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Geochemical and rock magnetic records from sediments of the Cenozoic Pagodroma Group, Prince Charles Mountains, East Antarctica: implications for provenance and weathering

J. BLOEMENDAL[1], W. EHRMANN[2], M.J. HAMBREY[3], B.C. MCKELVEY[4], R. MATTHEWS[3] and J.M. WHITEHEAD[5, 6]

[1]*Department of Geography, University of Liverpool, Roxby Building, Liverpool L69 3BX, UK*
[2]*Institut für Geophysik und Geologie, Universität Leipzig, Talstrasse 35, D-04193 Leipzig, Germany*
[3]*Centre for Glaciology, Institute of Geography and Earth Sciences, University of Wales, Aberystwyth SY23 3DB, UK*
[4]*Division of Earth Sciences, School of Physical Sciences, University of New England, Armidale, NSW 2351, Australia*
[5]*Department of Geosciences, University of Nebraska-Lincoln, Lincoln, NE 68588-0340, USA*
[6]*Antarctic Cooperative Research Centre and Institute of Antarctic and Southern Ocean Studies, University of Tasmania, Hobart, TAS 7001, Australia*

Abstract: Geochemical and magnetic data from glacigenic sediments can be useful indicators of past environments and climate. In this paper, the results of X-ray fluorescence (XRF) and rock magnetic analyses are presented for samples from the Pagodroma Group, an assemblage of pre-Quaternary glacimarine sediments preserved as remnants along the raised flanks of the Lambert Graben, Prince Charles Mountains, East Antarctica. Samples were obtained from four formations: Mount Johnston, Battye Glacier, Fisher Bench and Bardin Bluffs, which range in age from late Oligocene or early Miocene through to Pliocene or early Pleistocene. Principal component analysis of the XRF data indicates the occurrence of two main element assemblages, which we infer are determined by the presence in the Bardin Bluffs formation of a significant component derived from Permo–Triassic sedimentary rocks of the Amery Group. Calculation of chemical indices of alteration suggests that the values reflect provenance differences rather than the syndepositional weathering environment. Multidomain ferrimagnetic grains mainly dominate the magnetic mineral assemblages of the samples, probably magnetite, with varying concentrations of high coercivity material, probably hematite.

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Key words: Antarctica, Cenozoic glaciomarine sediments, East Antarctic ice sheet, magnetic and geochemical properties, Pagodroma Group

Introduction

The aim of this paper is to examine the geochemical and rock magnetic signatures of the Pagodroma Group, an assemblage of pre-Quaternary glacigenic sediments that are preserved as remnants along the raised flanks of the Lambert Graben, East Antarctica. Through this graben flows the largest outlet glacier from the East Antarctic ice sheet. Geological investigations, undertaken over the last 15 years on a *c.* 1000 km long transect from the innermost rock exposures through Prydz Bay to the continental rise, have provided a detailed data-set for reconstructing East Antarctic ice sheet history. The value of the Lambert system is that ice has flowed through a conduit that may have existed since Permian time (Stagg 1985), and thus the sedimentary successions are likely to record ice-sheet scale changes. Cenozoic glacigenic sediments are now widely known from the many nunataks on the western flank of the Lambert Graben between Amery Oasis in the north and Mount Menzies in the south (Fig. 1), an area known as the Prince Charles Mountains.

The Pagodroma Group has been described lithostratigraphically from two areas of the northern Prince Charles Mountains, Amery Oasis and Fisher Massif (Hambrey & McKelvey 2000a, 2000b, McKelvey *et al.* 2001). Complementing these onshore data are the results from drilling by Ocean Drilling Program's Legs 119 and 188 in adjacent Prydz Bay, where a record of shelf progradation from the onset of glaciation around the Eocene/Oligocene boundary is preserved (Barron *et al.* 1989, Barron & Mahood 1993, O'Brien *et al.* 2001). Conceptual models have been developed to explain:

i) the palaeoenvironments in which the Pagodroma and offshore sediments were formed (Hambrey 1991, Hambrey & McKelvey 2000a), and

ii) how, by linking between offshore sediments drilled in adjacent Prydz Bay with those onshore, the scale of glacier fluctuations through the Cenozoic Era can be derived (Hambrey & McKelvey 2000b).

Facies analysis has led to the proposition that sedimentation took place under fjordal glacimarine conditions when the

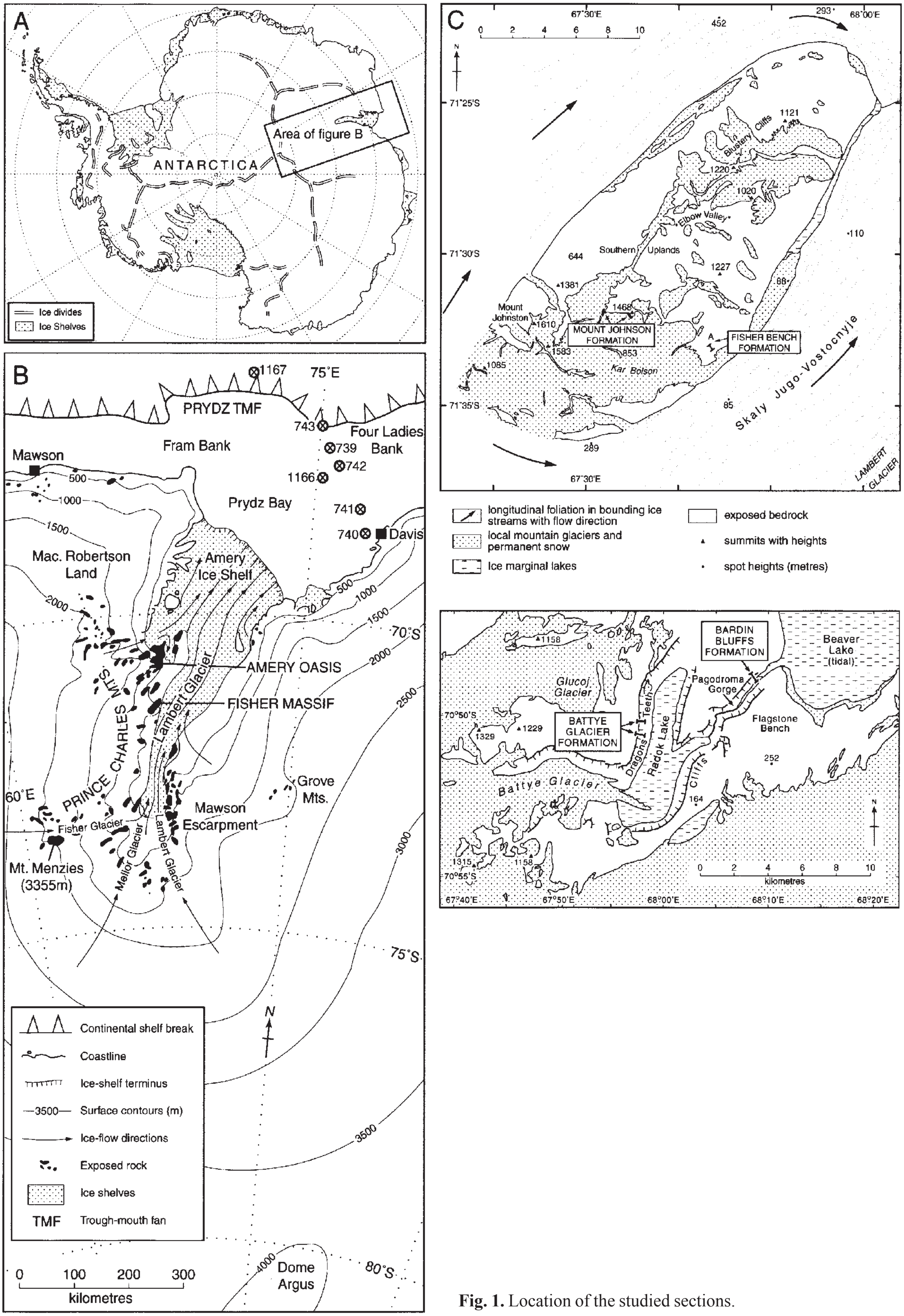

Fig. 1. Location of the studied sections.

climate was significantly warmer than that of today. However, there is a need for supporting data from a variety of field locations to confirm or reject this hypothesis, and to examine such questions as what are the weathering characteristics (which reflect the local climate prior to erosion) and provenance of the sediments, especially in order to discriminate between distal basement and proximal sedimentary sources. The elemental and rock magnetic data presented here supplement earlier mineralogical work on the Bardin Bluffs Formation (Bardin 1982), and provide the basis for a comparison to be made with the detailed geochemical data that will emerge from recent drilling (ODP Leg 188) in Prydz Bay.

Geochemical data can help to identify climatic trends, and to discriminate between different stratigraphical successions where no other data are available. One widely used indicator of palaeoclimate is the chemical index of alteration (CIA) of Nesbitt & Young (1984). This index is based on the major element geochemistry of bulk sediment samples, and ideally provides a means of quantifying the extent to which sediments have undergone chemical weathering. In a context where chemical weathering has been consistently low, as in an environment dominated by persistent glacial activity, major element geochemistry is more strongly influenced by changing provenance. Thus, it may be possible to determine whether changes in provenance are evident in individual stratigraphical successions, and whether there are significant differences in provenance between successions. Unfortunately, in an area like the Lambert Basin, as for most of the East Antarctic ice sheet, few rocks are exposed in the source areas of the ice that supplied the sediment to the Pagodroma Group. Nevertheless, particular geochemical signatures should provide the means to facilitate correlation between areas in future. Geochemical studies of this nature have been applied with some success to cores through Eocene to Quaternary sediments in the western Ross Sea (Krissek & Kyle 1998, 2000).

Environmental magnetic investigations are commonly undertaken to obtain information about changes in sediment source and environmental conditions in a sedimentary basin and its surrounding region, using variations in the concentration, mineralogy and grain-size of magnetic particles in sedimentary sequences (e.g. Thompson & Oldfield 1986, Verosub & Roberts 1995, Walden *et al.* 1999). The magnetic properties commonly used are: mass magnetic susceptibility (χ), anhysteretic remanent magnetisation (ARM) and isothermal remanent magnetisation (IRM) and high-field hysteresis characteristics. Variations in these properties can be used to examine changes in diagenesis, weathering and provenance, and may be viewed as complementary to geochemical studies. Magnetic studies of this nature are routinely made on offshore drilling projects, and the most recent results from Antarctica come from Eocene to Quaternary cores from the western Ross Sea (Sagnotti *et al.* 1998, Verosub *et al.* 2000).

Area of investigation

Glaciology

The Lambert Glacier–Amery Ice Shelf system drains approximately 1 million km^2 or 13% of the total area of the East Antarctic ice sheet (Allison 1979, Higham *et al.* 1997) (Fig. 1). The ice-divide at the head of the catchment lies near the centre of the ice sheet. From this divide, ice from three major ice streams (the Lambert, Fisher and Mellor glaciers) converges on the Lambert Graben and flows via the Amery Ice Shelf into Prydz Bay (Budd *et al.* 1982, Hambrey 1991, Hambrey & Dowdeswell 1994). At the seaward end of the Lambert system, as much as a third of the ice volume comes from the northern Prince Charles Mountains, which reflects increasing snow accumulation towards the coast (Hambrey, 1991).

Topographical setting

The northern Prince Charles Mountains rise sharply above the western margin of the Lambert Glacier/Amery ice shelf to elevations of over 1500 m. They are represented by a series of nunataks and small ranges, which represent the exposed elements of a mostly ice-buried mountain complex. Two main areas were studied as part of the current project. The first is represented by one of the largest ice-free areas in Antarctica: the Amery Oasis, covering approximately 1800 km^2; and the second is an oval-shaped nunatak named Fisher Massif, measuring 30 by 12 km, and rising in a series of raised platforms to elevations of 1610 m (Fig. 1). Small local glaciers occupy cirques and valleys in these two areas.

Geology

The geological basement in the Prince Charles Mountains is largely metamorphic rock. The metamorphic grade increases from north to south, which affects the mineralogical provenance throughout this region. The geology of the northern Prince Charles Mountains consists predominantly of Proterozoic basement rocks, which are part of an extensive high-grade metamorphic terrain within the East Antarctic shield (Tingey 1991). The rocks are mainly granulite and upper amphibolite facies metamorphic rocks (Stephenson & Cook 1997), intruded by charnockite and granite plutons, and by felsic and alkaline dykes. In the Amery Oasis, there is a down-faulted outlier of Permo–Triassic sandstones and coal measures (the Amery Group), which is also thought to underlie the Lambert Graben (McKelvey & Stephenson 1990, Fielding & Webb 1996, McLoughlin & Drinnan 1997).

Extensive Cenozoic deposits, commonly occurring in loose, low-angle (30–50°) cliff sections up to 300 m in

Table I. Modified chemical index of alteration CIA) data for the Prince Charles Mountains samples.

Formation	Age	CIA mean	CIA SD
Bardin Bluffs Formation	Late Pliocene or Early Pleistocene	19.1	1.8
Fisher Bench Formation	Middle Miocene	9.9	1.1
Battye Glacier Formation	Middle–Late Miocene	13.8	2.1
Mount Johnston Formation	Late Oligocene or Early Miocene	10.3	1.4

thickness, occur at discrete levels in the two field areas. They have been formally defined as the Pagodroma Group, and comprise four formations (Hambrey & McKelvey 2000a, McKelvey *et al*. 2001) (Table I). At Fisher Massif, the Fisher Bench Formation of middle Miocene age (Laiba & Pushina 1997, Whitehead 2000) fills a raised, truncated fjordal trough, cut in basement, whose base is at about 500 m above sea level and peak out at elevations over 800 m. Near the top of the massif, the Mount Johnston Formation (late Oligocene to early Miocene age (Whitehead 2000) covers an undulating basement surface above elevations of 1250 m to a thickness that exceeds 100 m in places. At Amery Oasis, the Pliocene Bardin Bluffs Formation also exceeds 100 m in thickness, but its base in places is below current sea level, although everywhere it rests on palaeovalleys cut into Amery Group sandstones (Hambrey & McKelvey 2000a, McKelvey *et al*. 2001, Whitehead & McKelvey 2001). At a higher elevation, the Battye Glacier Formation of middle–late Miocene age (Whitehead, Harwood & McMinn, unpublished data) rests directly on basement granulites, and, in places, approaches 200 m in thickness.

Facies analysis of the Pagodroma Group indicates that the bulk of each of the four formations was deposited in an ice-proximal setting in fjords, although occasionally there are signs of ice grounding and erosion (Hambrey & McKelvey 2000a, McKelvey *et al*. 2001, Whitehead & McKelvey 2001). Comparison with modern glacial environments suggests a climatic regime characterized by polythermal glaciers, such as that which prevails today in areas such as East Greenland and Svalbard (Hambrey & McKelvey 2000a). The present elevations of the different formations, with the oldest occurring at the highest elevation, indicate significant uplift between depositional events. Diatom biostratigraphical data provide the basic framework for dating the Prince Charles Mountains and Prydz Bay successions (Baldauf & Barron 1991, Barron & Mahood 1993, Laiba & Pushina 1997, Mahood & Barron 1996, Whitehead 2000, McKelvey *et al*. 2001, O'Brien *et al*. 2001), although a variety of other microfossils (e.g. foraminifera, ebridians, silicoflagellates) and macrofauna (molluscs) are also present in the Pagodroma Group (Bardin & Kolosova 1983, Laiba & Pushina 1997, Whitehead 2000, McKelvey *et al*. 2001).

Further south, in the Mount Menzies region (Fig. 1), the Cenozoic glacigenic sediments occur in sections up to 150 m in thickness (Whitehead 2000). Preliminary indications suggest that these sediments are non-marine (Whitehead & McKelvey in press). No biostratigraphical data have yet been acquired.

Methods

Samples for the present study were collected during the 1994/95 field season when section-logging was undertaken (Hambrey & McKelvey 2000a, McKelvey *et al*. 2001), and were intended primarily for grain-size and clast-shape analysis. Sufficient quantities of sediment matrix were sampled to also undertake geochemical, rock magnetic and clay mineral analysis. The sampling strategy, which was constrained by the available time, the hazardous nature of the sections and the weight of the samples, focused on defining the main facies. Closely-spaced systematic sampling, as is normally undertaken on core material, was not feasible during this field season, but it would be advantageous on a future occasion. Sample density is therefore inadequate to define vertical trends in magnetic and geochemical properties, but it is sufficient to characterise individual formations.

Radioisotope-source X-ray fluorescence (XRF) measurements

All analyses were made on disaggregated, air-dried samples. The < 63 µm fraction was used for XRF measurements. A Metorex (Finland) XMET920 system was used to measure the concentrations of Al, Ti, Ca, K, Fe, Mn, S, Cl, Cu, Pb, Zn, Br, Zr, Rb, Sr, Cr, Ni, Y and Nb. Na could not be measured reliably because for this element the x-rays are absorbed by the air between the sample and the proportional counter. The instrument uses two probes, a 0.8–5.9 keV probe with ^{55}Fe source for lighter elements and a 3–20 keV probe with ^{109}Cd source for heavier elements. The results were deconvolved using an in-house PASCAL computer program DECONV (Boyle 2000), and were calibrated using standard samples of known elemental concentration. The concentrations of Cl, Cu, Br, Rb, Ni, Y and Nb were too low to give reliable results and so these elements were removed from the data set. The data for Al were retained, but need to be interpreted with caution because of the close proximity of its peak with that for Si.

Magnetic measurements

Magnetic measurements were made on both the < 63 µm (silt+clay) and the 63–2000 µm (sand) fractions. Comparison of the results for the two fractions provides an indication of the importance of variations in sediment grain-size as a control on the magnetic properties of these samples. The following sequence of measurements was

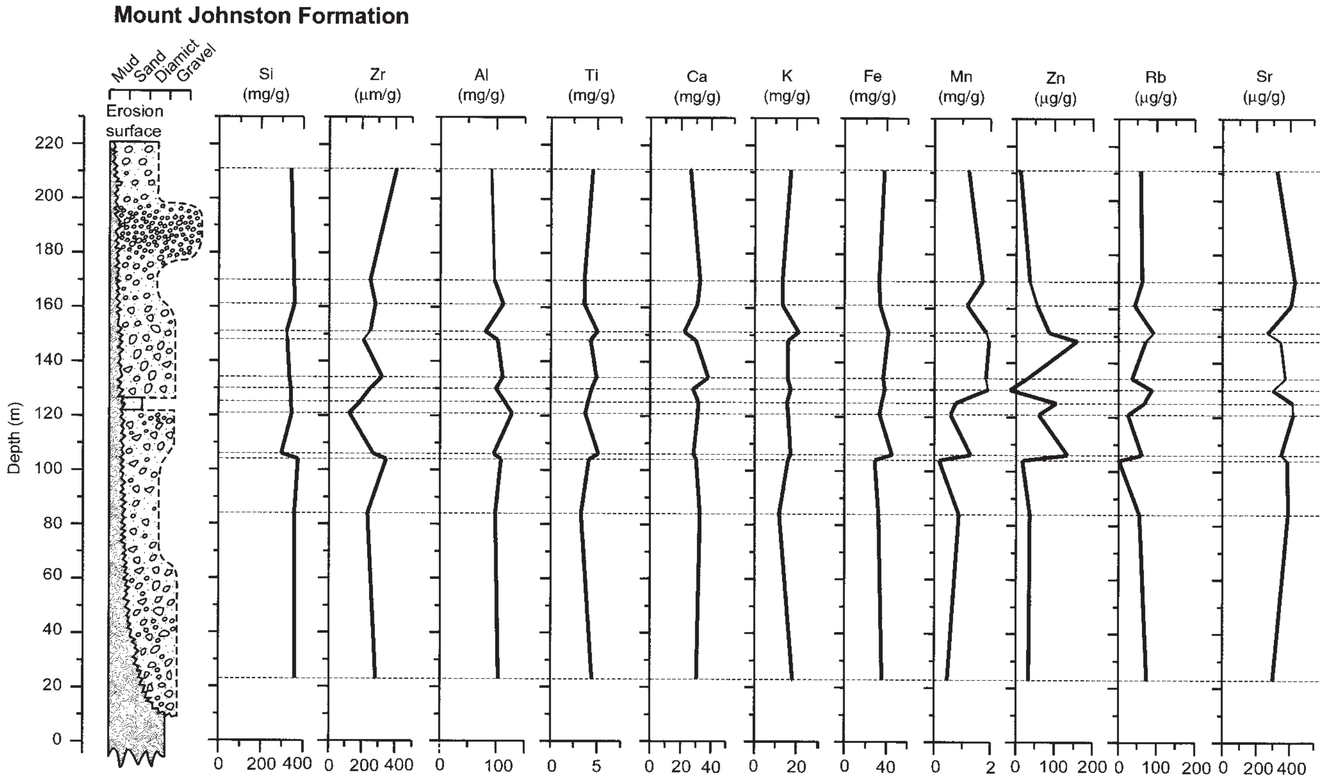

Fig. 2. Stratigraphical variations of the measured element concentrations for the Mount Johnston Formation section.

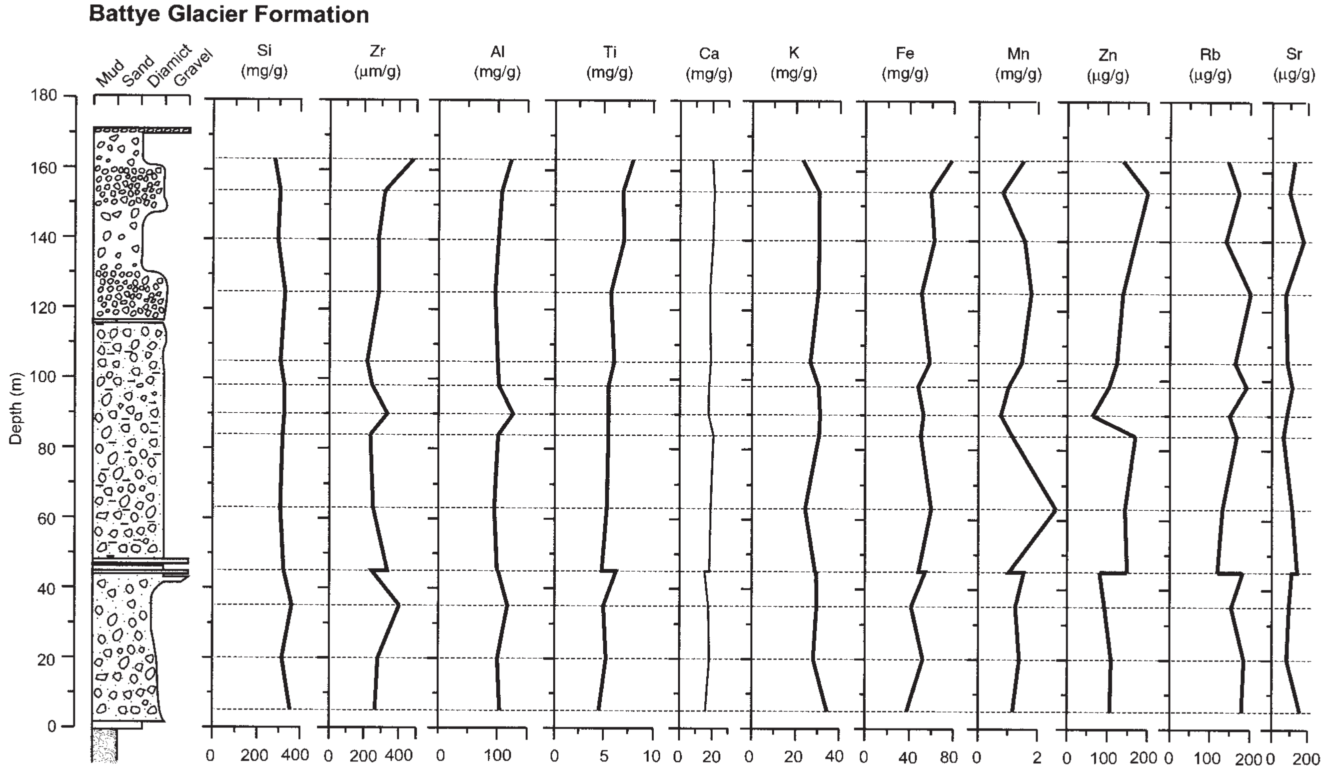

Fig. 3. Stratigraphical variations of the measured element concentrations for the Battye Glacier Formation section.

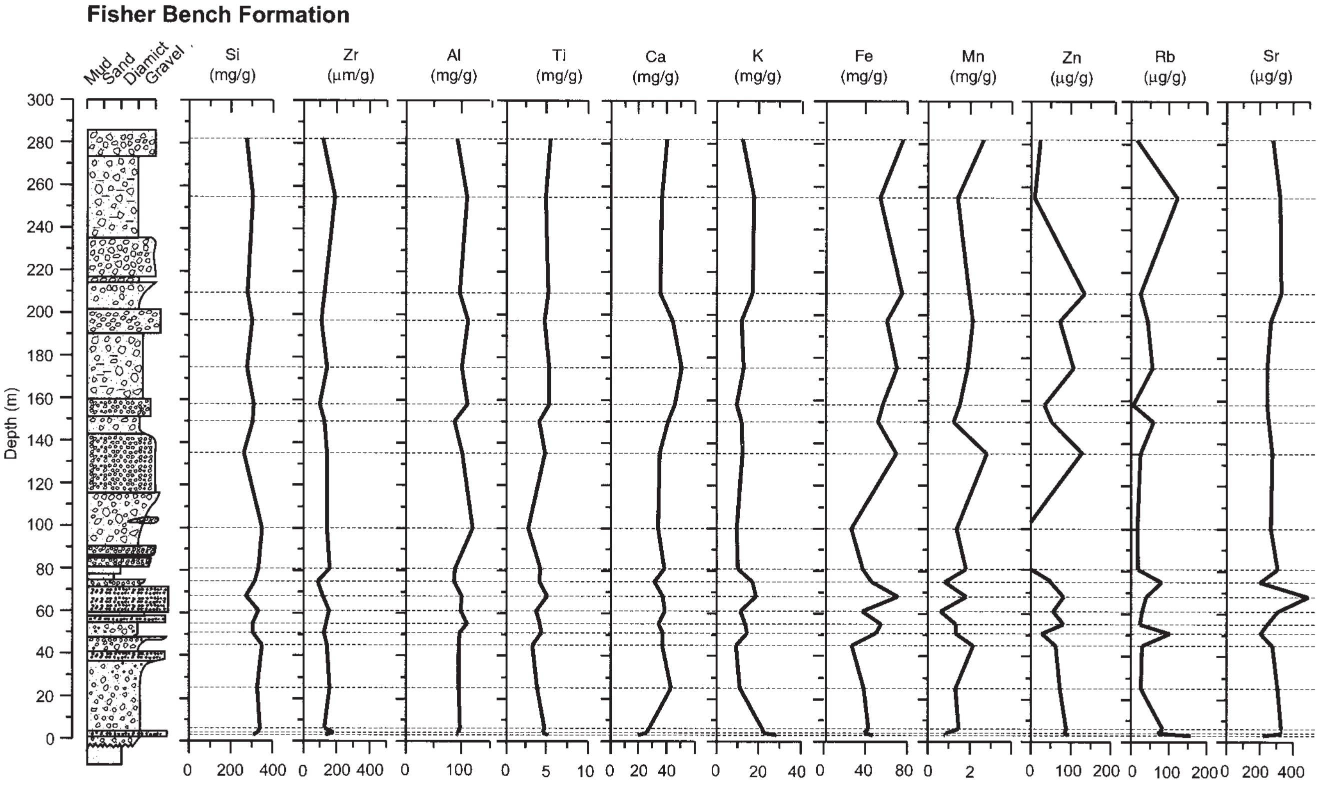

Fig. 4. Stratigraphical variations of the measured element concentrations for the Fisher Bench Formation section.

performed:

i) Magnetic susceptibility (χ) measurements were made using a KLY-2 Kappabridge system. Measurement of a representative subset of samples using a Bartington Instruments meter and dual frequency MS2B sensor indicated minimal frequency dependence of magnetic susceptibility.

ii) Susceptibility of anhysteretic remanence (χ_{ARM}) was imparted using a DTECH alternating-field demagnetiser with 100 mT peak alternating field and 0.04 mT DC field superimposed.

iii) Saturation isothermal remanent magnetisation (SIRM) was imparted at 1000 mT using a MMPM 5 pulse magnetizer.

iv) After growth and measurement of SIRM, the samples were subjected to four reverse fields (20, 40, 100 and 300 mT) of increasing strength and the change in remanence was measured after each step.

All remanences were measured on a Molspin spinner magnetometer. The measured magnetic parameters, together with various interparametric ratios, enable broad inferences to be made about magnetic mineral concentration, grain-size and mineralogy. Briefly, variations of magnetic susceptibility, ARM and SIRM in these samples are likely to reflect variations in the content of ferrimagnetic minerals, probably magnetite χ_{ARM} /χ, χ_{ARM}/SIRM are likely to reflect variations in ferrimagnetic grain size. The HIRM (calculated as SIRM+IRM$_{0.3T}$/2) reflects the high coercivity mineral (hematite plus goethite) content. The -IRM$_{-0.3T}$/SIRM ratio reflects the proportion of ferrimagnetic to high coercivity minerals. More diagnostic measurements (e.g. of temperature-dependent magnetic properties) would be required to determine more precisely the magnetic minerals present.

Results

XRF measurements

Figures 2–5 show stratigraphical variations in the analysed elements. The concentrations of all elements are comparable with the values for the global averages for intermediate and felsic rocks (Krauskopf 1982), and are therefore consistent with the local bedrock geology. As would be expected, in terms of percentage composition Si dominates the element assemblages, with a mean concentration of 31% (standard deviation 2.9%) for all sections. Therefore, variations in the concentration of this dominant component could significantly affect the concentrations of other elements *via* dilution or concentration effects, which are unrelated to changes in provenance. This has prompted some workers to recalculate elemental concentrations on a silica-free basis (e.g. Walden

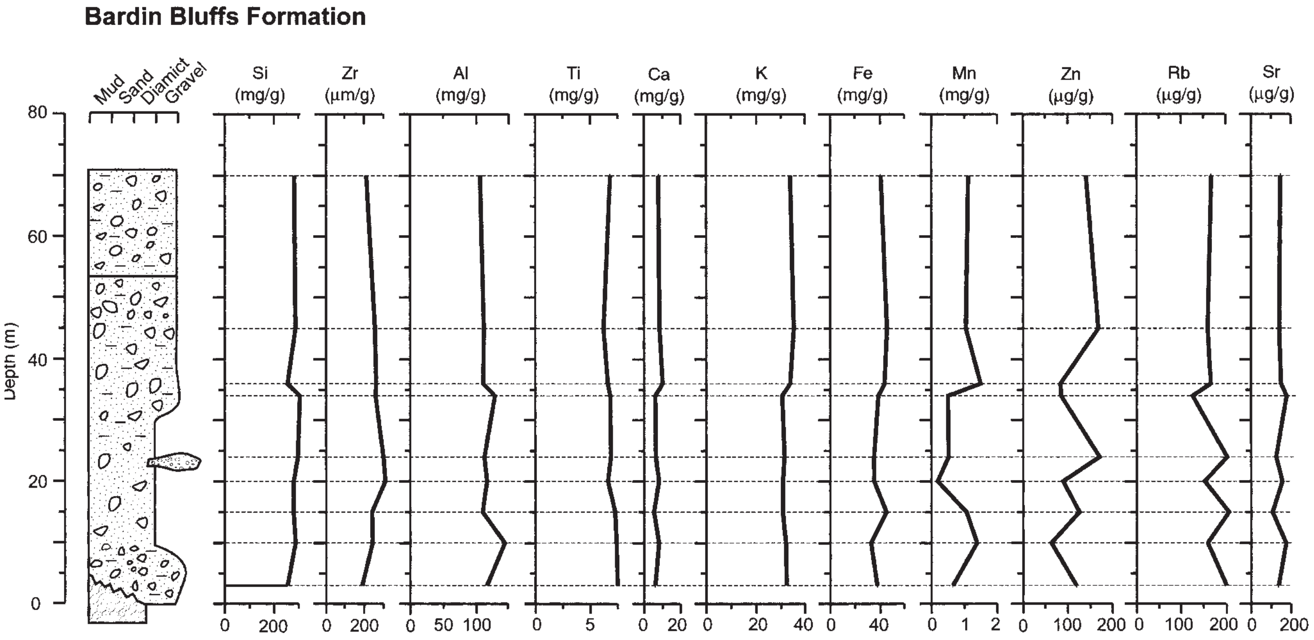

Fig. 5. Stratigraphical variations of the measured element concentrations for the Bardin Bluffs Formation section.

et al. 1996). However, in the case of the samples from the Lambert Glacier region, the low standard deviation for Si probably makes this unnecessary. In general, the sampling density does not permit clear characterisation of stratigraphical variations in element concentrations; nevertheless there does not appear to be any relationship between elemental concentrations and gross sediment lithology (i.e. proportions of gravel/diamict/sand/mud). Exceptions are the slightly increased Ti and Fe concentrations above *c*. 160 m in the Fisher Bench

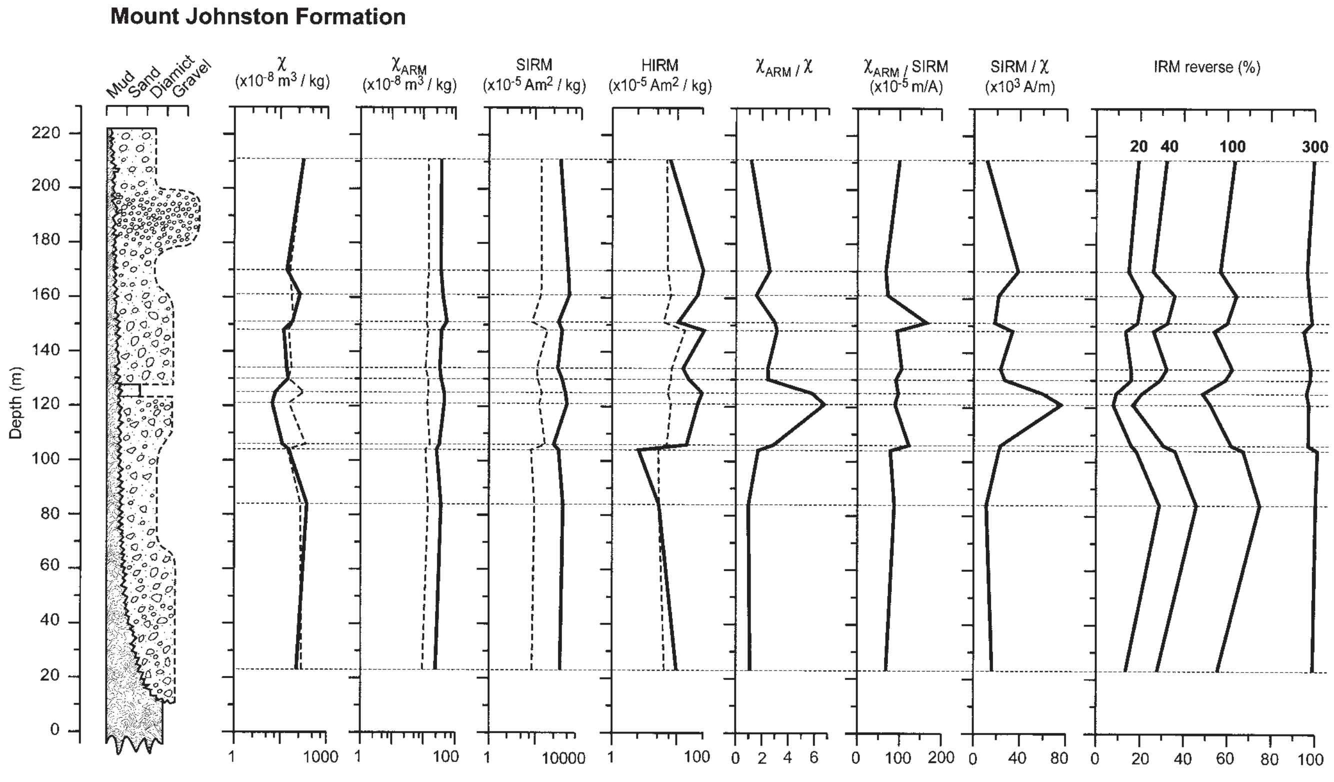

Fig. 6. Stratigraphical variations of the measured magnetic properties of the Mount Johnston Formation section.

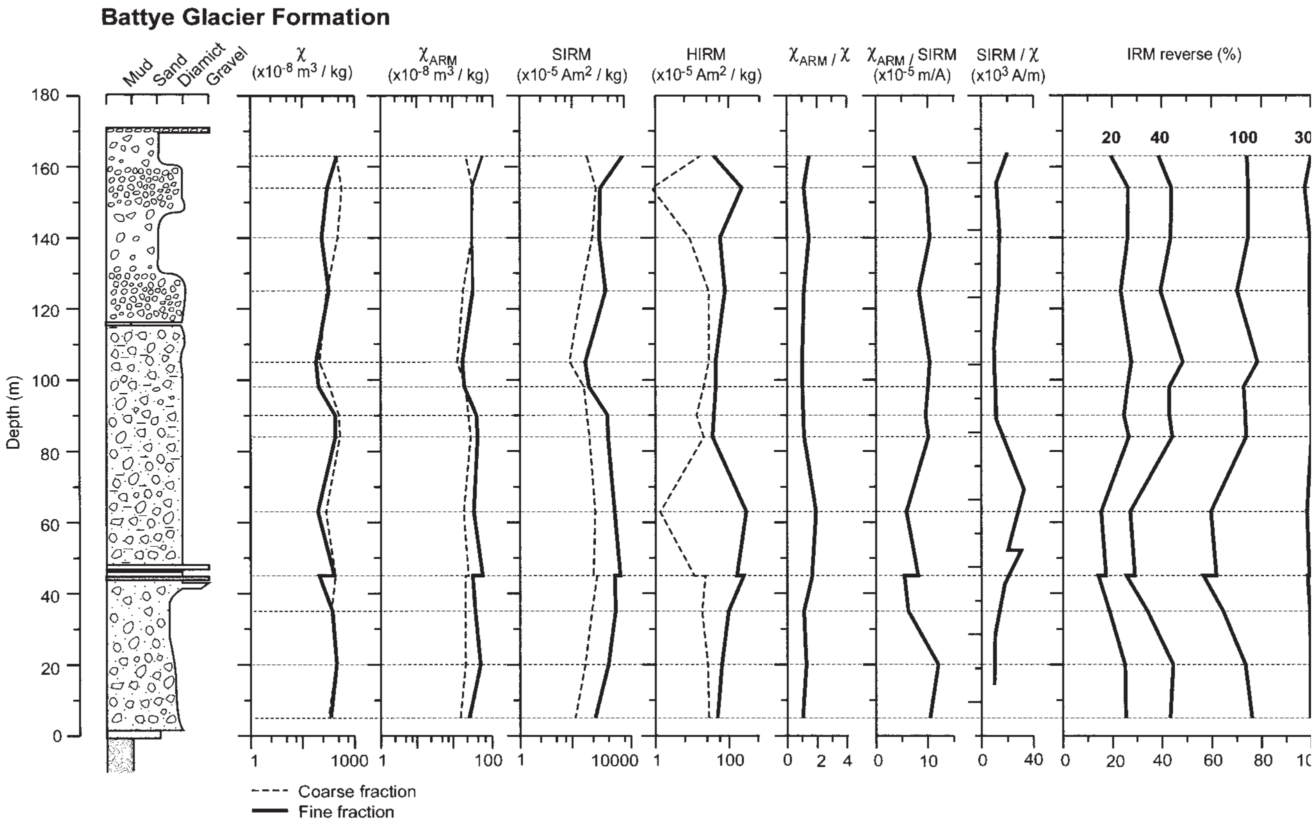

Fig. 7. Stratigraphical variations of the measured magnetic properties of the Battye Glacier Formation section.

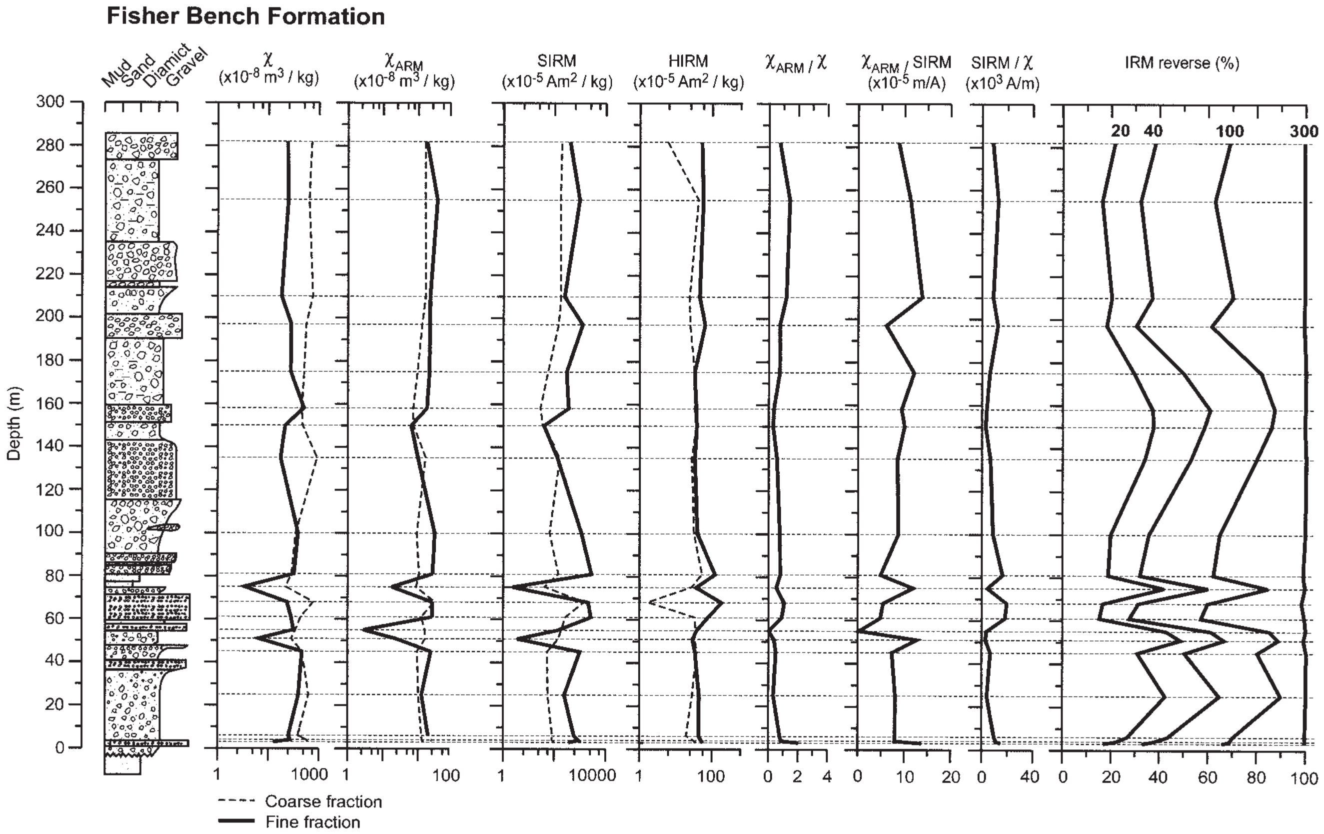

Fig. 8. Stratigraphical variations of the measured magnetic properties of the Fisher Bench Formation section.

Formation section, and the interval between *c.* 150–105 m in the Mount Johnston Formation which, shows distinct peaks in Zn concentration together with fluctuations in several of the other elements.

Chemical index of alteration

A chemical index of alteration was calculated in order to detect any possible chemical weathering-induced modification of the elemental assemblages. The index is modified from Krissek & Kyle (1998):

$$\mathrm{CIA} = [\mathrm{TiO_2}/(\mathrm{TiO_2} + \mathrm{CaO} + \mathrm{K_2O})] \times 100$$

TiO_2 was substituted for Al_2O_3 and Na_2O was eliminated because of the unreliability of the Al and Na data. The CIA provides a measure of the relative abundance of unweathered and weathered material based on the loss of Ca and K from feldspars during chemical weathering. However, changes in both grain-size and provenance will also affect the CIA (Krissek & Kyle 1998).

Table I shows the mean and standard deviation of the CIA for the four formations. The Fisher Bench Formation has the lowest values, while the Bardin Bluffs Formation, the youngest of the four, has the highest. A *t*-test indicates that the values for the Fisher Bench and Mount Johnson Formations are not significantly different at the 99% confidence level. It is clear that there is no trend of increasing CIA values with increasing age. Since it is clear that chemical weathering would be inhibited under glacial conditions, it might be expected that the youngest samples would have the lowest CIA values. In fact, Krissek & Kyle (1998) noted a weak up-section trend of declining CIA in sediments of Miocene and Quaternary age from McMurdo Sound, Ross Sea. The results from the Prince Charles Mountains therefore suggest that the CIA is more likely to be controlled by provenance than by weathering intensity. The slightly higher CIA for the Battye Glacier Formation may also be related to different provenance of basement rocks (here dominated by granulites), compared with the Fisher Massif sections. The Bardin Bluffs Formation stands out as having a substantially higher CIA than the other formations. This probably reflects the high proportion of sedimentary material from the Amery Group (notably sandstone and siltstone, with minor coal).

Magnetic measurements

Figures 6–9 show stratigraphical variations in the measured magnetic properties. The graphs for the parameters related to magnetic mineral concentration (χ, χ_{ARM}, SIRM and HIRM) include results for the two size fractions (0–63 µm and 63–2000 µm) (continuous and dotted curves, respectively). The general co-variation of the two curves indicates that the concentration of magnetic minerals within the clay+silt and sand fractions is similar, and that down-profile and between profile changes in these grain-size components is unlikely to significantly affect the magnetic properties. As was the case for the XRF data, there does not appear to be any relationship between magnetic properties and sediment lithology (i.e. proportions of

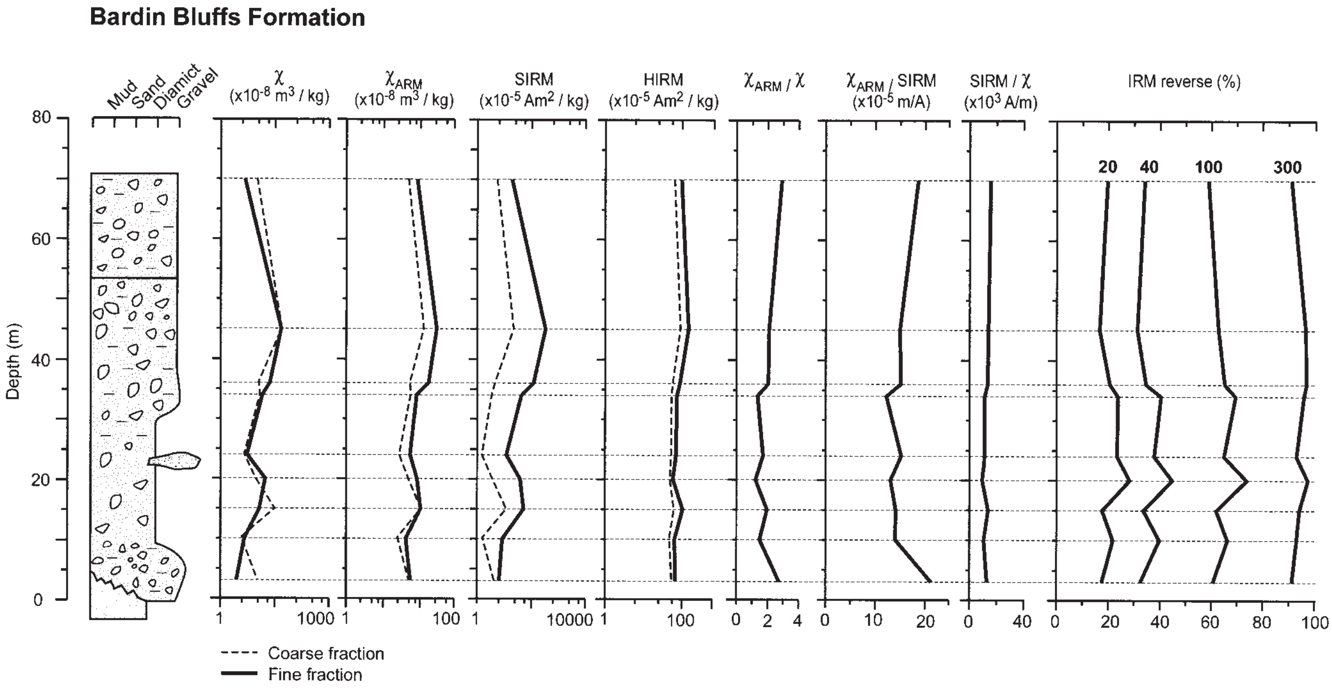

Fig. 9. Stratigraphical variations of the measured magnetic properties of the Bardin Bluffs Formation section.

gravel/diamict/sand/mud). The magnetic susceptibility values for the entire sample set range between *c.* 20–500 $\times 10^{-8}$ m^3 kg^{-1} (with a mean of *c.* 30 $\times 10^{-8}$ m^3 kg^{-1}), indicating that the magnetic properties are dominated by ferrimagnetic minerals, probably magnetite, and that contributions from paramagnetic minerals are insignificant. The values are in the range expected for coarse metamorphic rocks and acid and intermediate igneous rocks (e.g. Dearing 1999). Measurement of frequency-dependent magnetic susceptibility on a subset of samples gave values of *c.* 2% or less, indicating an insignificant contribution from the ultra-fine grained viscous superparamagnetic grains that are associated with weathering and soil formation (Maher 1988, Dearing *et al.* 1996). Assuming that the magnetic properties are dominated by magnetite (see below), the χ_{ARM}/χ ratios (range *c.* 0.1–7; mean *c.* 1) and χ_{ARM}/SIRM ratios (range *c.* 0.5–25 $\times 10^5$ mA^{-1}; mean *c.* 10) are indicative of multidomain (> *c.* 1 µm) magnetite grains (King *et al.* 1982, Maher 1988). The percentage of unreversed SIRM after the application of a 300 mT reversed field (-IRM$_{-0.3T}$/SIRM) averages over 98% and indicates a small contribution from high coercivity minerals like hematite. Overall, these magnetic characteristics are quite compatible with the local basement geology.

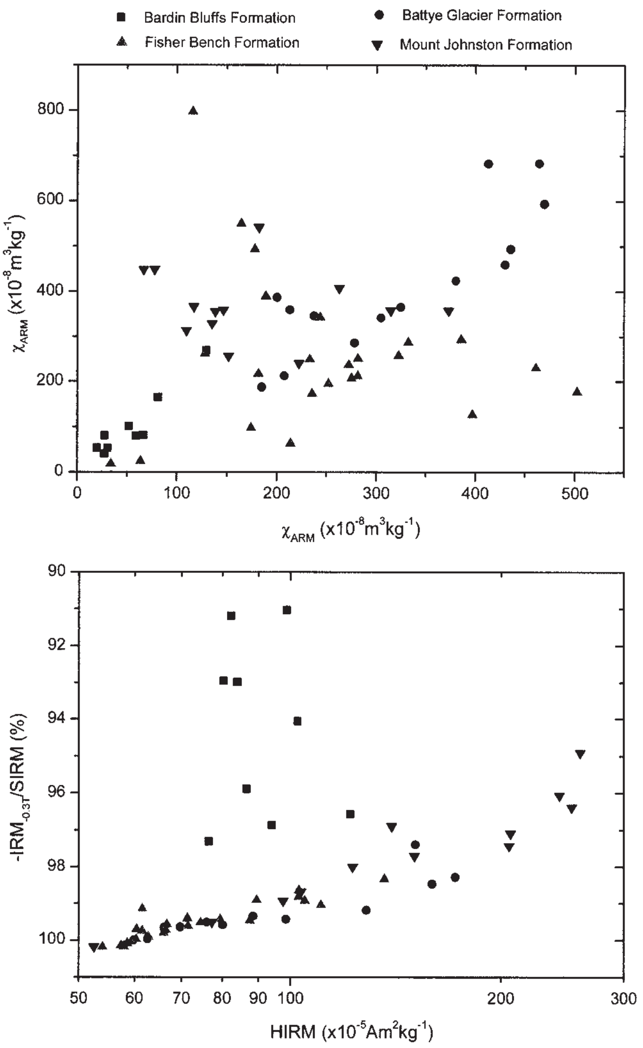

Fig. 10. Biplots of selected magnetic parameters. Figure 10a (upper) indicates variations in ferrimagnetic concentration (distance of samples points from the origin), and in ferrimagnetic grain-size (gradient of the imaginary line joining each sample point to the origin). Figure 10a (lower) indicates gradients in high coercivity magnetic mineral concentration (x axis) and in the ratio of ferrimagnetic to high coercivity magnetic components (y axis). See text for further explanation.

Despite the low sampling density, stratigraphical variability in magnetic properties can be observed in some cases. For example, the interval between *c.* 110–170 m in the Mount Johnston Formation section is characterized by higher χ_{ARM}, HIRM and SIRM/χ (up to *c.* 80 x10^{3}Am^{-1}) values, and by lower reverse field IRM/SIRM ratios than the sediments above and below. This suggests an interval of finer ferrimagnetic grain sizes, and one with both a higher hematite concentration and an increased proportion of high coercivity to ferrimagnetic material. The two samples for the interval between *c.* 38–62 m in the Battye Glacier Formation section show similar characteristics.

Figure 10 graphically summarises the range of variation in four magnetic parameters for the entire sample set: Figure 10a plots χ versus χ_{ARM}, whilst Fig. 10b plots the -IRM$_{-0.3T}$/SIRM ratio versus the SIRM. Assuming that ferrimagnetic grains dominate the magnetic properties of the samples, which is a reasonable but unconfirmed assumption in this case, then plots of χ versus χ_{ARM} can be used to summarise trends in magnetite concentration and grain size (King *et al.* 1982). The distance of each point from the origin reflects the magnetite concentration, and the gradient of the line joining each point with the origin indicates the grain size. As might be expected, the plot indicates a range of magnetite concentrations and grain sizes within the multidomain range. The Bardin Bluffs section has consistently lower magnetite concentrations and grain sizes than the samples from the other sections, which appears to reflect Permo–Triassic sedimentary sources. The Battye Glacier formation shows the widest range of magnetite concentration, and the Fisher Bench formation shows the widest grain-size range. The plot of HIRM versus -IRM$_{-0.3T}$/SIRM ordinates the samples on the basis of variations in the concentration of the high coercivity mineral concentration (hematite and/or goethite) and the ratio of high coercivity to ferrimagnetic minerals (most likely hematite:magnetite). Overall, there is an expected linear relationship between both the concentration and the proportion of 'hematite'. The Fisher Bench and Battye Glacier Formation samples show a roughly similar range of HIRM values, while the distribution for the Mount Johnston Formation shows both the lowest and the highest HIRM values. The Bardin Bluffs Formation samples show a distinctly different distribution from those of the other

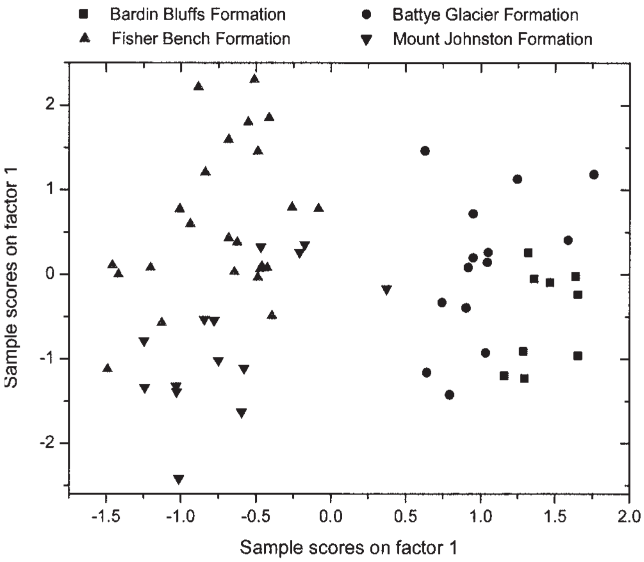

Fig. 11. Results of principal component analysis of the XRF data: sample scores on the first two principal components.

formations, with intermediate HIRM values and low values of -IRM$_{-0.3T}$/SIRM (higher proportion of hematite plus goethite). Once again, these differences probably reflect variations in provenance.

Principal component analysis of the XRF and magnetic data

Principal component analysis was used to further investigate differences in the element and magnetic assemblages among the four formations. For the XRF data, the first three principal components represent 45.9, 20.2 and 9.7% of the total variance, respectively. For component 1, K, Rb and Ti have the strongest positive correlations (R = 0.92, 0.90 and 0.88) and Ca and Sr the strongest negative correlations (R = -0.87 and -0.78). For component 2, Fe and Mn have the strongest correlations (R = 0.78 and 0.74); and for component 3, Al has the strongest correlation (R = 0.76). Figure 11 shows a bi-plot of the sample scores on the first two principal components. Two primary sampling groupings are evident:

i) Battye Glacier (BG) and Bardin Bluffs (BB) formations with positive scores on component 1, and

ii) Mount Johnston (MJ) and Fisher Bench (FB) formations with negative scores on component 1.

The existence of these two primary groupings was confirmed by the application of fuzzy cluster analysis (method and software of Höppner *et al*. 1999) of the sample scores on the first two principal components. There is visual evidence of subdivisions within the primary groupings: BG with lower, and BB with higher scores, respectively on component 1; FB with lower, and MJ with higher, scores on component 2, respectively. However, these main subdivisions were not confirmed by the statistical measures of cluster validity generated by the cluster analysis. For the magnetic data, only concentration-related parameters were used, and interparametric ratios were excluded. The parameters used were χ, χ_{ARM}, SIRM, HIRM and the remanence acquired within the following coercivity windows: 0–40 mT, 20–40 mT, 40–100 mT and 100–300 mT (IRM1–IRM4, respectively); all data being expressed as mass-specific concentrations. The first two components account for 70.7% and 19.3% of the total variance, respectively, which represents a high proportion of the total variance. Therefore, the magnetic data show significantly lower dimensionality than the geochemical data (cf Walden *et al*. 1991, Lees 1999). SIRM, χ_{ARM} and IRM1–4 all have correlation coefficients > 0.81 with component 1, which suggests that this component represents variations in the concentration of ferrimagnetic material. HIRM has the strongest correlation (0.87) with component 2 (with all other variables having significantly lower correlations) indicating that this component reflects variations in the concentration of high coercivity material. Therefore, the information return from this analysis is not significantly greater than that provided by the bivariate plots (Fig. 10b).

Discussion

Here an attempt is made to address the following three questions.

i) Is it possible to differentiate between the formations on the basis of the measured geochemical and magnetic properties, and to draw any inferences regarding the relative importance of proximal and distal sediment sources?

ii) Do the measured properties provide any information on the depositional environment and on weathering regime within the sediment source areas?

iii) Are there any significant stratigraphical variations in the magnetic and chemical properties measured, and hence any evidence for possible provenance changes within the stratigraphical successions?

Although our results are based on matrix samples, clast composition is also important in interpreting the data. Metavolcanic rocks, notably gneisses in fluctuating proportions, as well as minor acid and basic intrusive rocks and schist, dominate the Fisher Bench and Mount Johnston formations. The Battye Glacier Formation is dominated by granulites (acid and basic varieties), which typically account for 50–90% of the clasts, followed by intermediate intrusive rocks (15–35%), and minor lithologies (vein quartz and quartzite). However, no sedimentary clasts have been found in the Battye Glacier Formation. The neighbouring, but younger, Bardin Bluffs Formation typically has 55–65% of sedimentary clasts (sandstone, siltstone and minor coal), derived from the Permo–Triassic Amery Group on which it rests, the remainder being similar basement lithologies to those in the Battye Glacier Formation. This information has some bearing on interpretation of the geochemical and magnetic data.

The results enable some degree of differentiation of the formations. The sample scores on the first component generated by the principal component analysis of the geochemical data provide a clear separation of the Battye Glacier and Bardin Bluffs formations, with positive scores, and the Mount Johnston and Fisher Bench Formations, with negative scores, while the second provides some separation (with partial overlap) of the Fisher Bench and Mount Johnston Formations.

The magnetic properties provide a less convincing means for discrimination among the samples, since most of the formations show significantly overlapping sample distributions on the bivariate plots. However, the Bardin Bluffs Formation is a significant exception, emerging as a discrete group characterized by relatively low concentrations of ferrimagnetic minerals, intermediate concentrations of high coercivity minerals and especially by a relatively low ratio of high coercivity to ferrimagnetic minerals. This is to be expected in sandstone- and siltstone-dominated rocks.

Component 1 of the principal component analysis of the geochemical data can be interpreted to represent a gradient of weathering intensity, since Ca and Sr are preferentially removed by chemical weathering, whilst Ti, K and Rb, which have greater geochemical stability, are typically concentrated by chemical weathering (e.g. Nesbitt *et al.* 1980, Liu *et al.* 1993). It also notable that the Battye Glacier and Bardin Bluffs formations have significantly higher average CIA values than the other two formations (t-test results at the 99% confidence level). The interpretation of this primary geochemical separation is supported by a parallel investigation of the clay mineralogy of the same sample set (Ehrmann *et al.* in press). This study shows that the samples from the Mount Johnston Formation on Fisher Massif and the younger, but neighbouring Fisher Bench Formation samples, are dominated by clay mineral assemblages indicative of physical weathering under glacial climatic regimes, with the inferred source being the locally abundant Precambrian metavolcanic rocks. In contrast, samples from the Battye Glacier and Bardin Bluffs Formations at Amery Oasis have quite different clay mineral assemblages, indicative of a greater degree of chemical weathering in their genesis. Therefore, both the geochemical and clay mineral analyses indicate that the sediments of the Battye Glacier and Bardin Bluffs formations have a considerably higher content of chemically weathered material than those of the Fisher Bench and Mount Johnston formations. The kaolinite in the Bardin Bluffs Formation is therefore compatible with a significant local contribution from the sedimentary rocks of the Amery Group, but it is more difficult to explain in the Battye Glacier Formation, unless it is derived from granulite clasts. In general, the geochemical characteristics of the sediments of the four formations are compatible with at least a substantial contribution from local rocks, which was also one of the main conclusions of the clay mineral analyses (Ehrmann *et al.* in press).

The density with which all of the sections were sampled has permitted only limited conclusions to be made about stratigraphical variations in the magnetic and chemical properties of the sediments. However, it is clear that neither has any relationship with the sedimentary facies, and that it is likely that the magnetic mineral and geochemical assemblages are determined by the character of the source rocks rather than by the syndepositional environmental conditions (climatic state or sedimentary environment).

Conclusions

i) Principal component analysis of the XRF measurements of the Pagodroma Group samples indicates the occurrence of two well-separated groups, the first comprising samples from the Fisher Bench and Mount Johnston formations, and the second comprising samples from the Battye Glacier and Bardin Bluffs formations. This primary separation probably reflects the presence of a substantial component of chemically weathered material in the latter group, which is tentatively attributed to sediment derived from Permo–Triassic sedimentary rocks of the Amery Group for the Bardin Bluffs Formation, but which may also be derived from weathered granulites. This interpretation is supported by the results of a parallel investigation of the clay mineral assemblages of the same samples (Ehrmann *et al.* in press). There is visual evidence of additional subdivisions within the two primary sample groupings, although their statistical validity is not confirmed by additional fuzzy cluster analysis. Calculation of chemical indices of alteration of the samples suggests that the values reflect provenance differences rather than the syndepositional or post-depositional weathering environment.

ii) Magnetic measurements indicate that the magnetic mineral assemblages are dominated mainly by multidomain ferrimagnetic grains, probably magnetite, with varying concentrations of high coercivity material, probably hematite. The samples from the Bardin Bluffs Formation emerge as magnetically distinctive, with a relatively high proportion of high coercivity to ferrimagnetic material, which reflects the influence of sedimentary sources rocks.

iii) Our sampling density is insufficient to fully characterize any stratigraphical variations in elemental and magnetic mineral assemblages; however, the available data suggest that such variations are probably limited.

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