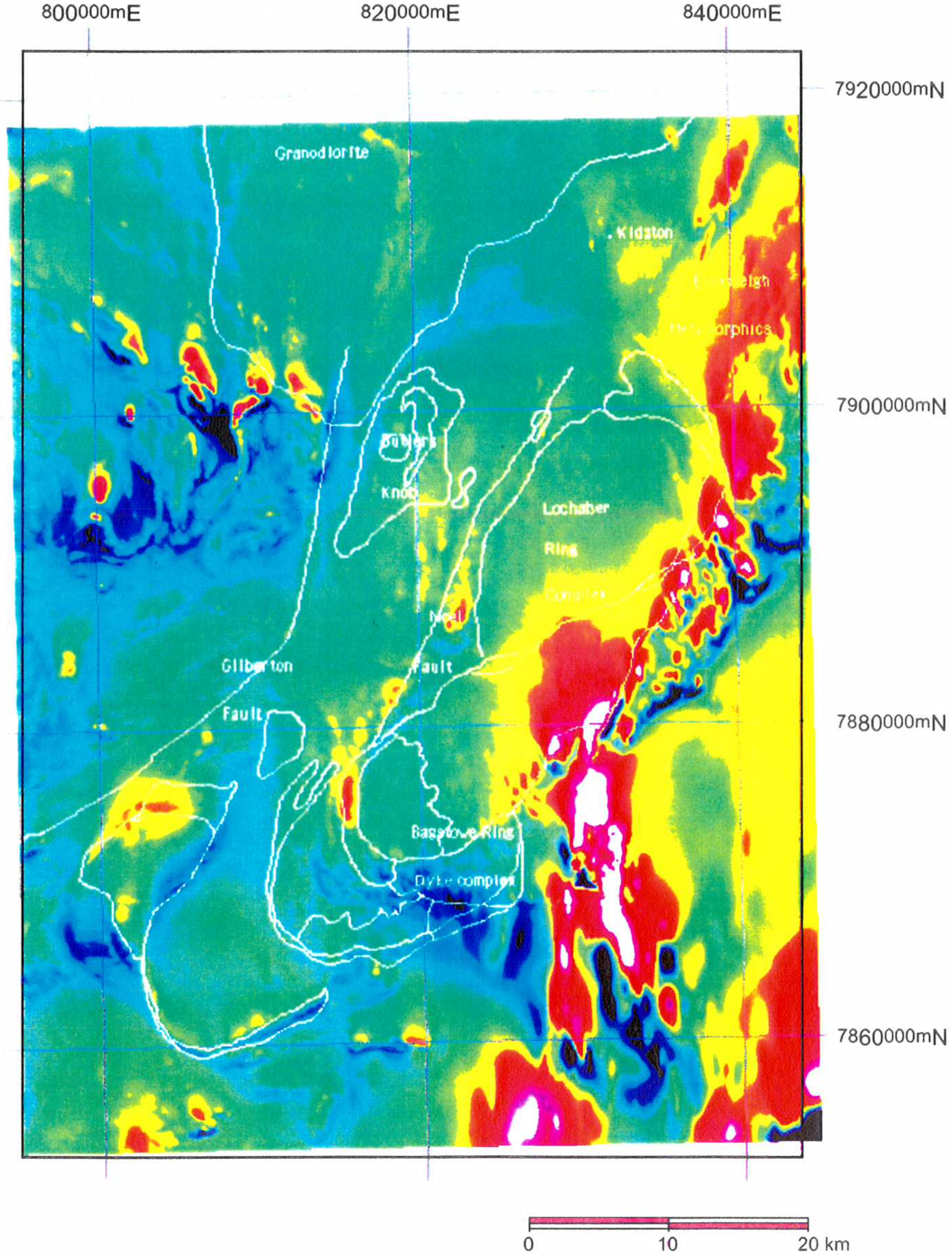


Fig.13. False colour image of TMI data for the Kidston-Lochaber-Bagstowe area.

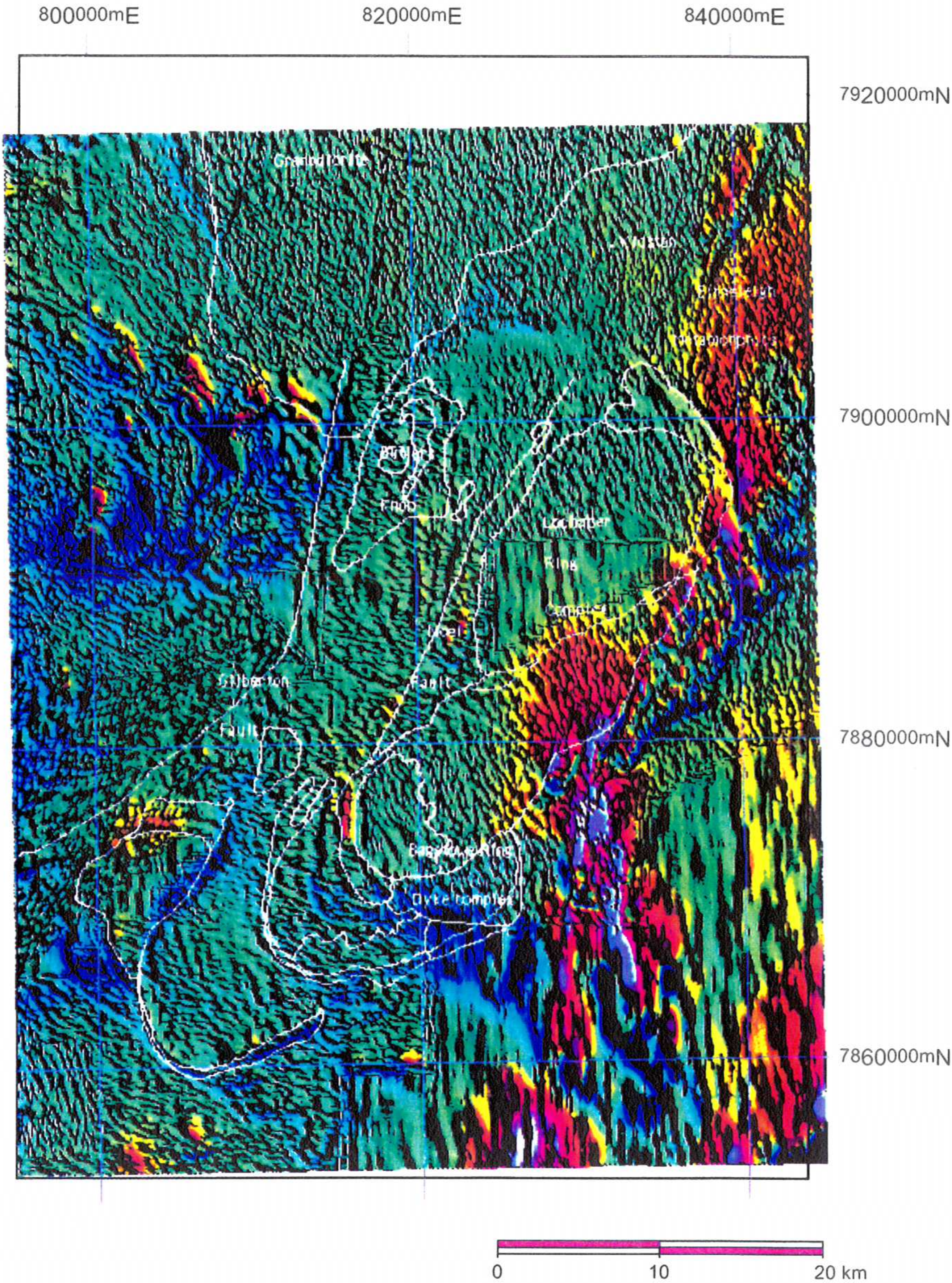


Fig.14. Image of magnetic data for the Kidston-Lochaber-Bagstowe area. The colour represents the reduced-to-the-pole TMI and the shading represents the first vertical derivative of the TMI.

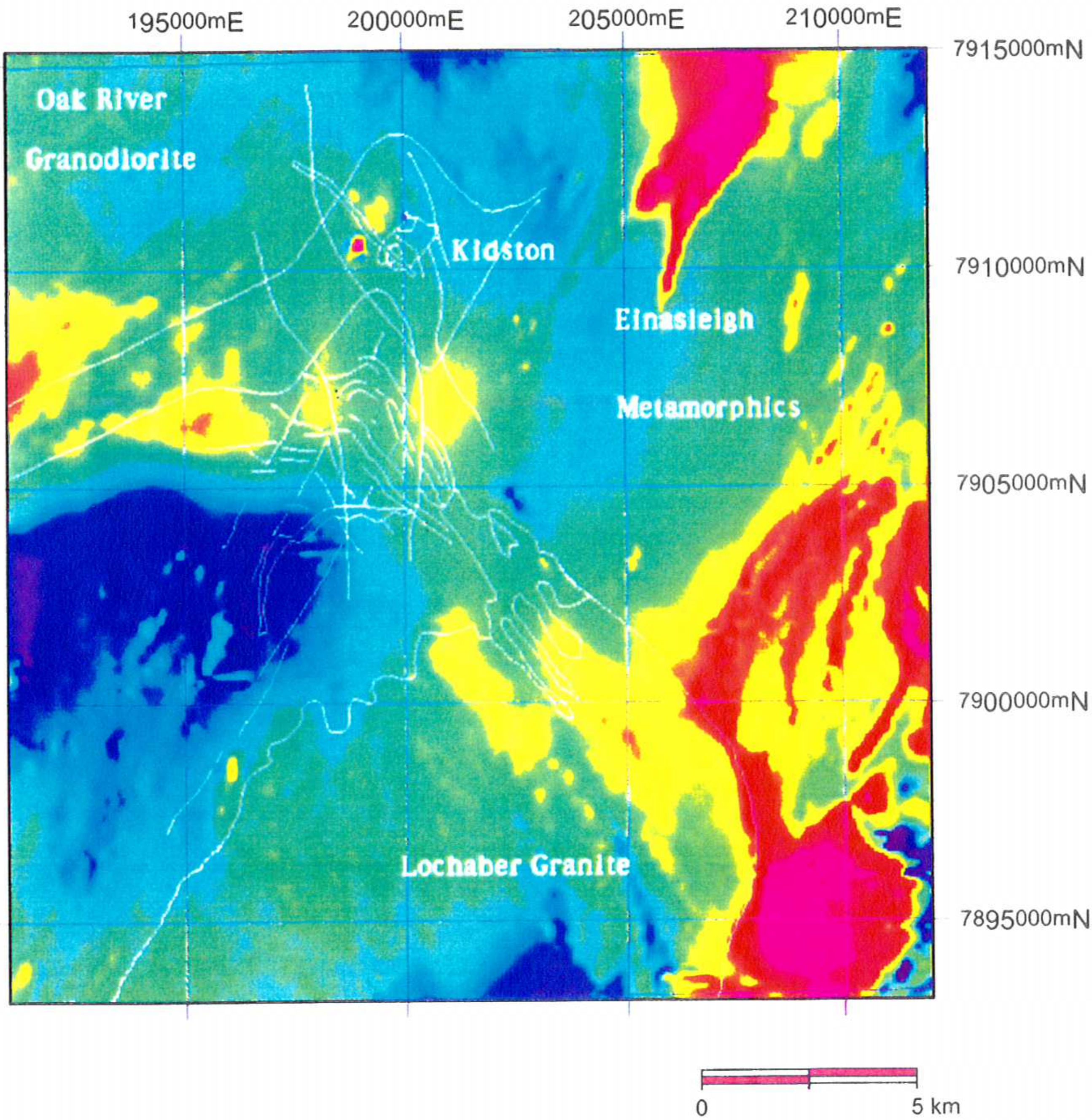


Fig.15. False colour image of TMI data for the Kidston- North Lochaber area.

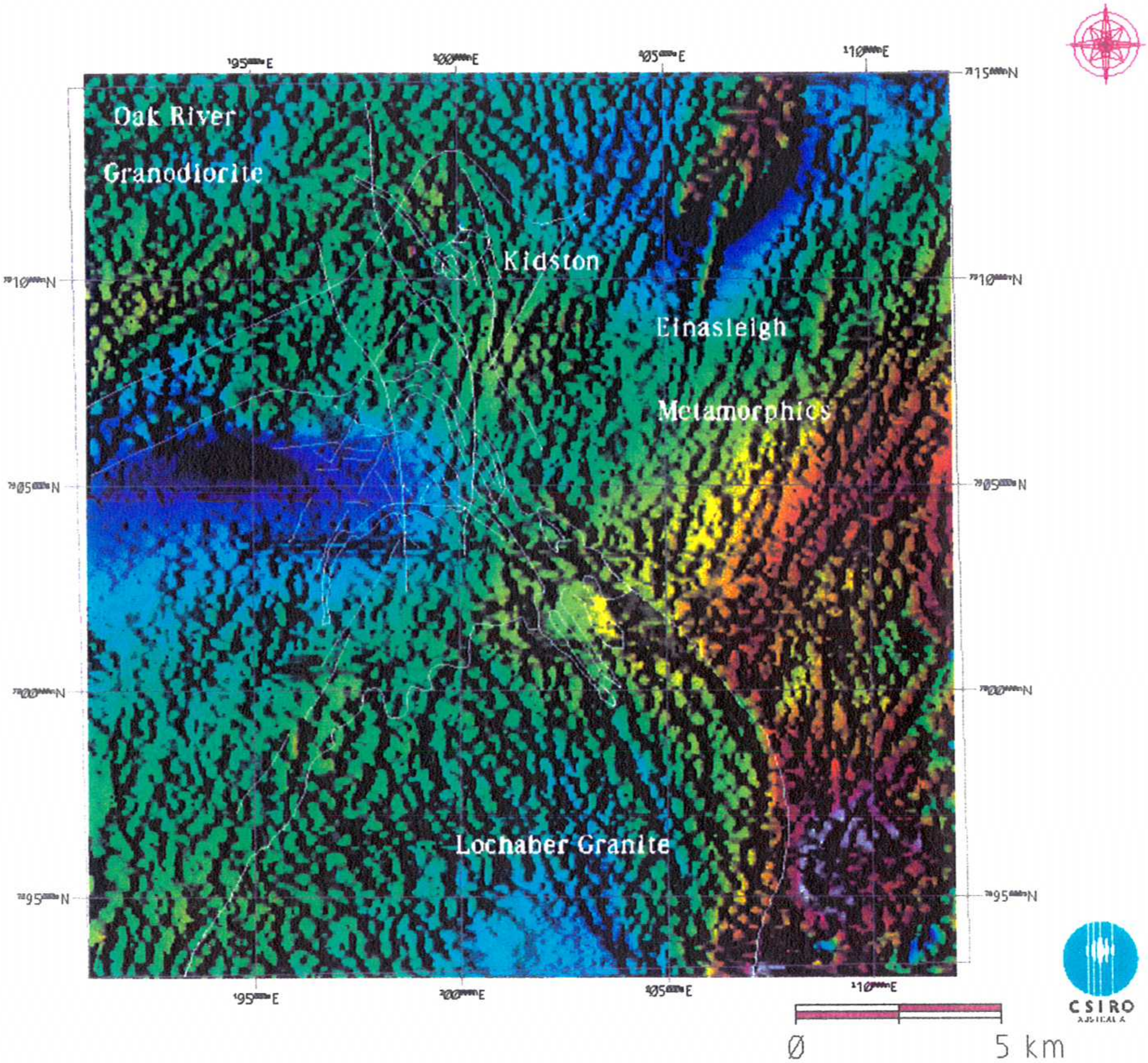


Fig.16. Image of magnetic data for the Kidston-North Lochaber area. The colour represents the reduced-to-the-pole TMI and the shading represents the first vertical derivative of the TMI. The mapped Noel Fault and extensions to the NE can be traced in the magnetics. This fault appears to control the NW margin of the inferred buried stock SE of Kidston. The Paddys Knob Dyke Swarm trend, extending from the NE margin of the Lochaber Granite towards Kidston, is evident close to the granite, but is only faintly discernible in the Kidston area. The contact between the mixed Oak River Granodiorite/Einasleigh Metamorphic zone, straddled by Kidston, and the main zone of metamorphics is marked by a linear zone with a steep gradient, low to the east. Boundaries between these units are also characterised by distinctly different structural grains. Sudden changes in predominant structural trend are also seen across linear structures, such as the Noel Fault.

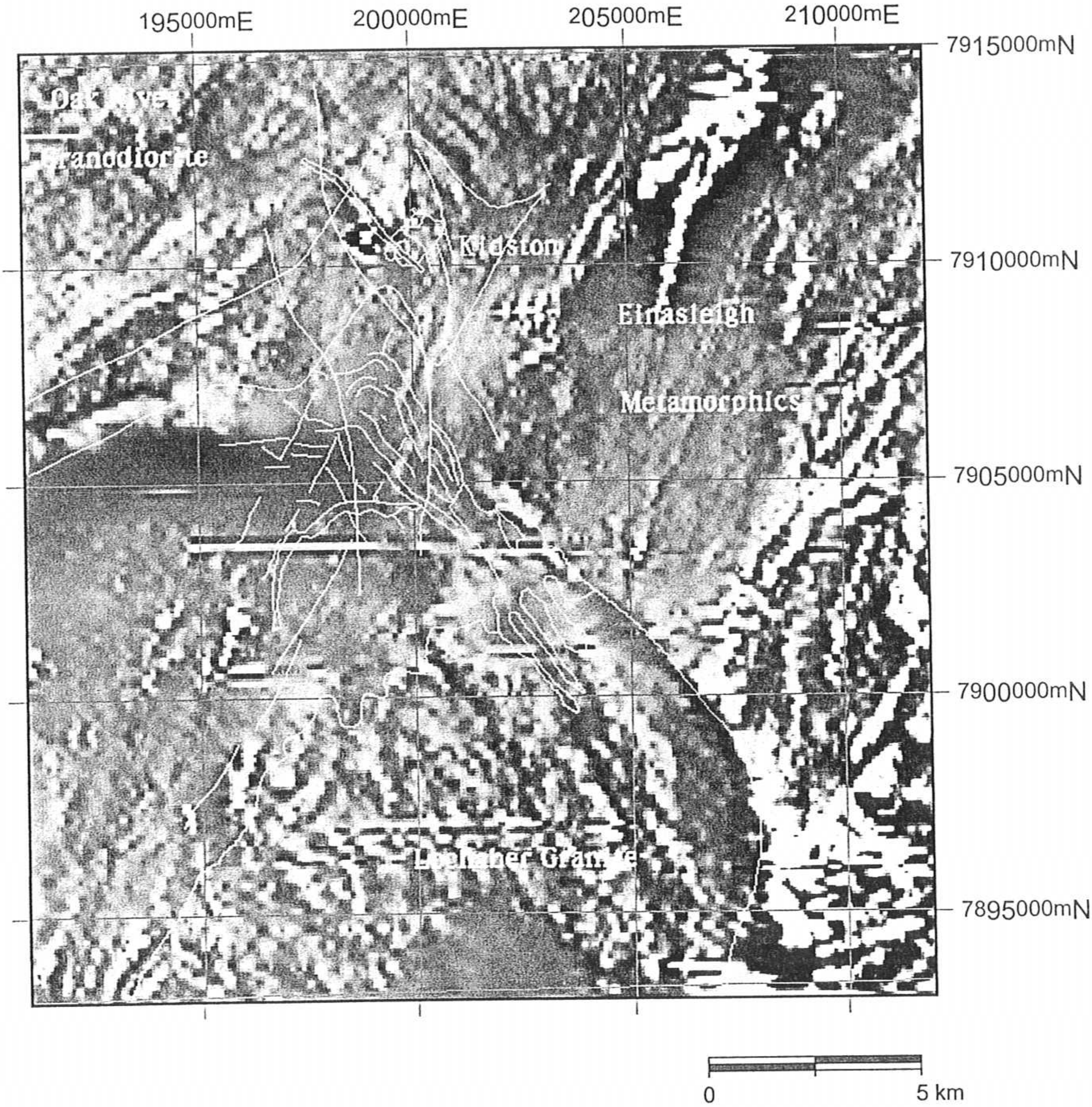


Fig.17. Greyscale image of the first vertical derivative of TMI data over the Kidston-North Lochaber area.

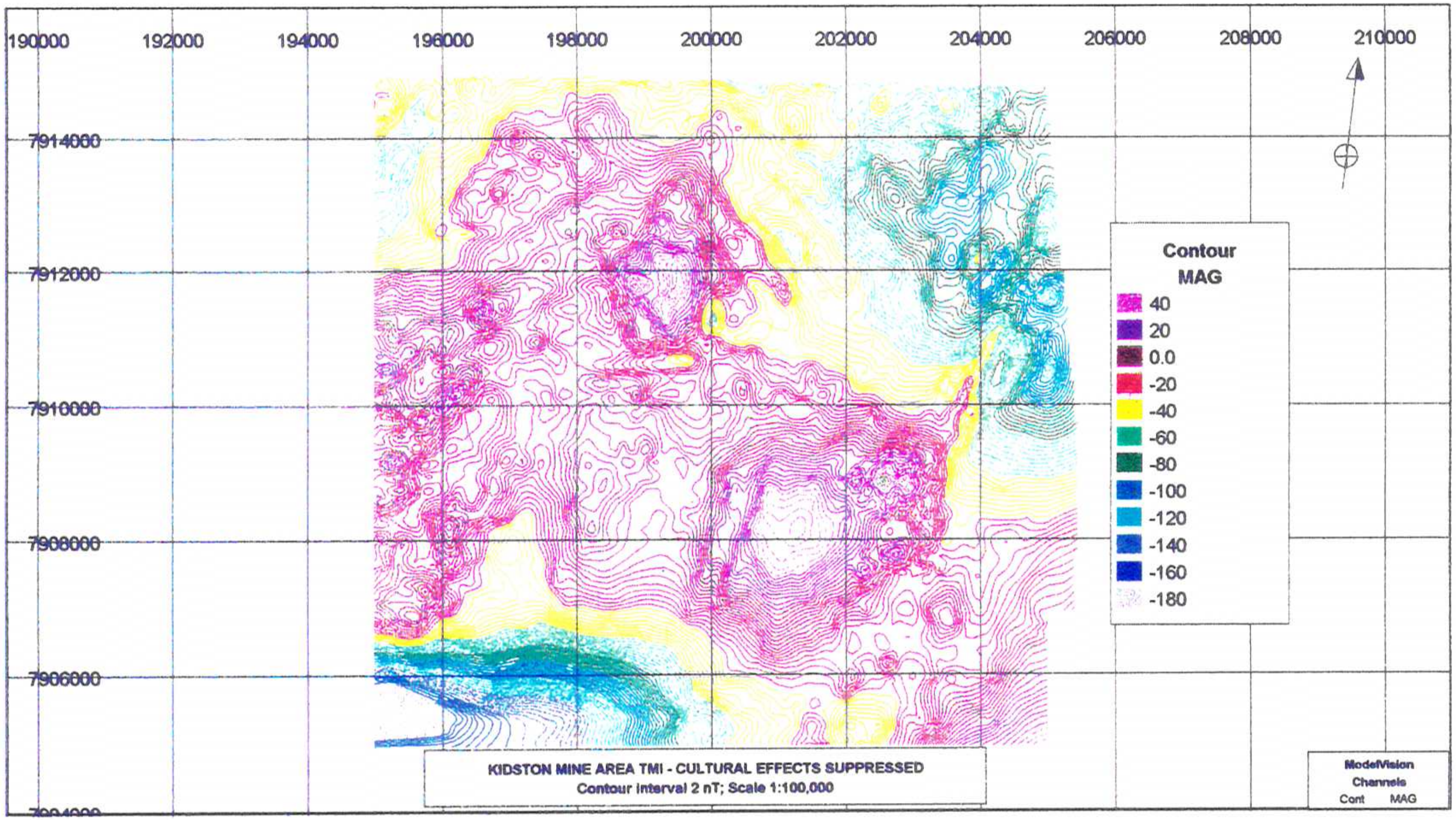


Fig.19. Colour contour map of TMI over the Kidston mine area, with the prominent cultural anomaly due to mine infrastructure suppressed.

Kidston Magnetic Survey

1st vertical derivative 1VD coloured with RTP TMI

Kidston mine area

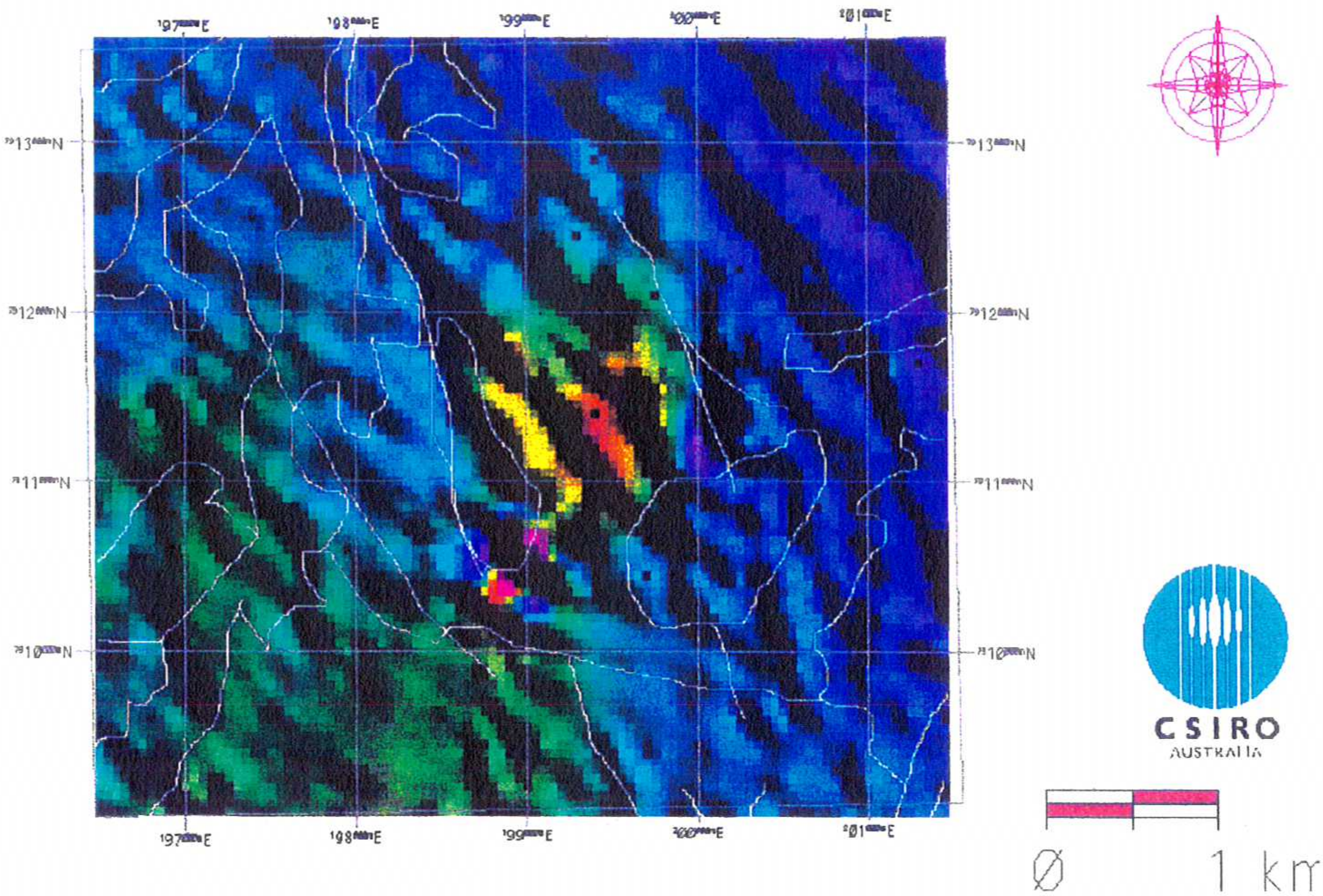
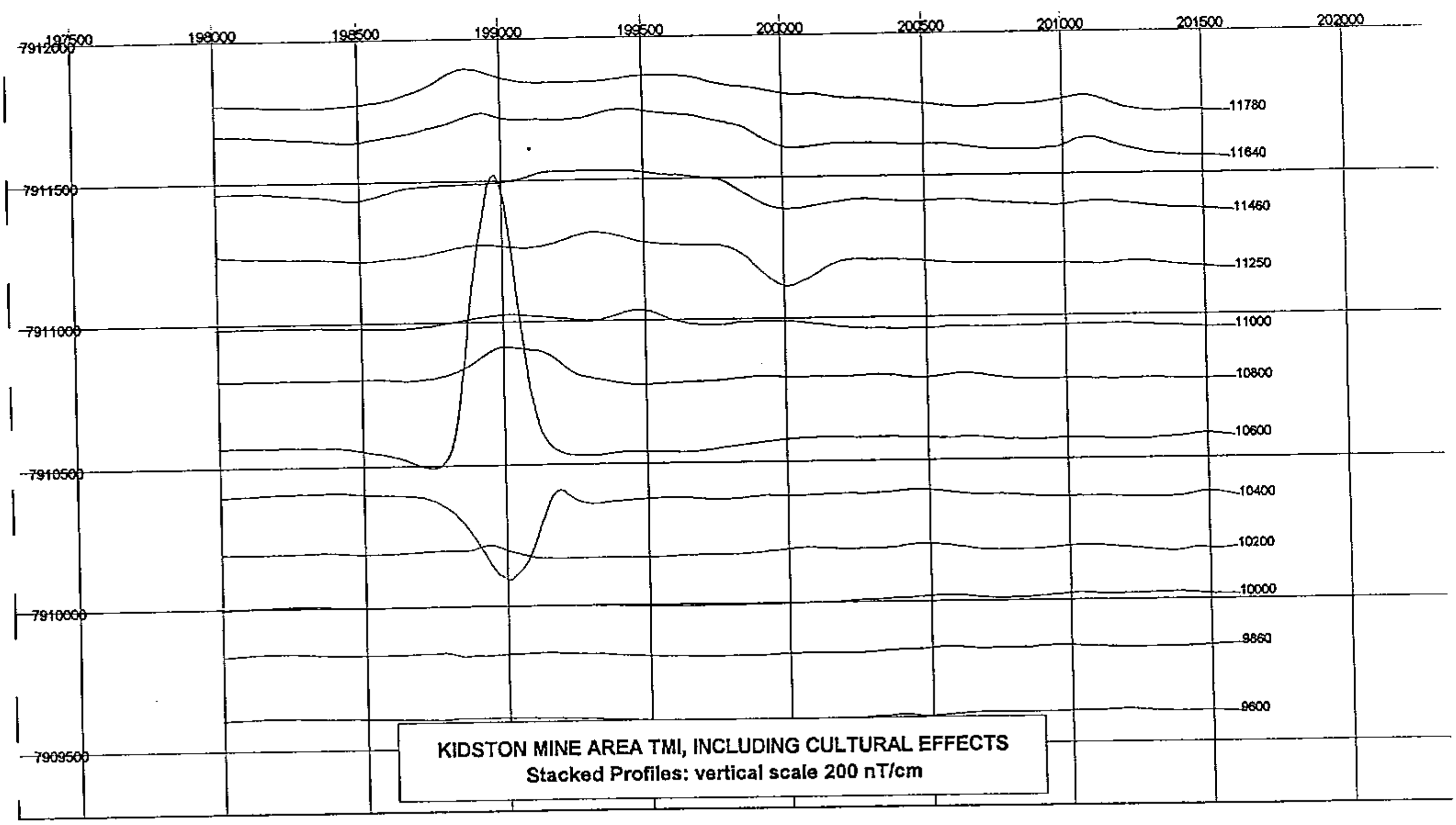


Fig.20. Image of magnetic data for the Kidston mine area. The colour represents the reduced-to-the-pole TMI and the shading represents the first vertical derivative of the TMI. Note the dominant NW Paddys Knob Dyke Swarm trend, which continues through the pipe, with slight disruption, but is not truncated by the NW-trending fault (part of the Noel Fault System) that controls the SE boundary of the pipe.



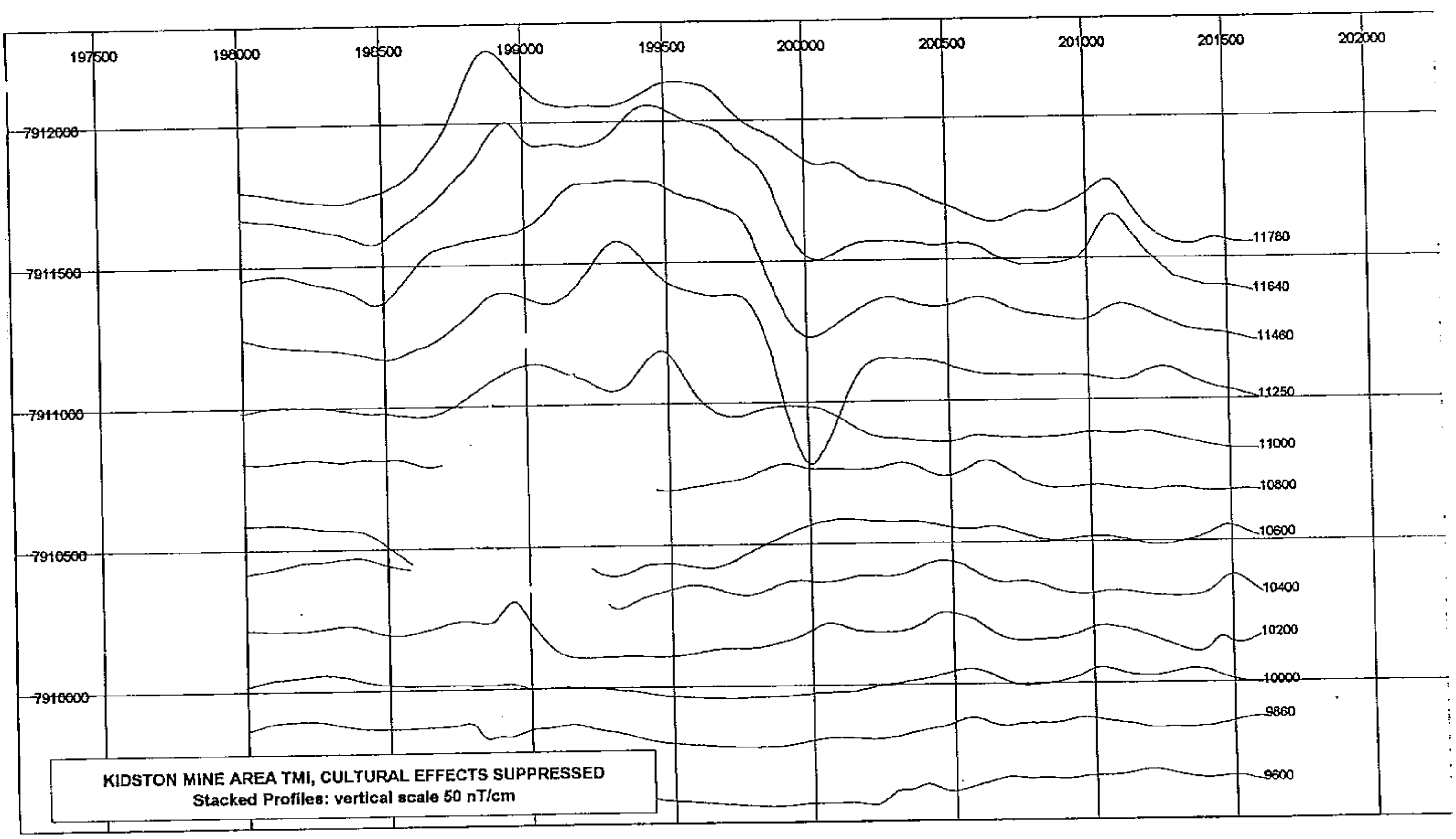


Fig.21. Stacked profiles of TMI data for the Kidston mine area.

The Kidston mine lies within a saddle zone of the magnetics, between the two magnetic highs that are interpreted as representing buried Carboniferous stocks. Immediately northeast of the mine the boundary between the mixed Oak River Granodiorite/Einasleigh Metamorphics zone and the main Einasleigh Metamorphics zone is marked by a strong magnetic gradient, with lower TMI in the NE, over the metamorphics.

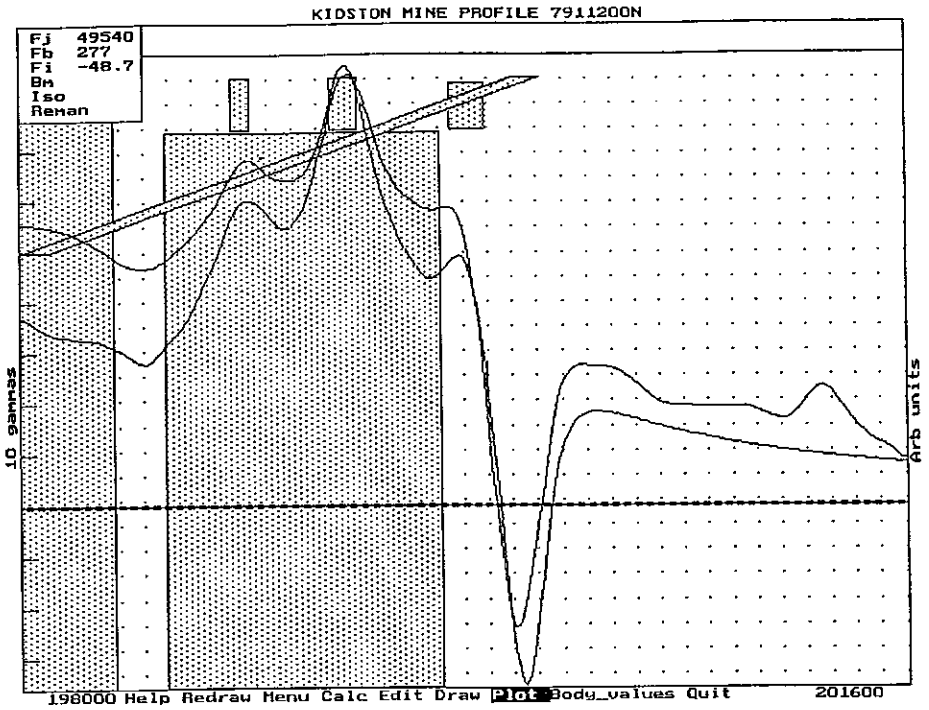
Figure 22 shows measured TMI profiles over the diffuse magnetic high SE of Kidston, together with calculated anomalies, due to large buried magnetic sources, that fit the observed data reasonably well. The relative smoothness of the substantial (100 nT) high in the western half of these profiles and the gradient on the flanks of the anomaly indicate that the main source is at considerable depth (> 500 m). The estimated depth to the top of this body is ~800 m. The local magnetic highs superimposed on the main anomaly are due to sources that extend to higher levels, probably to within 100-150 m below the survey level. Thus the tops of these magnetic bodies are interpreted to lie only 40-90 m below the surface. The susceptibility contrasts of the modelled bodies with the enclosing rocks are ~200 μG/Oe (2.5×10^{-3} SI). The strong magnetic gradient in the eastern half of the profiles reflects a major boundary between less magnetic rocks in the west and more magnetic rocks in the east. The inferred susceptibility contrast between the western and eastern zones is ~600 μG/Oe (0.0075 SI).

The overall form and geological setting of the interpreted sources of the magnetic highs flanking the Kidston mine area suggest that they represent major stocks emanating from the underlying batholith, with apophyses that extend to shallow depths. The inferred susceptibilities imply that the compositions of these stocks are somewhat less felsic than the Kidston intrusives. The likely composition of these intrusions is hornblende-biotite monzogranite to granodiorite. However there may be more felsic porphyries and intrusive breccias, which would have weak magnetic expression, emanating from these stocks. Detailed gravity surveys over the buried intrusions might define the subsurface distribution of porphyry and breccia phases, which could be prospective for Kidston-type mineralisation.

5.2 The Magnetic Signature of the Kidston Breccia Pipe

Figures 19-21 present the TMI data over the Kidston mine area in the form of a contour map, an image and stacked profiles respectively. The magnetic signature of the Kidston Breccia Pipe is subtle and not readily recognised in the regional aeromagnetics, without prior knowledge of its location. A number of factors conspire to render the magnetic response difficult to detect. The magnetisation of the host rocks, the Einasleigh Metamorphics and the Oak River Granodiorite, is variable and the geology around the pipe is complex. This creates a "busy" magnetic pattern in the vicinity of Kidston, which tends to obscure the weak magnetic response of the pipe. The Kidston pipe consists largely of country rocks that have been brecciated essentially *in situ*. The weakly altered portions of the pipe therefore have similar magnitude and spatial distribution of magnetisation as the surrounding area. The local magnetic pattern is dominated by large anomalies associated with mine infrastructure, which confuses the interpretation of the geological signal.

Careful examination of the data, however, particularly in the form of stacked profiles, confirms that the Kidston pipe does produce a detectable magnetic response. A substantial portion of the upper portion of the pipe is pervasively phyllically altered and is more weakly magnetic, on average, than the surrounding rocks. With the exception of the volumetrically



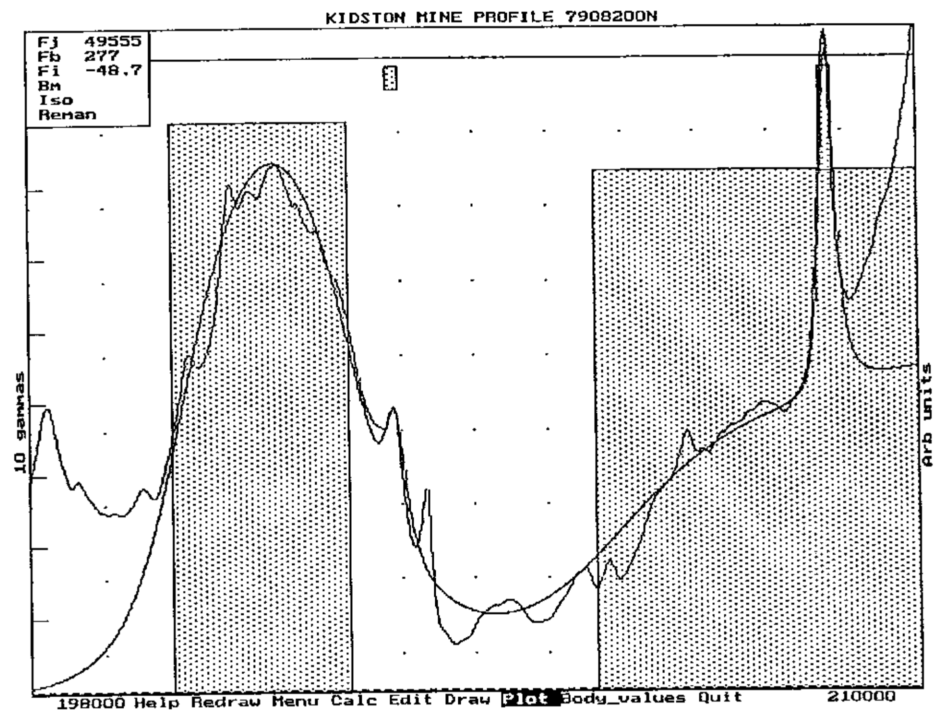


Fig.22. Measured TMI profiles over the broad magnetic highs NW (top) and SE (bottom) of Kidston, together with calculated anomalies, due to large buried magnetic sources, that fit the observed data reasonably well. Removal of linear regional trends would produce closer fits between observed and calculated anomalies. In the top plot, the west-dipping dyke represents the reversely remanently magnetised Macks Porphyry contact zone. The other bodies are 2D vertical sheets. The westernmost source is a basement contact that accounts for some of the regional gradient. The other sources are interpreted to represent slightly more mafic intrusions than the Kidston intrusives, containing 0.1-0.4 vol % magnetite. In the bottom plot, the sources are vertical cylinders with up to 0.5 vol % magnetite, apart from the easternmost source, which is a 2D geological contact within the Einasleigh Metamorphics.

minor andesite dyke, the other major components of the pipe are very weakly magnetic porphyry plugs and dykes. At the time of the magnetic survey, the pipe had been excavated to a depth of ~40 m below the general surface (~60 m below the summit of the original knobs) and the missing portion therefore has a negative magnetisation contrast with the country rocks. Because the susceptibility of the missing upper portion of the pipe was very low, the excavation has probably only had a minor effect on the magnetic response.

At depths greater than ~250 m, on the other hand, the deep phyllic alteration is associated with pyrrhotite, at the expense of pyrite. The pyrrhotite zone is characterised by moderate susceptibility, comparable to the average susceptibility of the country rocks, and relatively intense remanent magnetisation. The NRM carried by pyrrhotite is a dual polarity magnetisation of Carboniferous age. Koenigsberger ratios of individual samples are high, but the dual polarity produces partial cancellation of oppositely directed NRMs, lowering the overall Q. Normal polarities predominate, suggesting that the overall magnetisation of the pyrrhotite zone has normal polarity, with a moderate Q. This suggests that a reasonable first order model of the Kidston pipe comprises a shallow section that has a negative susceptibility contrast with the surrounding rocks and a deep portion with a positive magnetisation contrast. Remanent magnetisation of the country rocks can be ignored beacause these rocks have generally low Q, scattered NRM directions and a resultant NRM that is dominantly of recent viscous origin. Therefore the remanence of these rock units simply produces a slight increase in their effective susceptibility.

5.3 Magnetic Modelling of the Kidston Breccia Pipe

To a first approximation, the Kidston pipe may be represented as a vertical cylinder with a negative magnetisation contrast in the upper 250 m and a positive magnetisation contrast at greater depth. The diameter of the pipe is ~1000 m. The total magnetisation of the deep pyrrhotite zone is essentially due to remanence, given the relatively intense remanence and the small susceptibility contrast. The direction of this magnetisation can be predicted from the inferred age of magnetisation and the Carboniferous apparent polar wander path for Australia (Clark, 1996). For this purpose the ~325 Ma palaeopole from the Bathurst Granite and aureole (lat = 45°S, long = 72°E) was used. The corresponding palaeofield direction at Kidston is (dec = 48.0°; inc = -43.8°), which was used to model the response of the pyrrhotite zone.

The intense (~600 nT) narrow anomaly immediately west of the pipe, centred on 199,000 mE; 7910600 mN, arises from the mill. The sharpness of the anomaly constrains the depth below the sensor and the depth extent of the source, which can be modelled satisfactorily as a thin, highly magnetic disc at the surface. Because this anomaly is large compared to the nearby geological anomalies, it is necessary to model its source to determine the base level shift and magnetic gradient over the pipe associated with the flanks of the cultural anomaly.

When the cultural anomalies are excised from the aeromagnetic data set, the geological anomalies become more evident in both stacked profile and contour map presentations. These plots give a more realistic picture of the magnetic signature at Kidston that would have been observed in a survey flown prior to development of the mine.

A simple magnetic model that conforms to the broad geometry of the pipe, is consistent with the drilling information and the measured magnetic properties and provides a reasonable match to the observed anomaly was generated. The geometric and magnetic parameters of the model are:

Radius of upper and lower cylinders	500 m
Centre of cylinders	200,000 mE; 7910700 mN
Upper cylinder: depth below sensor	70 m
Upper cylinder: depth extent	250 m
Average country rock properties	k = 200 μG/Oe = 2510 μSI (Q = 0)
Upper cylinder: magnetisation contrast	-5γ = -50 mA/m (Δk = -100 μG/Oe; Q = 0)
Lower cylinder: depth below sensor	320 m
Lower cylinder: depth extent (minimum)	500 m
Lower cylinder: magnetisation contrast	20γ = 200 mA/m (Δk ≈ 0; NRM = 200 μG; Q = 2)
Lower cylinder: magnetisation direction	dec = 48.0°, inc = -43.8°

Figure 23 shows the observed and calculated anomalies for the Kidston mine area along lines 7910200 mN, 7910400 mN, 7910600 mN, 7910800 mN and 7911000 mN which pass over the pipe. The model is constrained by lines 7910600 mN and 7910800 mN, which straddle the centre of the pipe. Examination of these plots shows that the anomaly associated with the pipe is characterised by:
(i) a magnetic high of amplitude ~15 nT, slightly wider than the pipe itself,
(ii) a positive slope across the pipe, from west to east, with the anomaly about 10 nT higher on the eastern flank of the pipe,
(iii) small positive bumps near each flank of the pipe.

By varying parameters of the model it can be established that the overall magnetic high is attributable to the deep pyrrhotite zone. Within this high a smaller low occurs due to the negative magnetisation contrast of the upper pyritic zone. This low is slightly narrower than the main high, due to the shallowness of the source, resulting in the flanking bumps.

Anomalies arising from induced magnetisation alone would exhibit symmetry along the E-W lines. The slope of the magnetic high is attributable to the remanent magnetisation, which is directed ~NE and has moderate negative (upward) inclination, and is therefore oblique to the geomagnetic field. The depth extent of the lower cylinder is not well defined by the magnetics. A cylinder with infinite depth extent and a slightly lower remanent intensity (15γ = 150 mA/m, corresponding to Q ≈ 1.5) fits the observations equally well.

The overall form of the observed anomalies conforms reasonably well to that of the calculated anomalies, but a number of narrow bumps with amplitudes of a few nanoteslas are present over the pipe, probably representing heterogeneity of magnetisation assocciated with varying lithologies, affected by alteration of varying type and intensity. Enhanced susceptibilities within the pipe could be associated with zones of breccia dominated by clasts of weakly altered, relatively magnetic country rocks; with local zones of potassic alteration; or with the andesite dyke.

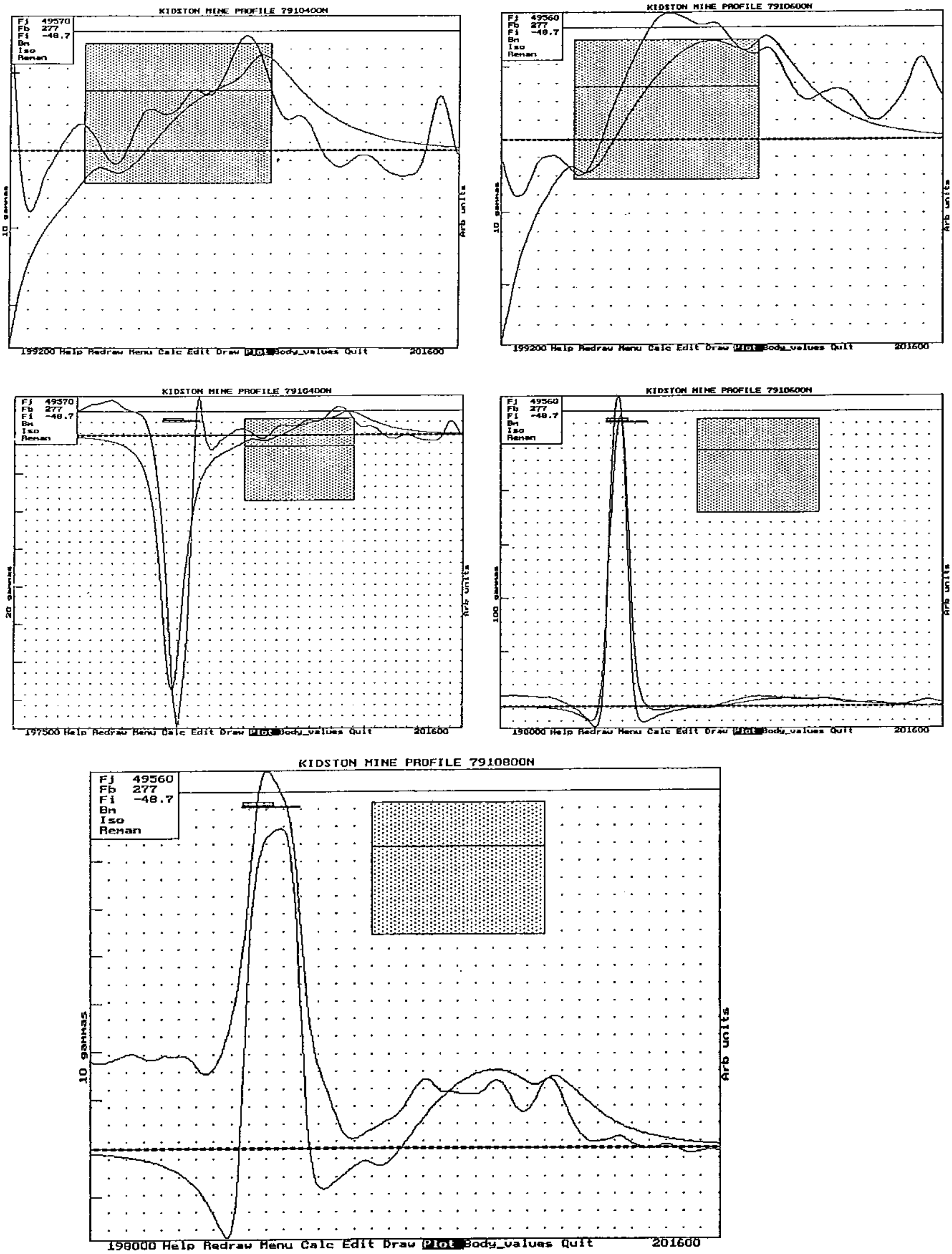


Fig.23. Measured TMI profiles along lines 7910400 mN, 7910600 mN and 7910800 mN over the Kidston Breccia Pipe, together with calculated anomalies, that fit the observed data reasonably well. The breccia pipe is modelled as a vertical cylinder of 500 m radius and 250 m depth extent, representing the weakly magnetic pyritic upper zone, above a coaxial cylinder that represents the more magnetic pyrrhotitic zone. The magnetisation contrast with the country rocks of the upper zone is negative, whereas the lower zone has similar susceptibility to the country rocks, but carries remanence that gives it a positive magnetisation contrast.

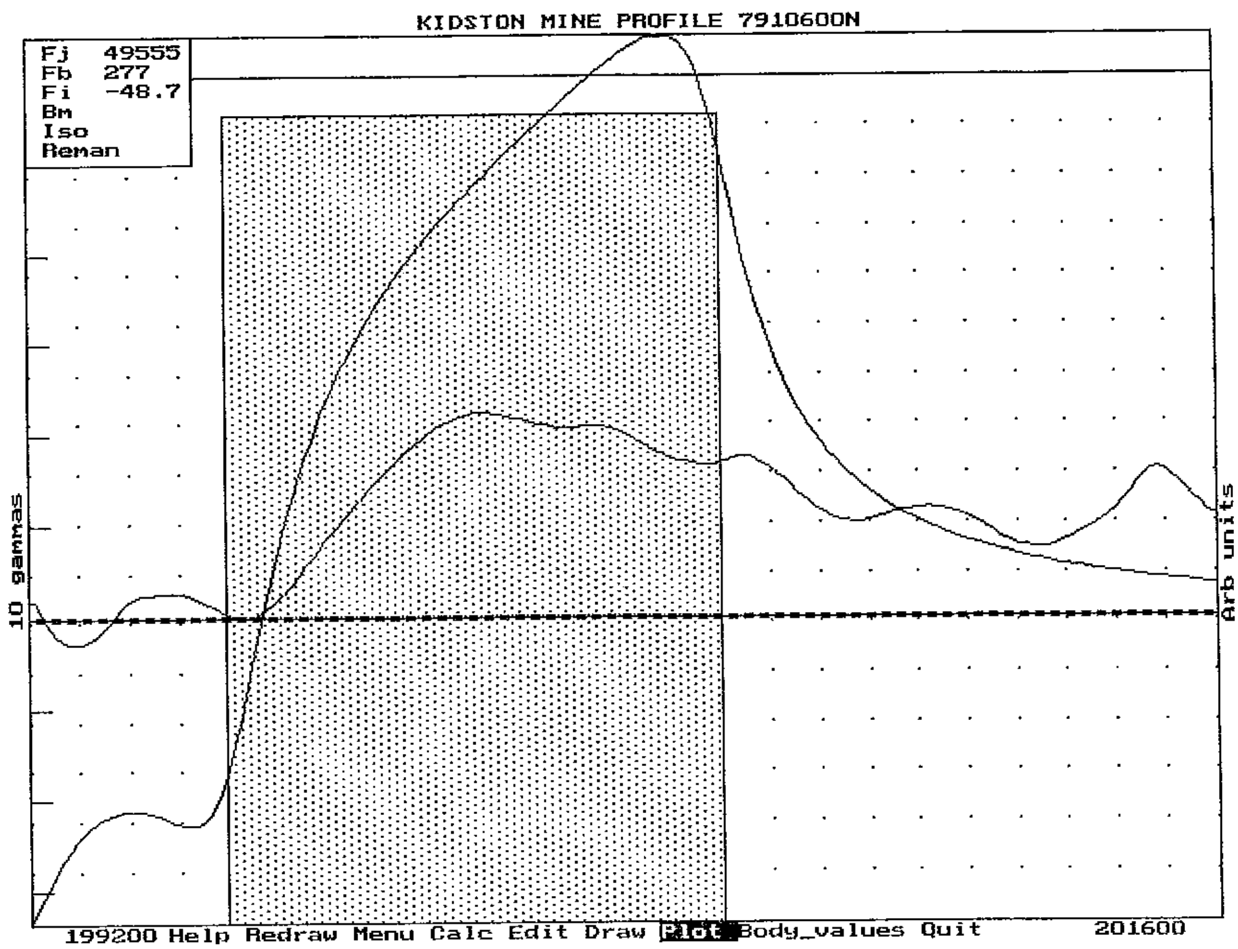


Fig.24. Predicted TMI profile along line 7910600 mN over the Kidston Breccia Pipe, assuming that a greater depth of erosion has exhumed the magnetic pyrrhotitic zone. Note the enhanced amplitude of the anomaly, compared to Fig.23.

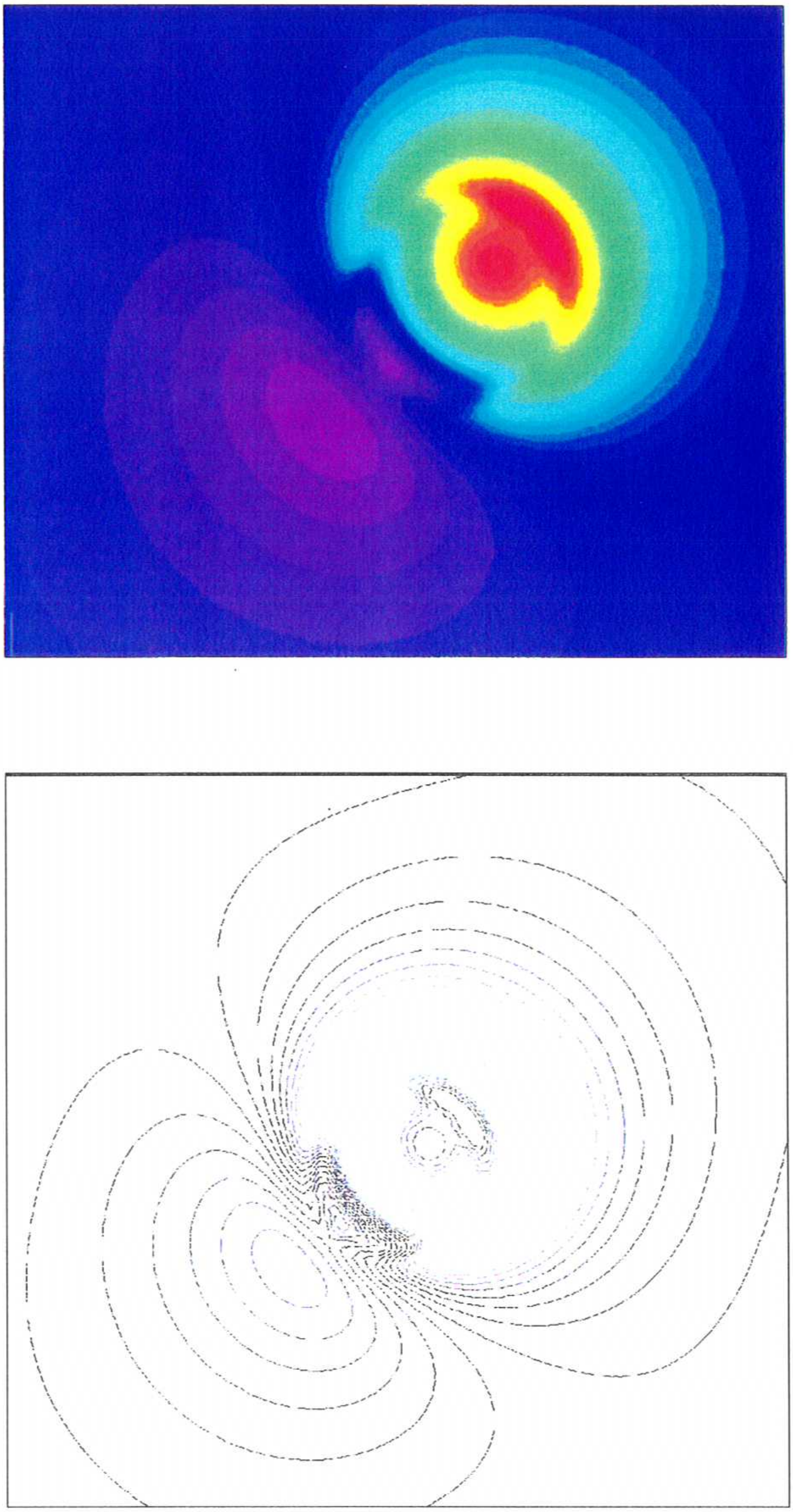
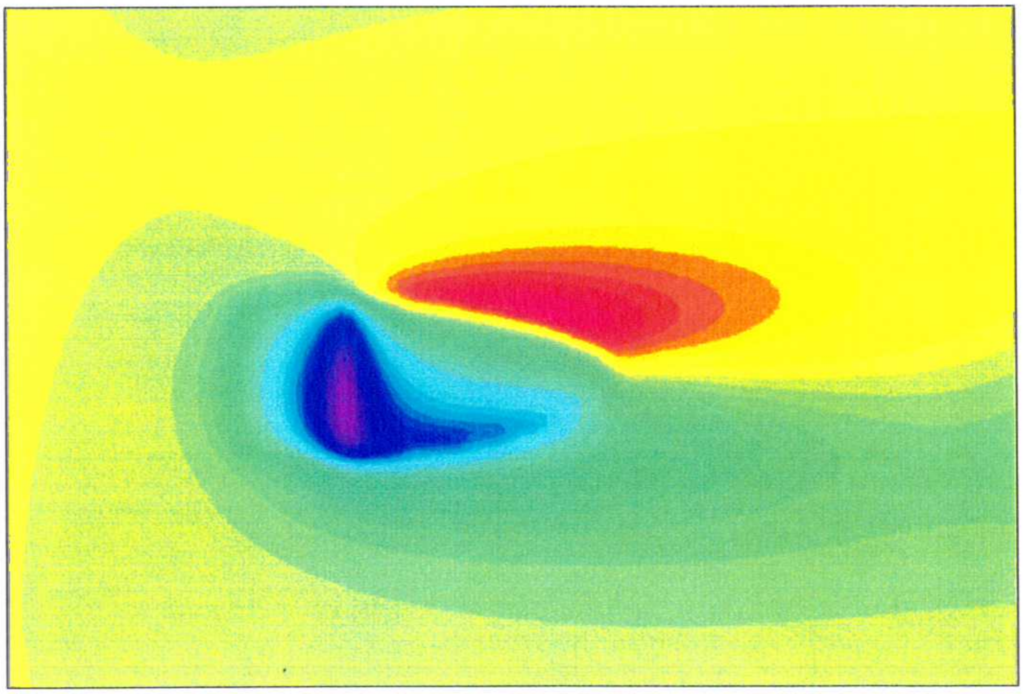


Fig.25. Predicted reduced-to-the-pole TMI anomaly over an analogue of the Kidston Breccia Pipe, assuming no tilting. Contour interval in contour map is 1 nT.



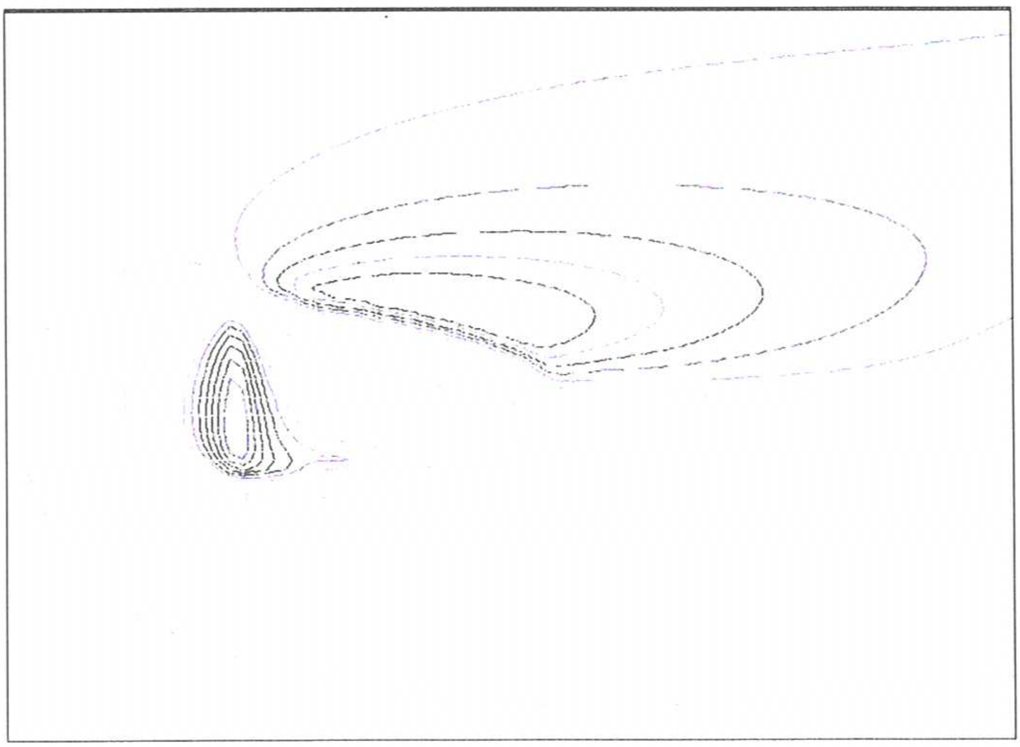


Fig.26. Predicted RTP TMI anomalies over an analogue of the Kidston Breccia Pipe, assuming 70° of tilting, producing a plunge of 20° to the east, following remanence acquisition. Contour interval in contour map is 5 nT.

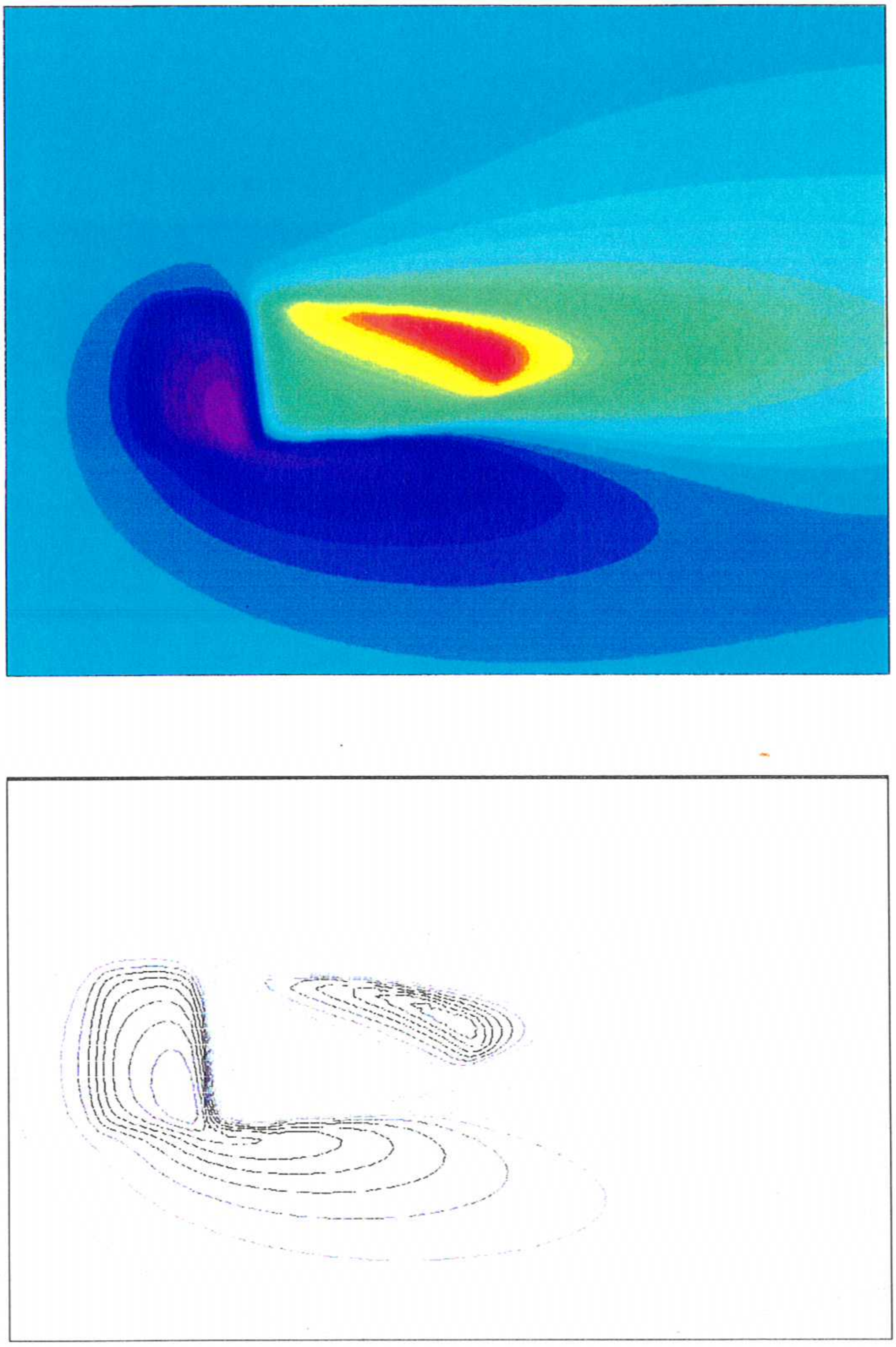


Fig.27. Predicted RTP TMI anomalies over an analogue of the Kidston Breccia Pipe, assuming 70° of tilting, producing a plunge of 20° to the east, *prior* to remanence acquisition. Contour interval in contour map is 5 nT.

This magnetic model can be used to predict the expected magnetic response over Kidston with a greater depth of erosion (Fig.24). Exhumation of the pyrrhotite zone would produce a much more prominent anomaly of ~70 nT. Unfortunately, this would remove the high grade orebody! It appears that in this environment, areas of greater vertical uplift and erosion would have exposed subeconomic root zones of Kidston-type systems that are more easily located magnetically than Kidston itself.

Figures 25-27 show, respectively, the RTP TMI anomalies that would be associated with a Kidston-type pipe that is untilted; that has been subjected to ~70° of tilting, so that it is now lying almost on its side, with pre-tilting remanence; and the post-tilting remanence case for the same tilting. Although this type of tectonic rotation has not occurred in the Georgetown Inlier since the Carboniferous, it is known to have taken place in other provinces, particularly in some of the Laramide age porphyry copper deposits of the American southwest and may be relatively common in fold and thrust belts around the Pacific rim. A Kidston-type pipe with shallow plunge at shallow depth should exhibit a much more prominent anomaly, substantially larger in amplitude and of considerable extent parallel to the plunge azimuth.

The weakly magnetic, pyrite-dominated, high grade zone would be associated with a smooth magnetic low, with an amplitude that depends on the background susceptibility of the country rocks. This low could be quite prominent if the country rock susceptibility is substantial and may also be evident from a change in texture of the magnetic patterns, particularly in derivative anomalies. The direction of remanence in the pyrrhotitic zone would depend on the thermal history. If the tectonic rotation was accompanied by low grade metamorphism, with a peak temperature exceeding ~250°C, the remanence would have been reset and would therefore align with the prevailing palaeofield immediately after cooling. On the other hand, if the pyrrhotitic zone has never been subjected to post-formation temperatures greater than ~150°C, the remanence can be assumed to have rotated with the pipe. The anomaly shapes resulting from these two scenarios differ substantially, because the anomaly associated with the pyrrhotitic zone is dominated by remanent magnetisation.

6. Interpretation and Modelling of Radiometrics of the Kidston Complex

6.1 Introduction

The radiometric response of the ground comes from the topmost 20 - 30 cm of the ground i.e. generally soil with small amounts of outcrop. An airborne survey reflects surface weathering effects, such as gossan development, and soil forming processes such as aeolian and colluvial transport. Further, at a flying height of 80 - 100 m above ground, the airborne detectors receive radiation from an area of ~150 m radius. Measurement times are typically 1 sec. during which time the aircraft moves forward approximately 70 m. Thus, in the 1 sec count time, radiation is measured from an area of approximately 300 m wide and 400 m long. Count-rates are generally low and each measurement may have an uncertainty ranging from 10 % (for K) to 60 % (for U). The signal is thus equivalent to a moving average with varying noise and the response from small features such as narrow dykes can be easily obscured by the surrounding host rocks.

6.2 Evaluation of the Kidston Aerial Gamma-Ray Survey

Two sets of radiometric survey data was provided by Placer Pacific for use by the project. The first survey was made with 33 litre crystal, with mean terrain clearance of 70 m and flight line spacing of 250 m (plus 125 m infill lines over deposit). It was flown in 1981 prior to major mining in 1984, although open pit mining had occurred in the area from 1910 to the late 1940's. The second survey comprised a large regional compilation of a number of regional surveys covering a wide area south, west and north of Kidston. This survey was flown post-mining and the effects of mine development around Kidston can be clearly seen. For example, there is water in the head of the tailings dam and several rock storage areas to the west of the mine show an elevated K signal.

Four images of the data from the initial survey prior to mining are shown in Fig 28. Figures 28(a)-(c) show the K, eU and eTh images separately, whilst Fig.28(d) shows a false colour composite with K = red, U = blue and Th = green draped over a pre-mining digital elevation model of the area. The data was histogram normalised prior to display. The breccia pipe is distinguished by a high K content particularly in the Wises Hill and Macks Knobs area. Immediately north of Macks Knob a QFP dyke trending NNW is also prominent, having a rich K and eTh signature. Another QFP dyke ~1 km west of the pipe (the Big Red Dyke; a member of the PKD5 suite) is responsible for a linear zone of high K. An area with abundant leucogranitoid and microgranite dykes south and south-west of the pipe also shows elevated K and elevated eTh, though generally not in coincidence. Quaternary alluvium in the Copperfield River (SE of the pipe) and in the Charles Creek (to the west) also show as K-rich. Finally, a high K area in the north-west corner of the image is not identified in the available geology maps but the lack of association with eU or eTh may suggest that it is an area of pegmatite. The Oak River Granodiorite generally has a low K signature and the Einasleigh Metamorphics a much higher K content, in agreement with the laboratory results.

The eU distribution in the area (Fig.28(b)) does not show great variations although the image appears zoned approximately east-west with the pipe occurring within the low eU zone. An area of higher eU to the south-west of the pipe may reflect leucogranitoids in that area.

The eTh image (Fig.28(c)) shows the breccia pipe has some relatively eTh-rich areas compared to the surrounding Oak River Granodiorite and Einasleigh Metamorphics rocks although these are not coincident with the K-rich areas. They appear to be indicating a zone of post-breccia intrusive dykes. As mentioned above, the leucogranitoids to the south-west of the pipe and the "Big Red" rhyolite dyke to the west both show a eTh-rich signature. As with K, the Oak River Granodiorite appears to have lower eTh than Einasleigh Metamorphics, in agreement with the laboratory results. Oak River-dominated breccia in the south-west of the pipe also shows a low eTh-signature.

The false colour composite draped over the pre-mining DEM of the area (Fig.28(d)) shows that the Wises and Macks Porphyries were both prominent topographically and well as radiometrically. This topographic relationship helps distinguish the porphyry bodies from the radioelement-rich leucogranitoids which have generally been weathered to flat-lying bodies.

The regional survey shows the Lochaber-Bagstowe Granites and the Butler Volcanics to their west as prominent, radioelement-rich units. To their north, a large area of rocks with K > U ~ Th shows as red tones. This is the Oak River Granodiorite. It is cut by rivers and streams carrying material of a different radioelement signature, one of these being the Copperfield River. Between the northern portion of the Lochaber Granite and the Oak River Granodiorite is an area of mixed signatures

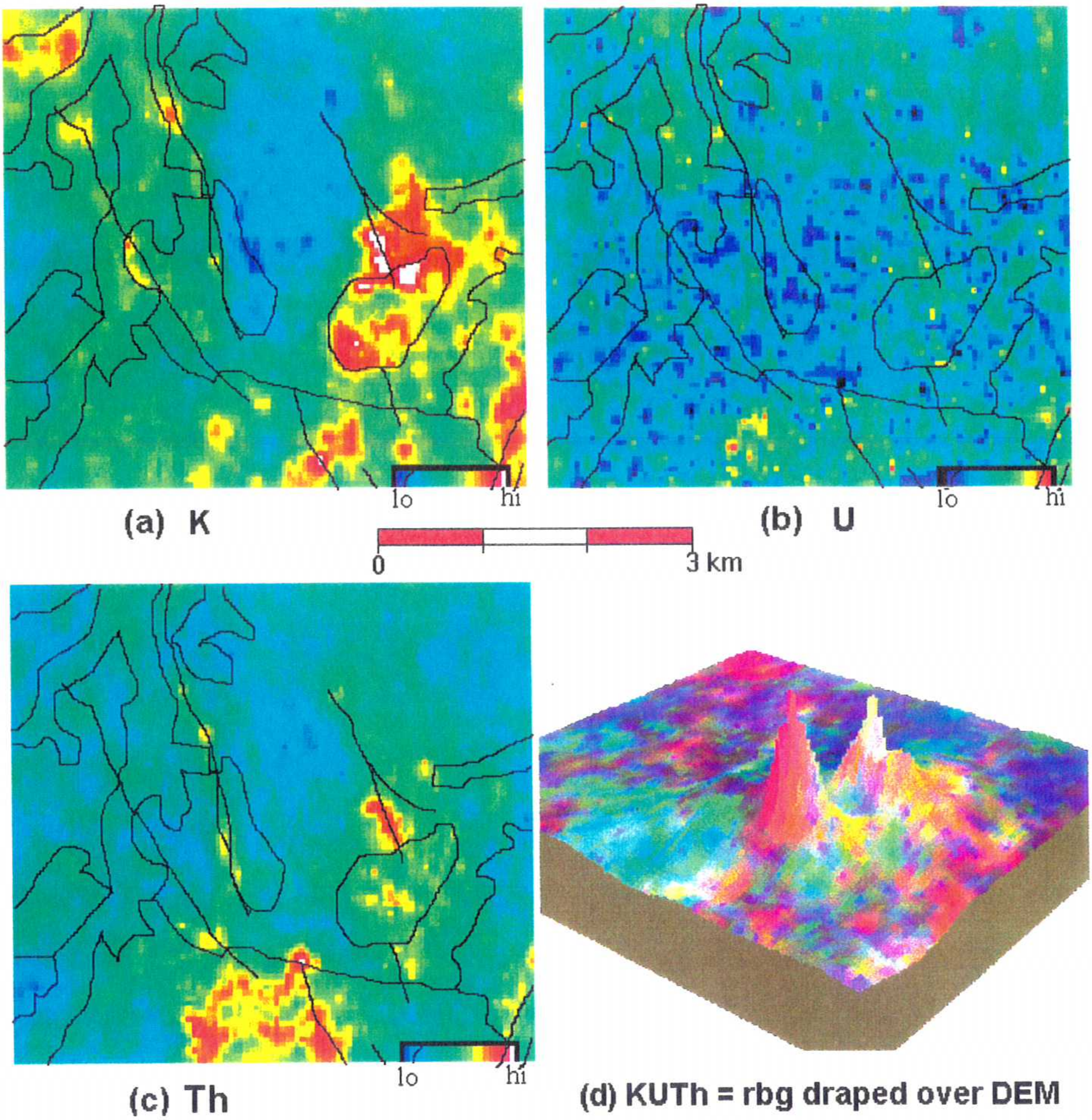


Fig.28. Images of radiometric data over the Kidston mine area, (a) K, (b) eU, (c) eTh, (d) a false colour composite with K = red, U = blue and Th = green draped over a pre-mining digital elevation model of the area. The data were histogram normalised prior to display.

Fig.29. False colour composite image of regional radiometric compilation with K = red, U = blue and Th = green.

(Fig.29). The Kidston Complex lies within this area but is not prominent in any stretch of the whole scene data. The Big Red Dyke is still visible in the regional survey, although not strongly prominent. Its major feature is that it trends NNW whereas the trend of structure in the adjacent country rocks (especially to the east) is NNE. The rhyolite dyke north of Macks Knob can still be seen, although because of the wider line spacing, this dyke is reduced to a single "hot" pixel. Other radioelement-rich pixels also occur in this area but outside the Complex boundary and may be effects of mining. Other effects of mining can be seen such as a rock dump west of the mine and water in the head of the tailings dam. The leucogranitoid SW of the mine and just west of the tailings dam, seen in the 1981 survey, is still prominent in the regional survey.

A variety of image combinations and ratios were examined to determine if the signature of the breccia complex could be enhanced in the regional survey. These are summarised below:

Radiometrics: Image Combinations and Ratios

Image combination	1981 local area survey	Regional survey covering area to Lochaber Granite
K/Th	shows variety of high ratio areas	highlights variation in Kidston Granite & Einasleigh Metamorphics
Th/U	shows north-south zoning, approximately N of complex	noisy image little information
K*U	highlights rhyolite dyke N of Macks Hill and several areas S & SE of the mine	highlights river and granites, with possible extent of dyke swarm towards Kidston
K*K/Th	highlights Wises Hill and pegmatite? to NW	highlights several rhyolite units & variation in Einasleigh Metamorphics

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Attempts were made to highlight the area around the complex using application of "Local area gain" filters. Such filters can show variations from the local average response and decreasing the effects of big variations through a survey area. For example, the mean and standard deviation of data in a window of 25 x 25 pixels (or 1250 x 1250 m) may be chosen and the central pixel set to the number of standard deviations it is away from the window mean. With the regional radiometric survey data, such techniques were not found to enhance the response of the Complex relative to the whole survey.

6.3 Modelling the Radiometric Response of the Kidston Complex

The rock data of Table 6 were used to model the radiometric response of the Kidston Complex. A simplified vector map of the complex was prepared (after Baker and Tullemans, 1990). This was converted to a raster with 10 m × 10 m pixels, with the pixel value identifying the rock type. A "Spatial Manipulation Language" (SML) procedure was written for the TNTMips® GIS to produce K, eU and eTh rasters using the rock data. To provide a "realistic" image to compare with the aerial data, these calculated rasters were then convolved with a filter that reproduces the running average

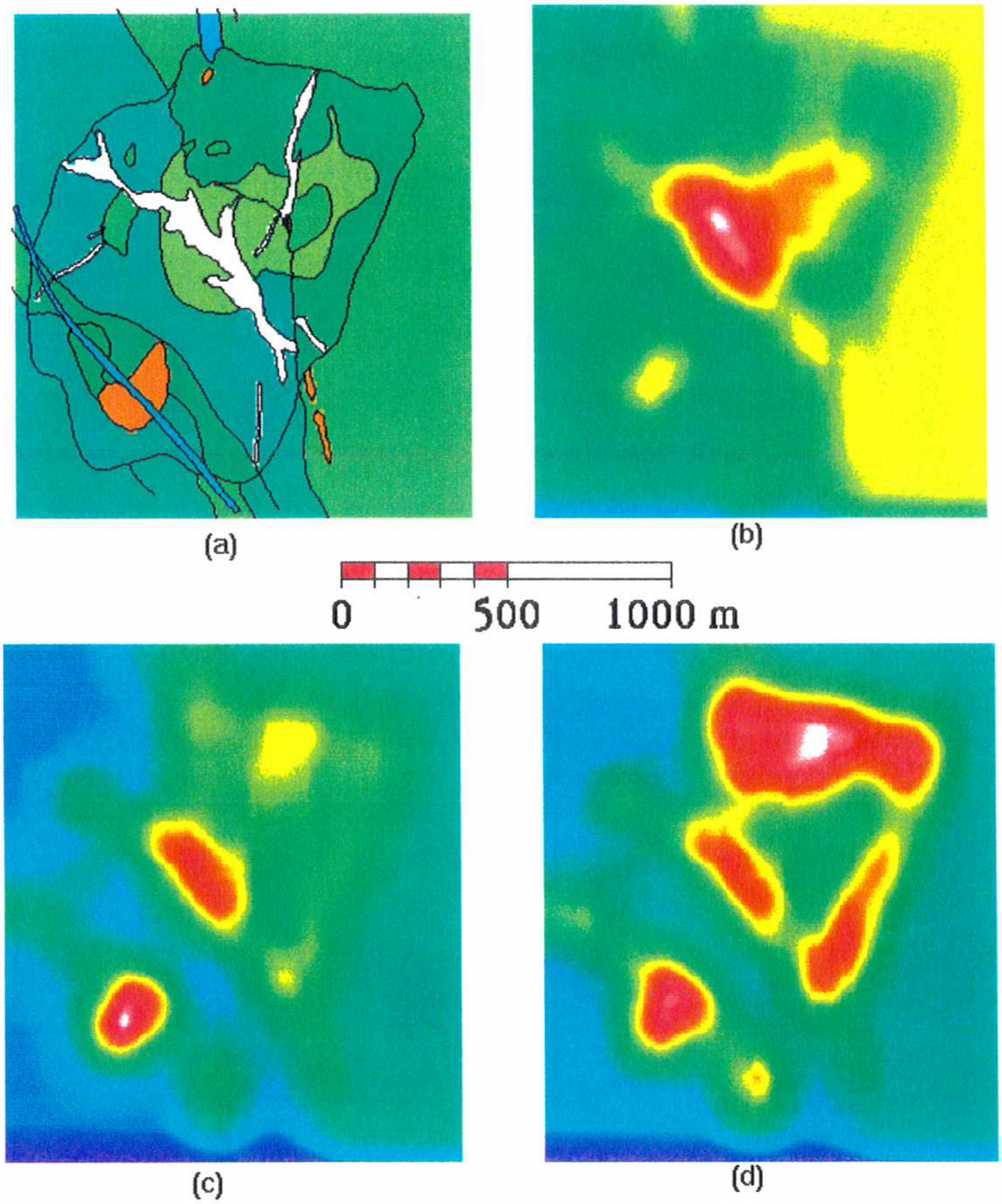

Fig.30 (a) Modelled K distribution over the Kidston Breccia Pipe, based on the geological map (overlay) from Baker and Tullemans (1990), (b) calculated K response after filtering to simulate aerial survey averaging and attenuation, (c) analogous filtered image for eU, (d) analogous filtered image for eTh.

effect of the aerial survey. Thus the contribution of each pixel in a 150 m square was determined to the central pixel using a weighting factor calculated as:

$$\text{factor} = \exp(-\mu x),$$

where μ are linear attenuation factors for K, U and Th radiation in air (Grasty, 1979) and x is the distance from the detector (assumed at 80 m elevation above the central pixel) and the contributing pixel. The resulting image has the fuzzy look of a aerial survey image but in fact still has more information than an actual survey as the survey is only measured along the flight lines and intermediate data is interpolated in the gridding process.

An example of the distribution of K over the Complex calculated using the rock data of Table 6 is shown in Fig.30. Fine detail such as the andesite dyke can be seen in this image. The Median dyke appears as a radioelement-rich feature across the Complex. After the "aerial detector" convolution is applied, the image obtained (Fig.30(b)) has lost all the fine detail and the response of the Median dyke is reduced to a central hot-spot.

7. Conclusions

7.1 Magnetic Petrophysics

- In spite of their very felsic composition, the Lochaber and Bagstowe Granites have moderate susceptibilites due to their oxidised nature, which favours partitioning of some of the limited available iron into magnetite (up to 0.1-0.2 vol %), giving susceptibilities of up to 400 μG/Oe (0.005 SI).
- The Black Cap Diorite, which rims the Bagstowe Granite and represents an early stage in the magmatic evolution of the Lochaber-Bagstowe Complex, is the most magnetic rock type sampled, with an average susceptibility of ~2600 μG/Oe (33×10^{-3} SI), reflecting the oxidised nature of the magma, coupled with its larger iron content. Compositionally similar andesite dykes at Kidston have similar susceptibilities, if they are relatively unaltered.
- Felsic dykes and porphyries are very weakly magnetic, with susceptibilities often less than 10 μG/Oe (0.13×10^{-3} SI). Their average susceptibility is 35 μG/Oe (0.44×10^{-3} SI).
- The magnetic properties of the breccia phases in the pipe are very variable, reflecting variability in clast lithology and degree and type of alteration. Susceptibilities range from 1-1000 μG/Oe ($0.01\text{-}13 \times 10^{-3}$ SI), but are generally low.
- Gneisses and amphibolites of the Einasleigh Metamorphics have generally low to moderate susceptibilities, except where altered at Kidston,
- Unaltered gneisses have average k ~ 60 μG/Oe (0.75×10^{-3} SI),
- Unaltered amphibolites have average k ~ 70 μG/Oe (0.9×10^{-3} SI),
- Biotite-altered amphibolite at Kidston has much higher susceptibility (~1200 μG/Oe = 15×10^{-3} SI),
- Siluro-Devonian Oak River Granodiorite and Proterozoic granodiorite have similar susceptibilities to each other and to the Lochaber and Bagstowe Granites (200-300 μG/Oe = $2.5\text{-}3.8 \times 10^{-3}$ SI).
- The dominant alteration types at Kidston (phyllic and albitic) are magnetite-destructive. On the other hand, early potassic (biotite) alteration, of restricted occurrence, is associated with magnetite and locally enhances magnetisation.

- At shallow levels phyllic alteration is associated with pyrite, whereas higher temperature, deep phyllic alteration is associated with pyrrhotite, which is the main magnetic mineral in the pipe, as well as pyrite.
- Weak propylitic alteration is largely magnetite-stable, whereas more intensely developed propylitic alteration is partially magnetite-destructive.

The palaeomagnetic results from reliable samples indicate:
- the magmatic and hydrothermal evolution of the Kidston-Lochaber suite spanned several geomagnetic reversals, suggesting a duration of several million years,
- the palaeofield directions recorded are NE with shallow to moderate negative (upward) inclination or SW with shallow to moderate positive inclination, the corresponding palaeopole is consistent with other reliable Early Carboniferous poles from Australia (Bathurst Granite in the Lachlan Fold Belt; Mt Eclipse Sandstone and Brewer Conglomerate in central Australia).

Remanence is subordinate to induced magnetisation in most rock units with the following exceptions:
- the deep phyllic, pyrrhotite-bearing zone in the Kidston Breccia Pipe, which carries relatively strong NRM of dual, but predominantly normal, polarity,
- moderately magnetic, potassically altered metamorphics adjacent to Macks Porphyry, which carry a reversed remanence, associated with moderate to high Koenigsberger ratios.

The direction of remanent magnetisation in these rocks can be inferred from the palaeomagnetic data.

7.2 Densities

Densities of the rock types represented in the Kidston-Lochaber area vary predictably with the content of mafic minerals in the rocks. Some density changes seem to be produced by alteration, but the effects on the overall density contrast between the pipe and its host rocks appear to be minor. Phyllic and albitic alteration appear to reduce the density of affected rocks by ~0.02 g/cm^3 , whereas alteration associated with pyrrhotite (deep phyllic and potassic with pyrrhotite veins) increases the density by a comparable amount. The data suggest that Kidston Breccia Pipe exhibits a small negative density contrast, possibly as much as -0.05 g/cm^3 on average, with the surrounding rocks. A density contrast of this order should produce a detectable gravity anomaly, with an amplitude of about -10 g.u. (-1 mgal) over the pipe. Detailed gravity surveys over the inferred buried intrusions flanking the Kidston mine area might define the subsurface distribution of porphyry and breccia phases, which could be prospective for Kidston-type mineralisation.

7.3 Radioelement Contents

Analyses of radioelements show that the Lochaber and Bagstowe Granites are particularly rich in radioelements, reflecting the felsic and fractionated nature of these intrusions. This enrichment is also seen in the quartz-feldspar porphyry dykes in the area between the granites and the Kidston complex. Two other porphyries (Wises and Macks) and the Median Dyke, associated with the complex, do not have the high eU and eTh contents found in the larger intrusions. Unaltered Oak River Granodiorite in the area has low abundances of the radioelements, especially eTh, relative to the Einasleigh Metamorphics. Alteration associated with mineralisation in brecciated granodiorite or polymictic breccia within the pipe is K-rich. Loss of K due to breakdown of feldspar during weathering is evident in soils developed over unaltered felsic rocks in the Kidston area, wheras muscovite associated with phyllic alteration is more resistant.

7.4 Magnetic Signatures

Significant features of the aeromagnetic data include:
- zonation of the Lochaber granite from a relatively magnetic margin to a less magnetic core, accompanied by a substantial increase in Th evident in the radiometrics,
- a prominent magnetic high rimming the western and southern margins of the Bagstowe Granite arises from the Black Cap Diorite,
- major magnetic lineaments corresponding to NE-trending structures, such as the Gilberton Fault and the Noel Fault, that appear to have influenced emplacement of the Lochaber-Bagstowe complex and, in the case of the Noel Fault, may have been a control on the Kidston pipe,
- a faintly discernible set of NNW-trending lineaments that passes through the Kidston area, parallel to the main trend of the Paddys Knob dyke swarm and coincides with the axis of the underlying batholith that has been interpreted from gravity data,
- structures that appear to be important in localising the Kidston Breccia Pipe are represented by truncations of narrow linear features in first vertical derivative images, or by changes in their trend,
- two diffuse highs, with superimposed local anomalies, immediately NW and SE of Kidston. These may represent stocks emanating from the underlying batholith, with apophyses that almost reach the present surface. The Kidston pipe sits within a saddle-like magnetic low between the two inferred stocks.

The zonation of the Lochaber Granite detected by the aeromagnetic data is contrary to that reflected in the susceptibility measurements of surface samples, which are affected to varying degrees by hydrothermal alteration. This indicates that the alteration is restricted to shallow depths and suggests that the presently exposed granite was near the roof of the intrusion.

Detailed examination of aeromagnetic profiles and magnetic modelling establish that a small (~15 nT), local, magnetic high, with narrow flanking bumps, occurs over the Kidston pipe. This magnetic high is largely attributable to the remanent magnetisation of the deep pyrrhotite zone. Within this high a smaller low occurs due to the negative magnetisation contrast of the weakly magnetic upper pyritic zone with the country rocks, which are moderately magnetic on average. This low is slightly narrower than the main high, due to the shallowness of the source, resulting in the flanking bumps. East-west asymmetry of the anomaly produced by the pyrrhotite zone arises from the obliquity of the Early Carboniferous palaeofield, which is recorded by the pyrrhotite, to the present geomagnetic field. The anomaly associated with the Kidston pipe is largely masked by the numerous local anomalies of comparable, or greater, magnitude associated with susceptibility variations within the Oak River Granodiorite and Einasleigh Metamorphics. A local magnetic low near Macks Porphyry arises from reversely remanently magnetised baked and/or potassically altered metamorphics, adjacent to the intrusion, that acquired an Early Carboniferous magnetisation during emplacement of the Macks Porphyry.

7.5 Radiometric Signatures

Significant features of the airborne radiometric data include:

- The Macks and Wises Porphyries were radioelement-rich compared to surrounding rocks, and being topographic highs, show prominently in a radiometric image draped over a digital elevation model.
- At a regional scale, the rocks of the complex are not radioelement-rich compared to those in the adjacent Lochaber and Bagstowe Granites, which are felsic and fractionated intrusions. The zoning of the Lochaber Granite is evident in the radiometrics, particularly in the Th channel. Similar radioelement-rich dykes cut the complex but fail to contribute significantly to the aerial survey. The dyke swarm connecting the top (north) of the Lochaber Granite to the complex has also not been detected, due to their relatively insignificant exposure, despite the high radioelement contents of these rocks compared to the host Einasleigh Metamorphics. Proterozoic leucogranitoids in the area are also similarly radioelement-rich and confuse the search for the Carboniferous dykes.
- Weathering effects exert an important influence on radiometric signatures around Kidston. Loss of K due to breakdown of feldspar is evident in soils developed over unaltered felsic rocks in the Kidston area. The enhanced potassium signature associated with phyllic alteration in the Kidston pipe tends is less depleted by weathering, because muscovite is more resistant than feldspar. Thus weathering can enhance the contrast between the breccia pipe and equivalent unaltered lithologies outside the pipe.
- However, Kidston is a difficult target for an aerial gamma-ray survey. The rocks of the complex are, to a large extent, the same as those outside the complex with the addition of some K. But, as other felsic rocks of the area also have higher K contents, distinguishing the altered rocks from unaltered K-rich rocks is difficult.

7.6 Exploration Implications

Although the Kidston pipe would not have been directly detectable from airborne magnetic/radiometric surveys, as its signature is neither strong nor very distinctive, the aerogeophysical data convey important geological information at all scales and therefore could assist exploration indirectly. Strong zoning of magnetite content, anticorrelated with Th and U concentrations, within the Lochaber and Bagstowe Granites is diagnostic of fractional crystallisation of oxidised, relatively felsic magmas, which is a necessary condition for development of intrusive-related Au(Cu, Mo) mineralisation. Related, minor mafic phases, which are suspected to be important for generation of economic Au mineralisation, via interaction with felsic magma in zoned magma chambers, are also evident in the magnetic and radiometric data. Major regional structures and local controlling structures at Kidston are prominent in the data, particularly in first vertical derivative magnetic images. The magnetic data also suggest the presence of buried intrusions, with apophyses reaching shallow levels, near Kidston. These bodies appear to link Kidston with the inferred underlying batholith and may be prospective for Kidston-type mineralisation. Detailed gravity data might define the geometry and lithology of these buried intrusive complexes. Analogues of the Kidston Breccia Pipe could produce detectable magnetic and radiometric signatures in a more favourable geologic setting if emplaced, for example, into more homogeneous country rocks (particularly somewhat more mafic country rocks), or if tilted to a shallow-plunging attitude.

8. Acknowledgements

The help in providing the samples and other information by our colleagues, Graham Taylor, Keith Scott and Chris Horsfall, is acknowledged. This study was greatly assisted by Frank Tullemans, Gary Burgess and other Kidston Gold Mines staff and by collaboration with Phil Blevin and Gregg Morrison.

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