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Mineral Reconnaissance Programme

Mineral exploration in Lewisian supracrustal and basic rocks of the Scottish Highlands and Islands

Department of Trade and Industry

MRP Report 146

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BRITISH GEOLOGICAL SURVEY

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SUMMARY

This report describes an exploration programme for gold and base metals in the Precambrian Lewisian terrain of north-west Scotland. Supracrustal rocks in the Lewisian have several of the characteristics of 'greenstone belts' in basement gneiss terrain which host many of the world's gold deposits. Often these deposits are closely associated with banded iron formations (BIFs) and iron-rich exhalites are present in the Gairloch and Loch Maree belts associated with a mixed volcano-sedimentary succession. The exhalites include massive and microbanded iron oxide facies, together with various banded silicate and sulphide facies rocks which form well-defined and laterally extensive suites. Although previously recognised at the Kerry Road copper-zinc-gold deposit near Gairloch, these lithologies had not, until the publication of MRP reports on Glenelg and Scardroy, been the subjects of extensive study as potential hosts for base- or precious-metal mineralisation.

Selective lithogeochemical sampling of prospective areas (Loch Maree, Flowerdale, Melvaig, Tiree, Coll, Uist, Benbecula and the Central Belt) was used as the preferred exploration medium. In addition to providing information on mineralisation styles, these data provided a means for correlation of the supracrustals between different areas. Lithogeochemical mapping was supported by ground geophysics, principally total field magnetics and VLF, which provided detail on the disposition and extent of potentially mineralised exhalative suites where concealed by glacial drift. Petrological investigations provided additional information on the complex primary mineral compositions and alteration assemblages at these localities. Data listings, together with detailed logs of samples, are available on request from the Minerals Programme, Minerals Group, BGS, Keyworth.

The tectono-stratigraphy of the Loch Maree and Flowerdale Forest areas has been clarified and can now be compared with the better known succession in the Gairloch area. In particular, the successions at Loch Maree and Gairloch have been correlated, and the chlorite schist at Abhainn na Fuirneis is thought to be comparable to that at Gairloch which forms the footwall to the Kerry Road deposit. This should provide a better framework to guide more detailed exploration of the supracrustal succession and its contained stratiform mineralisation. Detailed exploration of the rocks adjacent to chlorite schist at Abhainn na Fuirneis and the quartz-magnetite schist further to the north-east with 0.7 ppm gold is recommended.

The succession at Loch na Beinne (in the Flowerdale Forest area) is similar to that at Kerry Road and the presence of sulphide-bearing and banded iron formations with significant gold values (up to 4 g/t Au) is highly prospective. It is strongly recommended that detailed exploration should concentrate on the Lewisian concealed beneath a shallow cover of Torridonian rocks near Loch na Beinne and north-west along strike for 8 km. Reconnaissance traverses using ground magnetic and VLF-EM techniques have been successful in establishing the presence at several localities of high-amplitude anomalies of limited strike extent. At Loch na Beinne these anomalies are coincident with the exposure of banded oxide and sulphide facies exhalites containing up to 4 g/t gold. Similar methods should be applied to targets in the Lewisian beneath the shallow sedimentary cover and along the 8 km of concealed strike length. There is potential within this strike length for the discovery of a Besshi-style copper-zinc-gold deposit similar to that at Kerry Road.

INTRODUCTION

The Lewisian Complex of north-west Scotland forms part of an extensive Archaean to early-Proterozoic terrain which extends from the Churchill Province in Labrador via the Nagssugtoqidian belt of Greenland to the Karelian belt of Finland. The complex comprises a series of metamorphic tracts or belts, each distinctive in terms of lithological succession and structural history. Most of the complex is composed of high-grade metamorphic rocks of Archaean age (c. 2.9 Ga), hereafter described as 'basement', upon which are superimposed sequences of younger, early Proterozoic, lower-grade rocks which form the 'supracrustal' sequences. Deep crustal burial of the basement during late-Archaean times resulted in granulite facies metamorphism and the extreme modification of the basement protolith. Subsequently, the supracrustals were emplaced at higher structural levels where they were subjected to amphibolite grade metamorphism. As a consequence these lower grade rocks may be readily distinguished from the basement and identified as having volcanic and sedimentary protoliths.

The discovery by Consolidated Goldfields Ltd (Jones et al., 1987) of the sub-economic copper-zinc-gold deposit within a supracrustal suite at Kerry Road, near Gairloch (Figure 1) was one of the highlights of mineral exploration in Scotland in the past twenty years. Whilst mineral showings and old trials have long been known in Lewisian rocks, the discovery of significant tonnages of potentially economic mineralisation was a major breakthrough in exploration. The malachite-stained outcrop that led to the discovery is mentioned in the Survey memoir on the north-west Highlands (Peach et al., 1907) and modern geochemical and geophysical methods, followed by a large drilling programme, resulted in the discovery of the strongly deformed orebody. Two laterally extensive sulphide horizons were located within metabasic rocks of the Loch Maree Group. One of the sulphide horizons was traced intermittantly over 6 km and consists mainly of iron sulphides. The other, which has a strike length of at least 1 km, is composed of a 4 m thick quartz-carbonate schist with pyrite, pyrrhotite chalcopyrite, sphalerite and native gold. The footwall to the latter is a distinctive chloritic hornblende schist and the hanging wall contains quartz-magnetite schist (banded iron formation). Both sulphide horizons and the chloritic footwall have suffered intense ductile deformation. The sulphide horizons are of exhalative origin and the Cu-Zn-Au occurrence, known as the Kerry Road sulphide deposit, belongs to the Besshi-type group of deposits. The reader is referred to Jones et al. (1987) for a fuller description of the exploration and discovery of the orebody. The deposit is, however, too small and too irregular in shape to be economic and the company abandoned the prospect.

The primary aim of the Mineral Reconnaissance Programme is to encourage further commercial exploration in the UK, and it was decided to investigate other areas in the Lewisian that had potential for economic base metal and gold mineralisation. The Kerry Road mineralisation is hosted by the supracrustal Loch Maree Group of metasedimentary and metavolcanic rocks, and several other areas of the Lewisian were identified as prospective because of similar host rocks, possible correlation with the Loch Maree Group and the presence of mineral showings. These areas were Scardroy, Glenelg, Loch Maree and a number of smaller occurrences on the islands of Tiree, Coll and the Outer Hebrides (Figure 1). The results of exploration in the first of these areas has been presented in an Open File MRP Data Release (Coats et al., 1993) and the results of work completed in the Glenelg area as an MRP Report (Coats et al., 1996). Work in the Loch Maree area is described in this report, along with brief descriptions of reconnaissance studies on Tiree and other areas of supracrustal rocks in the Lewisian. These areas, Coll, the Outer Hebrides and the northern Lewisian, are identified on Figure 1. Little previous mineral exploration is known to have been carried out in the Loch Maree area,

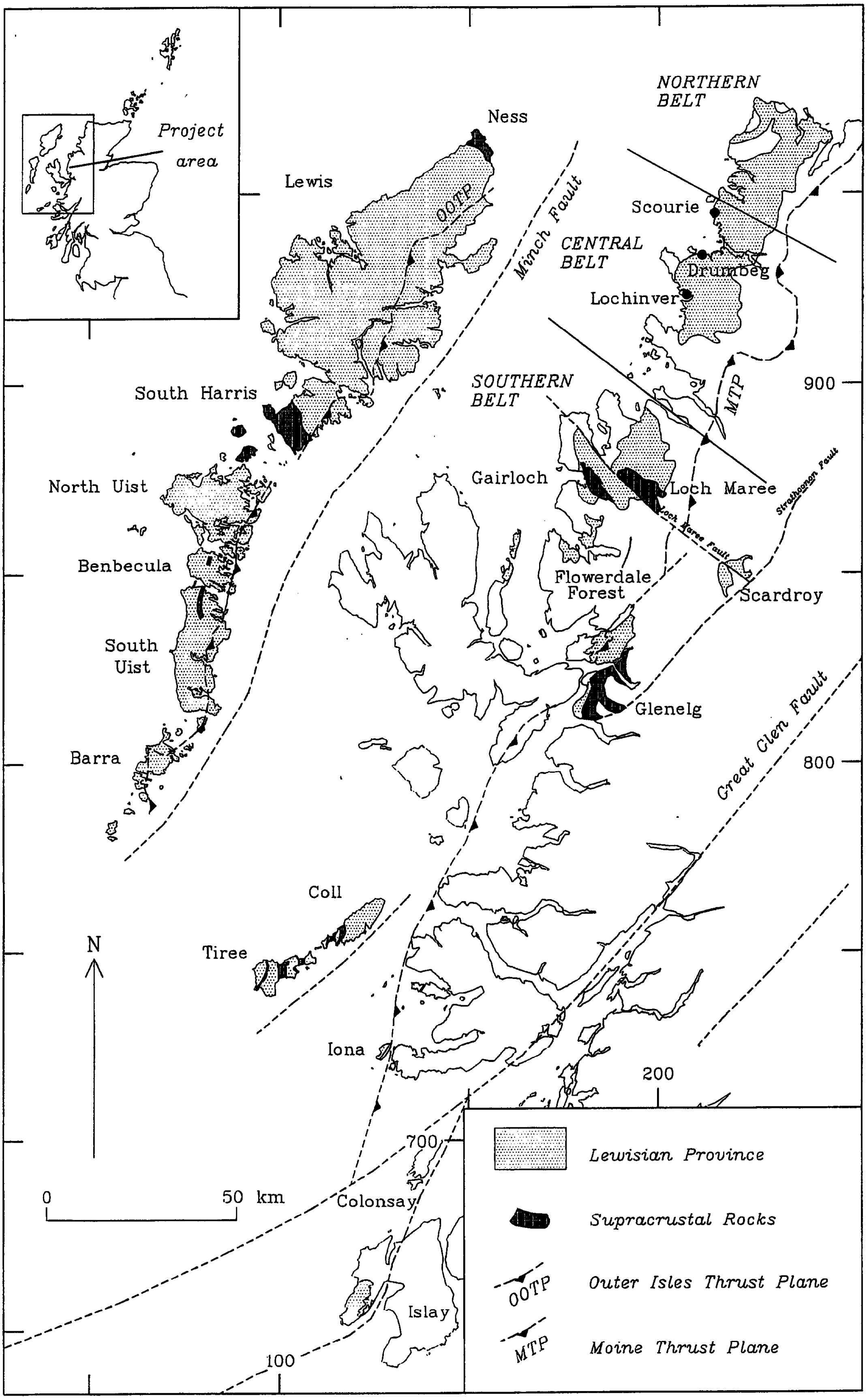

Figure 1 General map of the Lewisian showing location of Gairloch, Loch Maree, Coll and Tiree, Scardroy and Glenelg.

although it is briefly mentioned by Jones et al. (1987). Berridge (1969) provides the only summary of the mineral resources of the Lewisian as a whole, but is now rather dated.

Also included in this report are the results of two brief phases of reconnaissance investigation in 1986 and 1994, which were carried out over Lewisian basic and ultrabasic rocks in north-west Scotland. The basic and ultrabasic rocks in the Central Belt (Figure 1) were considered favourable for the occurrence of metallic mineralisation of two principal types. Firstly, they were regarded as potential hosts for stratiform magmatic platinum-group element (PGE) mineralisation of the type widely found in layered intrusions worldwide. Secondly, they were considered to have potential for Au- and PGE-bearing Cu-Ni mineralisation similar to that developed in Lower Proterozoic mafic layered intrusions of the Fennoscandian Shield in northern Finland. In this area, peridotites of the Koitelainen intrusion and the Keivitsa-Satvaara complex are markedly enriched in Ni, Cu, PGE and Au. The marginal series of several other intrusions belonging to this suite also host important PGE-bearing Cu-Ni deposits (Alapieti et al., 1990). During 1986, lithogeochemical sampling was conducted at localities between Loch Laxford in the north and Gruinard Bay in the south, where remnants of formerly extensive layered intrusions have been described in the literature. The platinum-group elements (PGE) were the main focus of interest during this phase of work. In the second programme, carried out in 1994, attention turned to Cu, Ni and Au, in addition to the PGE. During this period sampling was carried out principally in the Scourie, Lochinver and Drumbeg areas (Figure 1).

Drainage geochemistry in areas of high-grade terrains in mid to high latitudes is rarely effective because of the widespread shortage of mineral detritus. Mineral soils are generally poorly developed over the Lewisian, which was scoured of superficial material during successive Quaternary glaciations. Subsequently, bedrock impermeability and the effects of relatively cold-wet temperate climate have facilitated the development of wet-heath/bogland, whose relatively thick vegetation mats serve to inhibit the mechanical degradation of bedrock. The organic detritus formed provides the main alluvial component over most of the Lewisian terrain but is of little use as an exploration medium.

Lithogeochemical sampling had been used successfully at the reconnaissance stage by Consolidated Goldfields (Jones et al., 1987). The rocks are well exposed, giving a reasonably good sampling density, with the distinctive exhalative suites providing suitable markers for mineralisation along strike. The exploration methods used in this survey were therefore predominantly lithogeochemical, accompanied by rapid ground geophysical surveys using total field magnetic and VLF methods. A stratabound Besshi-style model was used for the gold and base-metal mineralisation, as proposed by Jones et al. (op. cit.) for the Kerry Road deposit, but in this study the model was extended to cover epigenetic replacement and late-metamorphic metasomatic sulphidation models proposed by Phillips et al., (1984), Macdonald (1990) and Ford and Duke (1993). The occurrence of banded iron formation (BIF) is seen as either an exhalative marker horizon for stratabound mineralisation in the Besshi-style model, and/or as a suitable host for deposition of gold in the alternative models.

Similar sampling and analytical methods were used throughout the survey, unless stated otherwise in the individual sections. Rock samples were collected from sites selected according to lithology or where mineralisation was observed. At each site 2–4 kg of unweathered rock was taken from several points on an exposure, or from a number of closely-spaced exposures, in order to obtain a representative sample. These were analysed for Au and, in some cases for Pt, Pd, and Rh down to levels of 1-2 ppb, by Acme Analytical of Vancouver employing a lead fire assay on 30 g samples followed by either a GFAAS or ICP-MS finish. In addition to Au, a wide range of elements was determined by XRF analysis of pressed powder pellets at the BGS laboratories.

PLANNING AND DEVELOPMENT FRAMEWORK

The north-west Highlands is an area of high unemployment and net emigration, and consequently attracts Government and European Union funding to promote employment. The development of a small mining operation could provide year-round employment, in contrast to seasonal work based on tourism. However, the fragile nature of the ecosystem and the undeveloped character of the countryside, are factors which militate against primary development, such as mining and quarrying.

The planning framework differs between the areas covered by the project. The Loch Maree and Flowerdale Forest areas are remote from roads and habitation, and are included in a National Scenic Area. The Loch Maree area forms part of an extensive tract of wilderness, where development and public access are constrained. The Flowerdale Forest area is inaccessible by wheeled vehicles due to the absence of suitable tracks. It also borders the Torridon Forest hill massif, which is popular with hill walkers and is owned by the National Trust for Scotland, and the lower gorge section of Srath Lungard, which has SSSI status.

The Melvaig area is of lower scenic value than the Loch Maree and Flowerdale Forest areas, being generally of lower relief and closer to habitation and the small port of Gairloch. Coll and Tiree are small islands which depend largely on the tourist industry, apart from some limited crofting. In addition, a large number of locations on Tiree have SSSI classification for a variety of environmental reasons which would undoubtedly draw strong opposition to any mining development. The Outer Hebrides are larger and less visited by tourists, and a small mine could well provide a very valuable source of employment for the small communities. Recent opposition to the development of a coastal superquarry at Rodel on South Harris (Dunion, 1995 and 1995a), was due in part to the massive scale of the operation and its probable effects on both scenic status and pollution of the sea floor.

REGIONAL GEOLOGY

The Lewisian Complex comprises rocks of late-Archaean and early-Proterozoic age, which represent a residual fragment of the Laurentia-Baltica continental mass (Winchester, 1988). Most of it comprises a basement of granulite and amphibolite facies gneisses. The protoliths of these rocks include intrusive rocks ranging from acid to ultramafic. The principal components of the complex were reworked during late-Archaean and early-Proterozoic times. On a regional scale this reworking involved *en bloc* tectonic displacements at mid-crustal depths, which resulted in the superimposition of supracrustal rocks on the crystalline basement. A Lewisian chronology has been given by Park et al. (1994) and a simplified version from Shihe and Park (1993) is shown in Table 1.

Depletion in the large-ion lithophiles (e.g. Th, U and Rb) in these gneisses is either due to changes in silicate chemistry during prograde to peak metamorphism at around 2.66 Ga (Pidgeon and Bowes, 1972; Cohen et al., 1991), or else reflects an earlier 'depleted' crust (Rollinson, 1996). Chemical modification undoubtedly took place during Inverian retrogression at mid-crustal levels at around 2.5 to 2.4 Ga. This resulted in the replacement of pyroxenes by hornblende and biotite, resulting from the introduction of fluids under amphibolite-facies conditions, and the modification of primary sulphide phases at temperatures of 500 to 625 °C (Cartwright, 1988) with the resultant loss of Au from the sulphide phases (Cameron, 1994).

Table 1 Simplified Lewisian chronology (after Shihe and Park, 1993)

Ga (approx)	Description
1.4–1.1	Late Lewisian and/or Grenvillian D4 deformation and brittle faulting
1.5	Late Laxfordian retrogressive metamorphism; D3 deformation, cataclasis
1.7	Main Laxfordian metamorphism; D2 deformation, ductile shear, mylonites
1.8	Early Laxfordian metamorphism: ? D1 deformation
2.4–2.0	Emplacement of Scourie dykes and Loch Maree supracrustals; possible continuation of major shear zone movements
2.6–2.4	Inverian metamorphism; major, mid-crustal shear zone movements
2.9–2.7	Formation of early Scourian (Badcallian) high-grade gneiss complex

The Lewisian Complex occupies a 200 km long tract of the north-west Scottish mainland, together with the Outer Hebridean islands of Harris and Lewis, North and South Uist, Benbecula and Barra, the Inner Hebridean islands of Coll and Tiree, and parts of Iona and Raasay. The majority of the complex occupies an ancient crustal region known as the Hebridean terrain which is separated from the orthotectonic Caledonian province by the Moine Thrust Zone (Figure 1). In addition to the aforementioned areas, allochthonous Lewisian inliers also occur within the Caledonian orogenic belt, to the east of the thrust zone.

Peak metamorphism of the basement took place during late-Archaean times (Table 1). Subsequently, during the early Proterozoic, the Northern and Southern belts (Figure 1) were uplifted and subjected to retrograde metamorphism to hornblende and localised greenschist facies. Tectonic superimposition of the metasedimentary/metavolcanic supracrustal successions took place in the Laxfordian.

Supracrustal rocks are present in the following areas: Ness, South Harris, North Uist, Benbecula, South Uist, Coll, Tiree, Gairloch and Loch Maree (Figure 1). Significantly, the supracrustal metasedimentary/metavolcanic packages present in these areas are absent from the Central and Northern belts of the mainland. However, minor outcrops of metasedimentary rocks of Badcallian age are known from the Central belt (Park et al., 1994). Most of the supracrustals may be of similar age and related to a single period of basin formation and rifting. However, the complex history of deformation and mid-crustal assimilation makes correlation between the assemblages difficult to unravel. For example, the Leverburgh and Langavat metasediments have been dated at 2.4 Ga (Cliff, 1989), and similarities between the South Harris igneous complex (2.2 Ga) and the Ness anorthosite and Corodale metagabbroic gneiss on South Uist indicate that they may be comparable in age to the Loch Maree Group (see Table 1). The Coll and Tiree metasediments are undated, and the contrast in metamorphic grade between the Archaean gneissose basement (granulite facies) and the superimposed supracrustals (amphibolite facies) has led Whitehouse and Robertson (1995) to suggest that they could represent either different crustal levels or distinct terrains. It is therefore possible that the Coll-Tiree supracrustals are similar in age to the Loch Maree Group or South Harris metasediments which are, likewise, metamorphosed to amphibolite facies.

Geology of the Southern Belt

The Southern belt comprises a basement terrain of dominantly hornblende-biotite migmatitic gneisses of Archaean age. The basement gneisses, between Loch Broom in the north and Loch Torridon in the south, are divided into three distinctive assemblages bounded by the Gruinard, Gairloch and Diabaig shear zones, which are thought to have originated in the Inverian. In the central part of the belt these gneisses are overlain by a suite of supracrustal rocks (the Loch Maree Group), consisting primarily of metasedimentary schists and tholeiitic metavolcanic amphibolites. Park et al. (1987) interpret the deposition of the supracrustals to crustal extension occurring above a low-angle shear zone resulting from previous Inverian movements. An early Proterozoic age for the supracrustals of ca. 2.0 Ga has been indicated by Park et al. (1994), approximately coincident with that of the younger Scourie dykes. The Loch Maree Group shares the same Laxfordian deformational and metamorphic history as the basement gneisses and the metamorphic assemblages are typical of the middle to upper amphibolite-facies.

Geographically the Loch Maree Group may be divided into two main areas, the Gairloch schist belt (36 km^2) and the Loch Maree schist belt (60 km^2), which are separated by the Loch Maree Fault (Figure 1). The two schist belts comprise broadly similar successions of tholeiitic metavolcanics and clastic and chemical sediments such as greywacke, shale and limestone, together with subordinate and relatively thin, discontinuous exhalative horizons dominated by silicate and oxide facies. The succession was subjected to intense deformation and amphibolite-facies metamorphism during the Laxfordian peak at around 1.7 Ga (Shihe and Park, 1993).

Geology of the basic and ultrabasic intrusive igneous rocks of the Central Belt

Basic and ultrabasic rock types have long been recognised within the Lewisian crystalline basement (Peach et al., 1907). Early basic and ultramafic bodies are particularly common in the Scourie and Assynt areas where they comprise up to 20% of the complex and have been subjected to granulite facies metamorphism. The scale of these bodies varies from a few centimetres to about a kilometre across and they appear in general to be older than the enclosing acid gneisses. The ultramafic enclaves vary compositionally from monomineralic masses of pyroxene or hornblende to large bodies of peridotitic or dunitic material. Basic bodies comprise pyroxene with variable amounts of plagioclase and accessory garnet and quartz. In areas affected by later amphibolite -facies metamorphism the pyroxene is replaced by hornblende.

Compositional and textural banding has been widely observed in both mafic and ultramafic lithologies, but its origin is controversial. One hypothesis is that this banding represents original igneous layering (Bowes et al., 1964), but an alternative origin related to deformation and chemical reaction between ultrabasic rocks and the country rock has also been proposed (O'Hara, 1961 and 1965). Field observations made in the present study are consistent with a deformation-related origin for much of the small-scale banding observed, but this evidence is not inconsistent with an original magmatic compositional variation which has been modified, disrupted or accentuated by tectonic processes. Indeed, the compositional and textural features observed by Davies (1974) over a wide area on the south side of Loch Laxford may be reasonably interpreted as representing disrupted layered mafic complexes. More recent geochemical data, in combination with the observation that the mafic-ultramafic masses are commonly associated with rocks of sedimentary origin, has led to speculation that the mafic-ultramafic rocks represent oceanic crust accreted into the continental crust at a subduction zone (Tarney and Weaver, 1987).

Regional geophysics

The Lewisian terrain is cut by strong north-north-west shear zones separating gneisses of differing metamorphic grade: namely Diabaig, Gruinard Front, Canisp, Laxford, South Harris and Ness shear zones. The region is also transected by a series of north-north-east faults showing strong Mesozoic extension and clearly identified in the Bouguer gravity anomaly map. The main faults are the Outer Isles Thrust, the Tiree-Coll-Rhum-Rona fault system and the Iona-Mull fault.

Comparable north-north-east structures across the northern Highlands, the Fannich (FA) and Strath Halladale (SH) lineations, can be inferred from the gravity data (Figure 2). Thick accumulations of Torridonian strata adjacent to the Outer Isles Thrust have also been used to suggest a Proterozoic phase of extension on the major north-north-east structures. A structural linkage between adjacent north-north-east structures can also be inferred from the gravity data in a pair of sigmoidal features cutting across the northern Highlands and the Minch: Rona-Shiant-Outer Isles; Oykell-Alness-Inverness. Lewisian gneisses have significant contrasts in density and susceptibility (Table 2), and reliable correlation of regional geophysical anomalies with basement structure is complicated by compositional variation within the gneisses.

In the Central Belt (Figure 1), the banded pyroxene granulite (Scourian) gneisses which outcrop between Loch Broom and Loch Laxford include numerous basic and ultrabasic lenses and are cut by east-west ultrabasic dykes and northwesterly trending basic dykes. Locally magnetic susceptibilities exceed 100 x 10^{-3} SI. The region has two prominent aeromagnetic anomalies with clear north-west orientation.

North of Loch Laxford, the predominant amphibolite-grade migmatised biotite-hornblende (Laxfordian) gneiss exposed at the surface has a low mean magnetic susceptibility (<10 x 10^{-3} SI). The prominent 450 nT aeromagnetic anomaly centred on Strath Dionard has been interpreted as Scourian gneiss at shallow depth beneath the Laxfordian gneiss (Bott et al., 1972) or as magnetic pegmatite-granite veins (Powell, 1970). On the basis of velocity analysis, Hall and Al-Haddad (1979) concluded that granulite-facies pyroxene gneisses of the Scourie belt could not underlie the amphibolite gneisses of the Northern Belt.

Table 2 Physical properties of the Lewisian rocks of Scotland

	No. of sites	Mean	Minimum	Maximum	Standard deviation	Total no. of measurements
Susceptibility (x 10^{-3} SI)	538	19.68	0.01	466.00	57.33	5577
Unsaturated Density (Mgm^{-3})	70	2.81	2.56	3.73	0.18	236
Saturated Density (Mgm^{-3})	23	2.87	2.58	3.74	0.24	71
Grain Density (Mgm^{-3})	23	2.90	2.62	3.78	0.24	71
Porosity (%)	23	1.48	0.27	3.70	0.96	71

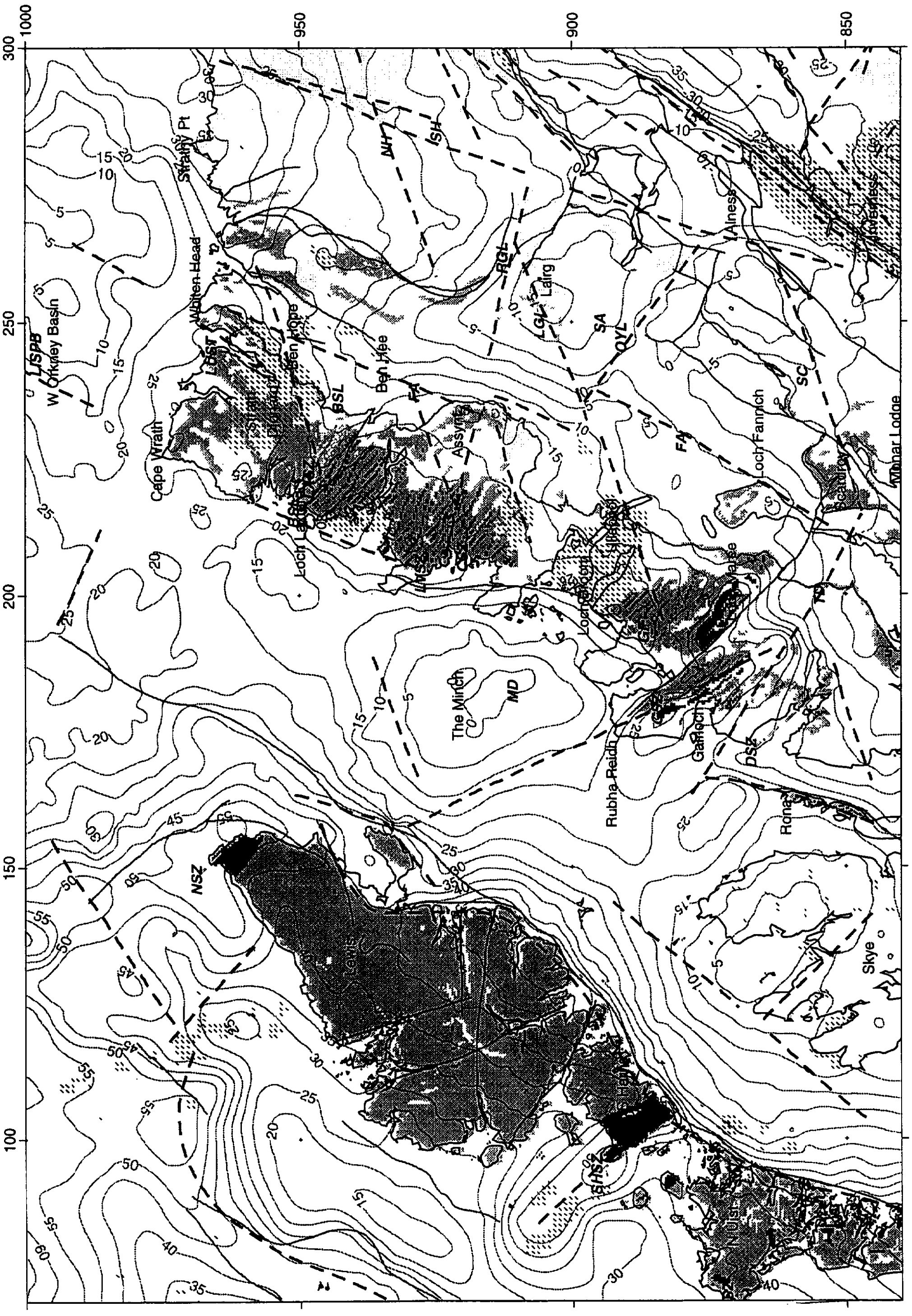

Figure 2 Geophysical anomalies over Lewisian outcrops of NW Scotland showing Bouguer gravity anomalies in mGal, gravity lineations (dashed lines), Lewisian gneiss (medium shading), metasedimentary rocks (dark shading) and late-tectonic granites (light shading). Stippled areas are zones where total magnetic field is above 200 nT.

The Lewisian of the Southern belt, from Loch Broom to Loch Torridon, is more varied and includes the Gruinard, Gairloch and Diabaig assemblages. The Gruinard assemblage, in the northern part of the region, comprises hornblende-biotite gneisses with many basic and ultrabasic intrusions and minor patches of pyroxene gneiss. The assemblage is chemically and geophysically similar to the Scourian rocks and is associated with a large aeromagnetic anomaly displaying a strong north-west magnetic fabric. Piper (1994) has identified a palaeomagnetic zone boundary approximately at the head of Gruinard Bay comparable with the Gruinard Front (Park and Tarney, 1987). This coincides with the mapped southern boundary of the Central Belt.

The strong aeromagnetic anomaly over the largely buried Scourian gneiss around Little Loch Broom extends eastwards beneath the Moine rocks as far as the Rhidoroch Forest. The aeromagnetic anomaly in this zone, just south of the Assynt window, exhibits a noticeable annular pattern, typical of large intermediate intrusions.

Supracrustal rocks of the Loch Maree Group outcropping adjacent to the Loch Maree Fault include hornblende schists, garnet-mica schists and, locally, quartz-magnetite schists which are associated with isolated positive anomalies sub-parallel to the Tertiary Minch dyke anomaly. To the south of Loch Maree, the Laxfordian biotite-hornblende gneiss, similar to the Lewisian of the Central Belt, is not associated with prominent aeromagnetic anomalies. Similar lithologies occur on South Rona and could underlie much of the Minch.

Much of the Outer Hebrides consists of (Laxfordian) biotite gneiss and hornblende-biotite quartz-feldspar gneiss with fairly low magnetisation. A broad regional magnetic anomaly occurs over the south-east side of Lewis, which is dissected by a major suite of north-north-west Tertiary dykes. This regional anomaly seems unrelated to the late Laxfordian Uig Hills granite vein complex in west Lewis.

Metasedimentary supracrustal rocks occur on South Harris, at Ness on Lewis and on North Uist. Late Scourian basic intrusives occur especially on Harris, South Uist and Barra. Parts of the gabbroic suite of the South Harris Igneous Complex have associated magnetic anomalies which are traceable offshore to the north-west. Meta-igneous basic gneisses above the Outer Isles Thrust on the east of North Uist are probably the cause of the aeromagnetic anomaly adjacent to the Minch Fault. Similarly, the ultrabasic meta-igneous Corodale Gneiss on the east side of South Uist, including mafic and pyroxene gneisses, is associated with a prominent aeromagnetic anomaly which extends southwards offshore, to the east of Barra. Similar rocks might be the source of the promiment anomaly south of Mingulay. A strong regional magnetic anomaly extends across the Skerryvore bank and covers Tiree and Coll. Western Tiree consists of little-altered Archaean gneisses dated at 2.79 Ga (Whitehouse and Robertson, 1995), similar to those at Scourie and on south-east Barra.

In the northern part of the northern Highlands, a prominent north-north-east lineation running through Loch Fannich (FA on Figure 2), observed in images of the regional gravity data, is considered to be a Mesozoic extensional fault extending through the upper crust and marking the eastward limit of exposed Lewisian rocks beneath the Moine. The lineation intersects the BIRPS MOIST line at a zone of easterly dipping reflections, which are considered to represent faults in Moine, Torridonian and Lower Palaeozoic sediments rather than mylonites in Caledonian ductile thrusts. By comparison with the Outer Isles Thrust, Torridonian strata might be preserved east of the Fannich feature. A thick down-faulted block of Moine and possibly syn-rift Torridonian sequences are presumed to occur beneath the Lairg gravity low. A comparable lineation runs approximately north-north-east along the west side of Strath Halladale (SH on Figure 2). The north-west Torridon lineament seen in the Bouguer gravity anomaly map appears to truncate the Loch Maree Group and links the Fannich feature and the Rona-Raasay Fault system. It marks a change in structural style of the Moine and probably a thickening of the orthotectonic nappe-thrust sequence to the south-west.

In the northern Highlands a set of lineations trending 070–080° is especially noticeable and can be related to the Wick Fault. These are considered relatively late structures (Mesozoic). The most prominent of these, from the Cromarty Firth to Loch Carron, might prevent correlation of the Kishorn Nappe onto Skye.

GAIRLOCH AREA

Geology and mineralisation

The Gairloch supracrustal succession comprises a volcano-sedimentary supracrustal sequence which has been metamorphosed to lower amphibolite facies and is multiply deformed. The metasediments fall into four main units, (1) Aundrary Basite, (2) Flowerdale schists, (3) Charlestown schists and part of the Kerrysdale basite and schists, and (4) Interdigitated Schists and gneisses (Jones et al., 1987). Within these occur a range of chemical sediments which include banded iron formation (BIF) and a variety of iron/manganese-enriched lithologies of exhalative and mixed clastic and exhalative origins (Jones et al., 1987; Williams et al. 1985; Williams, 1986). The exhalites include representatives of iron-dominated oxide facies (quartz-magnetite), sulphide facies to silicate facies (garnet-grunerite). These are intercalated with a range of sediments dominated by pelitic lithologies, together with thin metabasic sheets. Thick metabasic units, such as the Aundrary Basite, are also present. Under the regime of low to medium-grade metamorphism (Klein, 1973; Mel'nik, 1982) the iron-dominated facies have largely preserved their premetamorphic oxidation states and frequently appear to contain a minor primary carbonate component. In spite of deformation and locally developed high strain fabrics (mylonite and pseudotachylite), the sediments in places retain grading, cross lamination and oolitic texture characteristic of shallow water deposition (Williams, 1986).

Four major Laxfordian deformation phases have been identified in the Gairloch area. The early, mid-crustal (D1) and main, high-grade (D2) events took place at between 1.8 and 1.7 Ga, with metamorphism to amphibolite facies (Coward and Park, 1987). These were followed during late-Laxfordian times by retrogressive (D3) metamorphism to mid- to low-greenschist facies at around 1.5 Ga (Moorbath and Park, 1971), with the development of the Gairloch Shear Zone and Tollie Antiform. The final (D4) event resulted in the localised development of cataclasites with chlorite-bearing fabrics, concomitant with the development of north-west - south-east crush belts and north-south and east-west shearing at upper crustal depths (Shihe and Park, 1993). Within the basement gneisses, bedding and intrusive/extrusive contacts are generally parallel to the strongly developed early north-west foliation and lineation direction. This trend is the product of late-Scourian deformation and predates Scourian dyke suite emplacement between 2.4 and 2.0 Ga. In the Gairloch schist belt this fabric is steeply dipping and may be contrasted with the shallower dip of the Loch Maree Group which in Letterewe Synform (Park et al., 1987).

Accounts of stratiform sulphide facies and associated chemical sediments in the Lewisian of north-west Scotland are largely confined to the studies of Jones et al. (1983, 1987). Their combined geochemical and geophysical studies, on behalf of Consolidated Gold Fields Ltd, resulted in detailed accounts of a sulphide-enriched quartz-carbonate facies horizon in the Kerry Road area between Gairloch and Loch Maree [183 872]. Further detailed petrographic descriptions of these rocks added to the understanding of the mineralisation (Williams et al., 1985). Within the Gairloch schist belt the chemical sediment package has been mapped over a strike length of 5–6 km and the overall succession is defined from north-east (bottom) to south-west (top) in Table 3.

The Kerry Road sulphide deposit lies within a succession of locally mineralised supracrustals which extend south-eastwards to the western shore of Loch Bad na Sgalaig [184 871] and north-westwards as less well-exposed ground, towards the coast at Flowerdale Mains [182 875] (Williams, 1986). Sulphides locally form 15–20% of the rock and are dominantly pyrrhotite and pyrite. Other sulphides (chalcopyrite, sphalerite, marcasite and galena) are locally minor constituents. Silver-rich gold occurs as c. 10 micron size inclusions in chalcopyrite and, in smaller amounts, in pyrrhotite and gangue. The east-west trending ore zone is thrust-bounded on its east and west flanks and is traversed by a north-west–trending late fault. On the evidence of sub-equal proportions of mafic volcanics and greywacke and the absence of felsic volcanics, the Cu-Zn-Au deposit has been attributed to the Besshi-style of mineralisation.

Table 3 Lithological succession of the Loch Maree Group at Gairloch (after Park, 1964 and Jones et al., 1987)

Tectono-stratigraphic Unit	Lithology
Cloiche marble belt	thin marble bands, hornblende and quartz gneiss
Kerrysdale basite (remainder) Southern Hornblende Schist (Jones et al.)	massive hornblende schist
Kerrysdale schists Marker quartz-mica schist (Jones et al.) and Lower Hornblende schist	coarse quartz-mica schist with hornblendic bands
Kerrysdale basite (part) Upper Hornblende Schist (Jones et al.)	hornblende schist, porphyritic in parts
Flowerdale marble	thin marble, BIF, chlorite and graphite schist. 15 m thickness
Flowerdale semipelitic schists	quartz-mica schist
Aundrary Basite	foliated fine-grained hornblende schist
Creag Bhan schists and gneisses	thin bands of basite, mica and garnet schist
Am Feur-loch Marble	marble
Basement gneiss (Archaean)	granodioritic mica-epidotegneiss

Geophysics

Bouguer gravity anomalies in the Gairloch District indicate a clear positive anomaly associated with the supracrustal rocks south-west of the Gairloch Shear Zone, the anomaly extending from Melvaig to Loch na h-Oidhche. A secondary positive anomaly occurs over similar rocks on the north-east side of the Loch Maree Fault.

The most significant aeromagnetic anomaly in the Gairloch area (Figure 3) is to the north-east of Fionn Loch and is associated with the Scourian-type gneisses north-east of the Gruinard Front, most of which are covered with Torridonian strata. Anomaly amplitudes locally exceed 500 nT.

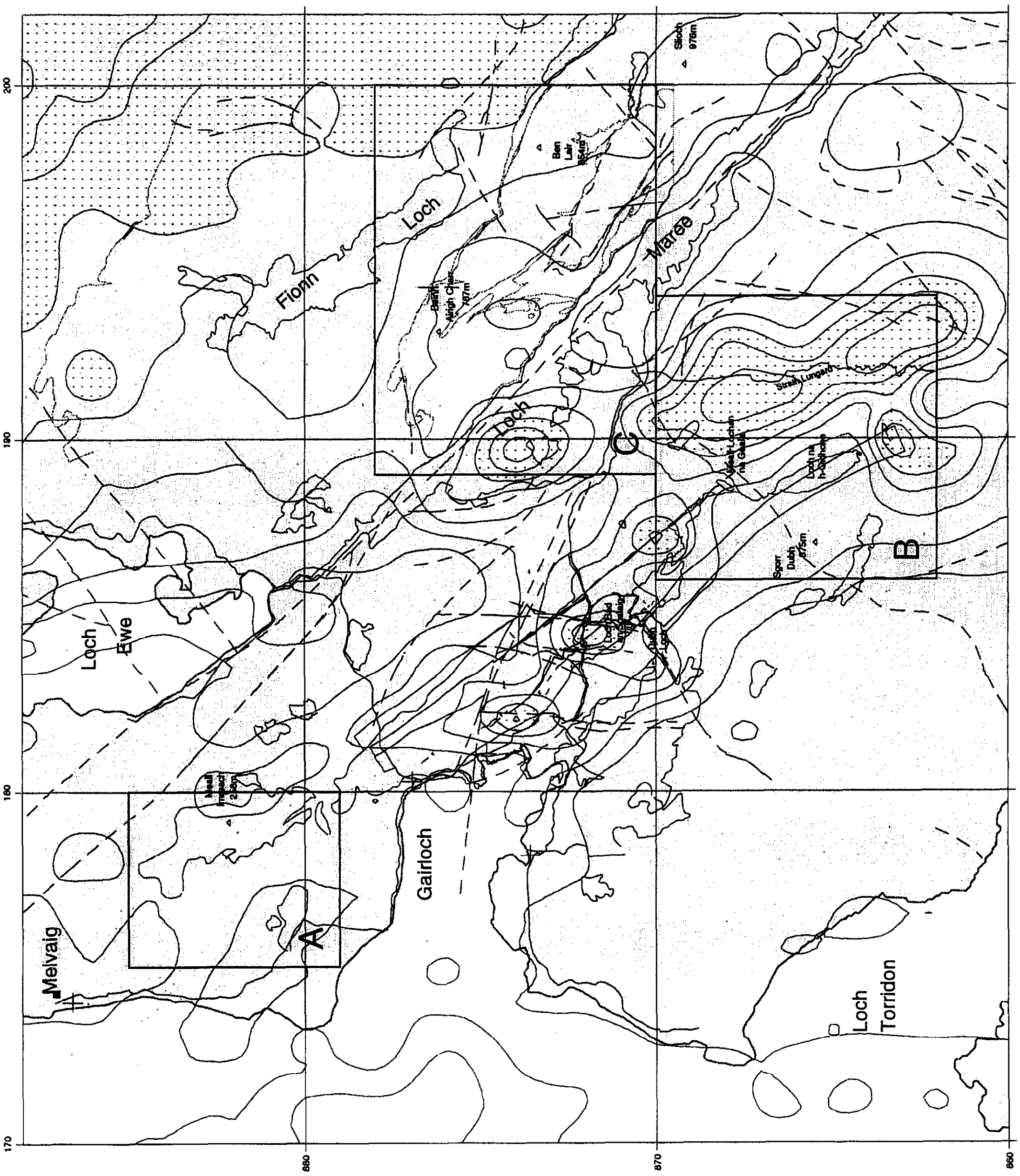

Figure 3 Aeromagnetic anomalies in the Gairloch region. Contours are the total magnetic field, after regional correction observed at 305 m above terrain. Insets show the detailed study areas: A Melvaig, B Flowerdale Forest, C Loch Maree.

A significant 200 nT anomaly occurs south-west of the Loch Maree Fault where the western arm of a 'Y' shaped positive anomaly (Figure 3) is associated with the exposed supracrustal rocks around Loch Bad an Sgalaig and to a lesser extent the minor exposures of Lewisian rocks south of Loch na h-Oidhche. The eastern part of the anomaly runs north-north-west through Srath Lungard and into Loch Maree, terminating at the Loch Maree Fault. The overall pattern of the aeromagnetic anomaly could be consistent with a strata-bound source disposed within a major anticline (Tollie Antiform), the axis of which would plunge to the south-east. However, there are significant north-north-east-trending faults cutting across the Torridonian strata and into Loch Maree at Talladale, so that correlation of the Gairloch sequences with those to the south-east is problematical.

The displacement history of the Loch Maree Fault is not known. Although the base of the Stoer Group is dextrally offset about 10–12 km at Loch Ewe, at the Moine Thrust, the Moine outcrop shows a dextral displacement of only a few kilometres. It is interesting that the prominent -150 nT anomaly associated with the Tertiary Minch dyke appears to terminate at the fault in Loch Ewe. Although a similar negative magnetic anomaly occurs offshore Rubha Reidh, this might be a separate dyke.

LOCH MAREE AREA

Introduction

The Loch Maree area is the largest of the exposed areas of supracrustal rocks in the Lewisian but, unlike the slightly smaller neighbouring Gairloch area, has only been poorly studied due to its relative remoteness and former restrictions on access. After the Geological Survey mapping (Peach et al., 1907) there was a long gap until the publication of two structural mapping theses by Keppie (1967) and Fernandes (1987). The only recent publication on the geology is that by Cattell and Williams (1988).

Geology

Despite the similarities beween the Gairloch and Loch Maree areas there has been no attempt to correlate the successions or to erect a broad tectono-stratigraphy. The succession defined below assumes that basement gneisses form the base of an essentially tectonic succession and that the rocks 'young' in an easterly or southerly direction (Table 4). In this event it follows that the Letterewe Gneiss, which forms the core of Letterewe synform, must be part of a sheet of 'basement-style' gneiss, overthrust during D2 deformation (see discussion of this in Park et al., 1987).

The Basement Gneiss to the north-east of the Loch Maree Group forms part of the extensive area of strongly deformed Archaean gneiss extending from the Fionn Loch northwards to Gruinard Bay. This northern part of the Southern belt (Figure 1) shows Inverian structures (see Table 1 for simplified Lewisian chronology), whereas in the southern part of the belt, to the south of Fionn Loch, they are obliterated by strong (D2) Laxfordian deformation. A major north-west upright D3 fold, the Carnmore antiform, crosses the area and the complementary Letterewe synform folds the Loch Maree Group to the south-west (Park et al., 1987).

The disposition of the metasedimentary bands in the Loch Maree area and their disruption by folding and thrusting does not allow the erection of a clear stratigraphic succession, as can be largely achieved in the better mapped Gairloch area (Park, 1964 and subsequent papers). Four suites of metasediments, the Gleann Tulucha, Beinn Airidh a'Char, Folais and Furnes bands (Table 4), were identified by Peach et al. (1907). The first and third of the bands contain marbles, and these two bands were correlated in their cross-section, but the different appearance of the two marbles was noted in the text (p.235).

The Loch Maree Group of supracrustal rocks has an oval outcrop bounded on the southern side by the Loch Maree fault and the rock types are arranged in a flattened arcuate ring around the central core of the Letterewe gneiss, which marks the axis of the Letterewe synform. To the east the succession is uncomformably overlain by Torridonian sediments. Correlation between tectonic units on the north-east and south-west sides of the synform is difficult. The main metabasite unit, named here as the Ben Lair Hornblende Schist, can be traced from Lochan Fada (Figure 4), Ben Lair, Meall Mheinnidh and Beinn Airigh Charr to the shore of Loch Maree at Creag Tharbh [192 873]. Between the Basement Gneiss and the Ben Lair Hornblende Schist a narrow unit of metasediments is exposed at intervals along the foot of the steep cliffs formed by the metabasic rock. This unit at [195780 875170] is composed of a thin, strongly tectonised, hornblende schist at the base, a 4 m grey marble band and a conspicuous 12 m thickness of black, pyritic graphite schist. The Basement Gneiss adjacent to the metasediments is a distinctive pink, acid quartz-feldspar gneiss. The grey marble unit can be traced north-westwards, and then south-westwards to a sheepfold and small quarry adjacent to the old lime kiln north of Ardlair [189535 876795], where 5–7 m of mica schist also form part of this unit. Peach et al. (1907) describes this unit as the Gleann Tulacha limestone, and up to four marble bands can be mapped in that valley.

The main Ben Lair Hornblende Schist comprises a fairly massive, foliated hornblende schist containing distinctive bands of anorthosite xenoliths as described by Clough in Peach et al. (1907) and, more recently, by Cattell and Williams (1988). The lithology is slightly pyritic in parts, which results in a rusty weathering surface. At [191655 876045], west of Beinn Airigh Charr, a 10–20 cm thick massive sulphide layer (rock samples KLR 4615-8) is visible and can be traced along strike for a few tens of metres before being faulted out. Near the top of the unit two narrow belts of exhalites and metasediments are found, the lower of which (to the north-east) is composed of iron formation and garnetiferous quartzite (coticule) and the upper of similiar lithologies plus graphitic schist. These are discussed further below.

Above the Ben Lair Hornblende Schist a unit of brown flaggy mica schist (Beinn Airigh Charr Mica Schist) occurs on the south-east face of Beinn Airigh Charr and can be mapped in an irregular belt south to Loch Maree. On the northern limb of the Letterewe Synform these mica schists are apparently sheared out and the outcrop thins to a narrow band. South-east of this unit another hornblende schist is seen and this may be part of the Creag Dharaich Hornblende Schist.

The Letterewe Gneiss (Leth Creag Gneiss of Fernandes (1987)), comprises a sequence of coarse pink quartz-feldspar banded rocks with biotite and muscovite rich layers. Some augen gneiss, which contains porphyryblastic K-feldspar crystals up to to 5 cm in length, is also present. Within the gneisses three types of amphibolite can be identified; namely banded, porphyritic and mafic varieties (Fernandes, 1987), which probably represent deformed Scourie dykes. The frequent disposition of these amphibolites within the Letterewe Gneiss is in marked contrast to their relative scarcity in the Basement Gneiss to the north.

The Creag Dharaich Hornblende Schist has a banded texture with fine pale feldspathic bands defining the foliation, contrasting with the more uniform Ben Lair Hornblende Schist. Garnet- and chlorite-bearing varieties are also present. Structurally above the Creag Dharaich Hornblende Schist the Folais band of Peach et al. (1907) contains the Letterewe Marble and associated schists. The marble varies in colour from dominant white or grey varieties to brown and pink colourations. It has been quarried from outcrops on the west side of Folais burn [195 872] and at one time a small tramway ran down the valley to the loch side. The thickness of the marble is up to 7 m and the band can be traced for about 4 km around the Letterewe Synform. Calc-silicate rocks are also seen, including actinolite, biotite and chlorite schists. Some finely foliated hornblende schists are interbanded with the marble,

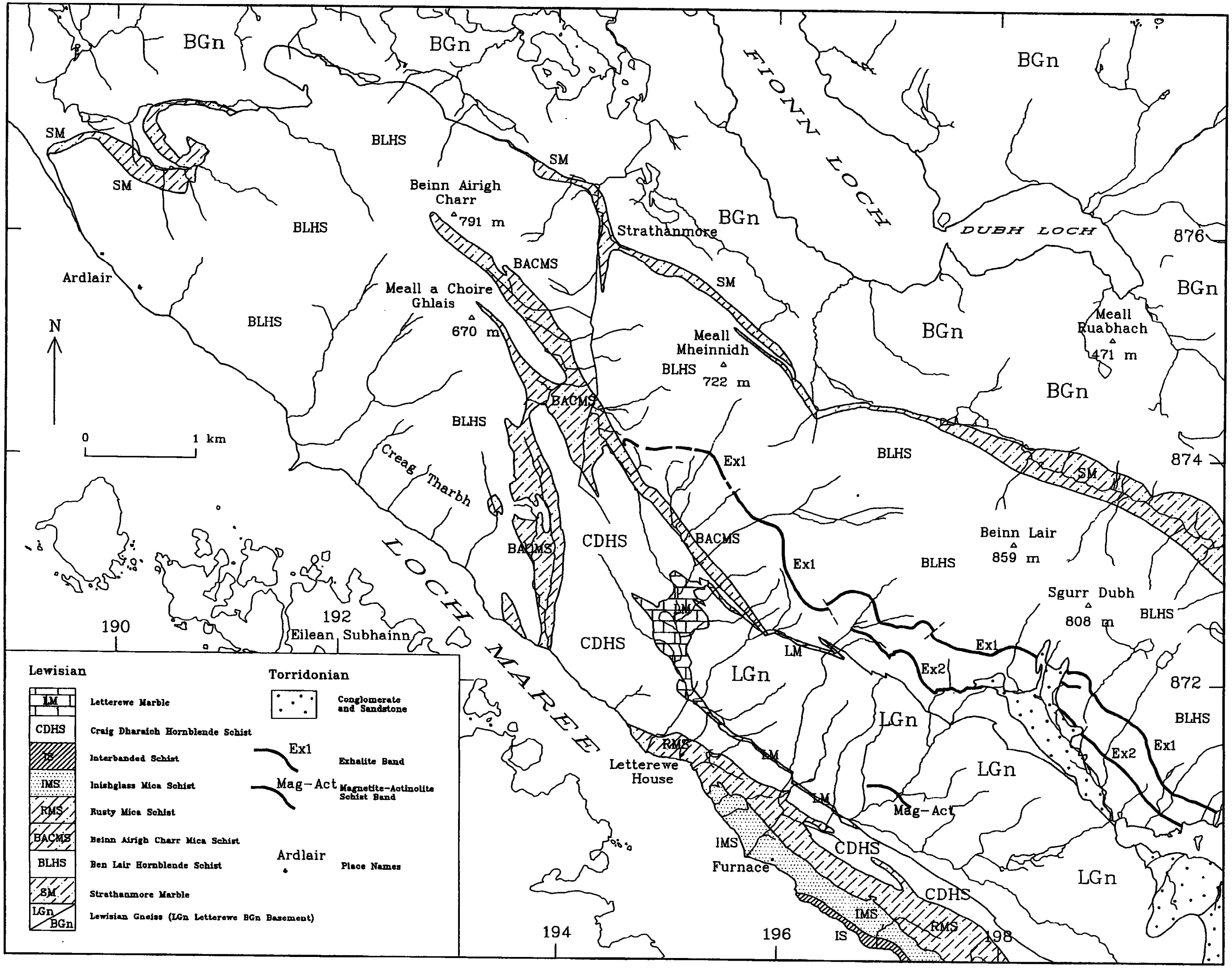

Figure 4 Schematic geology of the Loch Maree area.

and it is unclear if they represent an infolded part of the Creag Dharaich Hornblende Schist or a separate unit.

Table 4 Tectonic succession at Loch Maree from south-west (top) to north-east (base), mainly after Fernandes (1987)

Metasedimentary Band (Peach et al., 1907)	Tectonic Unit	Lithology
Furnace (Furnes)	Interbanded Schist	quartz-feldspar schist with hornblende and chlorite schist
	Inishglass Mica Schist	pale grey siliceous mica schist
	Rusty Mica Schist	rusty weathering, brown, pyritic mica and actinolite schists with graphitic schist at base
	Creag Dharaich Hornblende Schist	banded hornblende schist with garnet or chlorite bearing varieties
Folais	Letterewe Marble	pink marble with calc-silicate bands and biotite schist at top
	Letterewe Gneiss (Leth Creag gneiss, Peach et al. 1907)	pink quartz-feldspar gneiss with common hornblende schist bands. Thrust boundaries.
Beinn Airigh Charr (Beinn Airigh a'Char)	Beinn Airigh Charr Mica Schist	brown flaggy mica schist and hornblende schist
	Ben Lair Hornblende Schist	massive foliated hornblende schist, with anorthosite xenolithic and pyritic bands. Two BIF bands near top
Strathanmore (Gleann Tulacha)	Strathanmore Marble (Gleann Tulacha limestone, Peach et al. 1907)	graphitic schist, marble, quartz-schist
	Basement Gneiss	pink quartz-feldpar gneiss with hornblende streaks

The Furnace band is the thickest of the metasedimentary units, with an outcrop width reaching 600 m in the southern part of the area. Three units have been distinguished (Keppie, 1967 and 1969; Fernandes, 1987), Rusty Mica Schist (RMS), Inishglass Mica Schist (IMS) and Interbanded Schist. The RMS is mainly composed of quartz-mica schist, with lesser actinolite schist, mica schist and graphite schist, and it weathers a distinctive brown colour due to the oxidation of pyrite. Thin calcareous and graphitic bands are common. To the south-west of the Rusty Mica Schist, the Inishglass Mica Schist is pale grey in colour and lacks the distinctive brown weathering. The rock is also much more siliceous and harder than the previous unit, but Fernandes (1987) records a very similar mineralogy. The Interbanded Schists only occur in a narrow band along the shore of Loch

Maree, just south of Furnace. They are mainly quartz-mica schists but with thin bands of hornblende and chlorite schists. Light coloured quartzose bands are also found and these can contain large idioblastic garnets.

The Loch Maree Group is clearly strongly deformed and tectonised. Correlation between the metasedimentary units is difficult, and several of the units are bounded by zones of mylonite. A thrust boundary is clearly indicated by the presence of the Letterewe (Leth Creag) Gneiss tectonically overlying the Letterewe Marble and the whole supracrustal assemblage is probably overthrust on to the Basement Gneiss. Peach et al. (1907 and 1913) corrrelated the Ben Lair and Creag Dharaich Hornblende Schist bands but these have different textures and thicknesses. This interpretation also forces the correlation between the dissimilar Strathanmore and Letterewe Marbles. A correlation between the Furnace band and the Beinn Airigh Charr Mica Schist band is possible, if several of the more distinctive units of the former, such as the Inishglass Mica Schist, are cut out by another thrust at the base of the Creag Dharaich Hornblende Schist. The stratigraphic sucession in Table 5 is therefore proposed as a working hypothesis. As can be seen the two marble units form the top and bottom parts of this succession, and it is possible that they are the same unit repeated by an early D1 fold, but this is thought unlikely for the reasons given above.

Table 5 Tectono-stratigraphic succession at Loch Maree with major thrusts

Letterewe Gneiss
Thrust Letterewe Marble Creag Dharaich Hornblende Schist
Thrust Beinn Airigh Charr and Furnace Schist bands Ben Lair Hornblende Schist Strathanmore Marble
Thrust Basement Gneiss

Correlation with the Loch Maree Group in the Gairloch area indicates that the Strathanmore Marble is the equivalent of the Am Feur-loch Marble (cf Tables 3 and 5). The Ben Lair Hornblende Schist can be easily correlated with the Aundrary Basite, both in texture, in thickness and in the presence of pyritiferous layers. The Flowerdale Schist can be correlated with the Beinn Airigh Charr or Furnace bands and the Creag Dharaich Hornblende Schist is equivalent to at least part of the Kerrysdale basite group and may be equated to the Upper Hornblende Schist at the Kerry Road locality (Jones et al., 1987). Alternatively, the thin metasediment and exhalite layers at the top of the Ben Lair Hornblende Schist may be the representatives of the Flowerdale Schist, and this would correlate the main exhalite units at Loch Maree with those near the top of the Flowerdale Schist and in part of the Charlestown Schist. The correlation of the Letterewe Marble with the Cloiche Marble is possible but the inclusion of the latter in the Ialltaig - Mill na Claise Crush Belt (Shihe and Park, 1993) and intermixture with gneisses makes correlation very difficult.

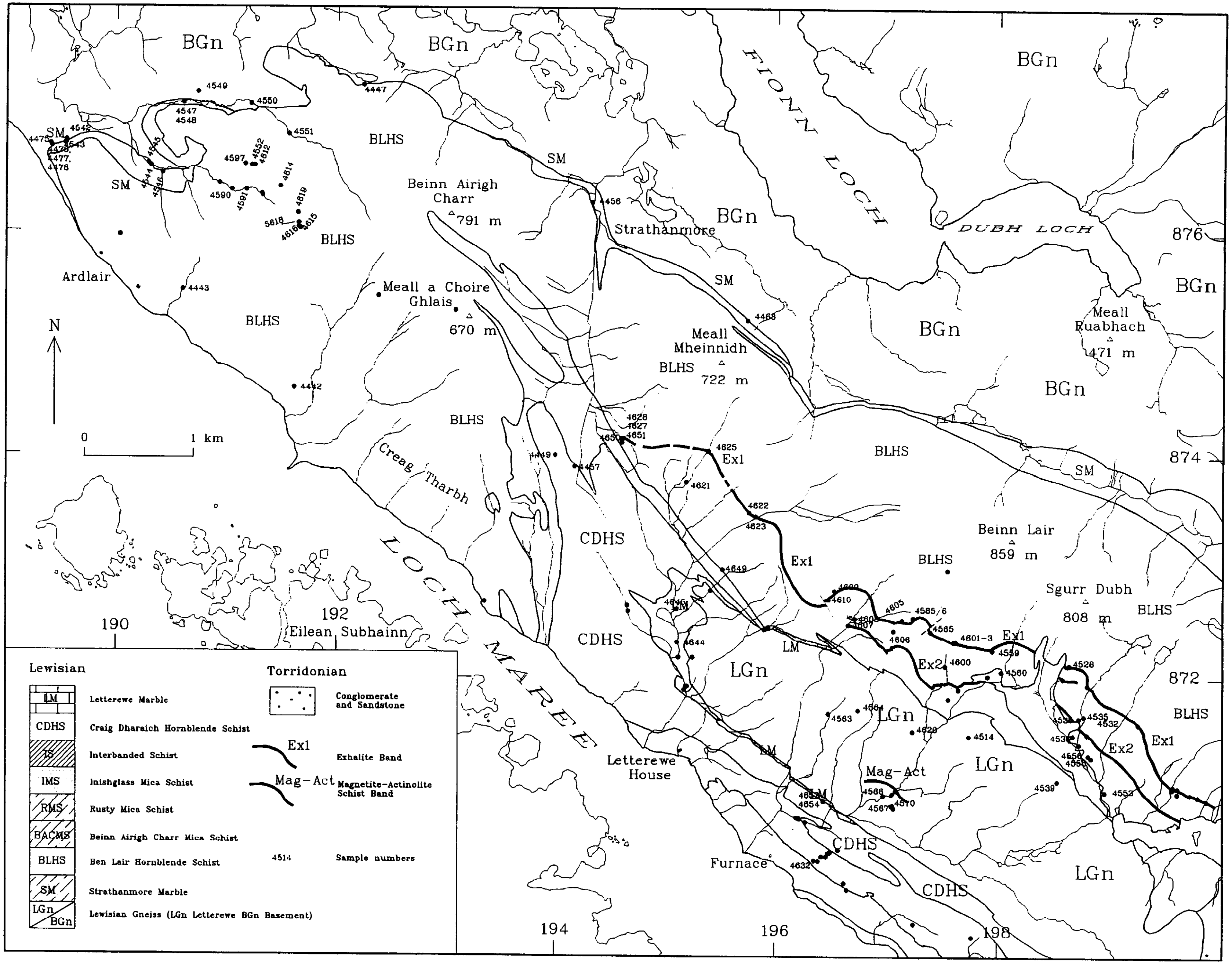

Figure 5 Location of rock samples from the Loch Maree area. Ornament omitted from map for clarity (see Figure 4).

Lithogeochemistry

A total of 183 rock samples were collected from the Loch Maree area, mainly from outcrops, but in a few places from float material where the BIF is poorly exposed. Rock samples of approximately 2–3 kg were collected from each site and, after grinding, analysed by X-ray fluorescence in the BGS Laboratories for As, Ba, Bi, Ca, Cr, Cu, Fe, Mn, Ni, Pb, Sb, Sr, Ti, U, V, and Zn. A 30 g subsample was analysed for gold by ACME Laboratories, Vancouver, Canada using by fire assay and ICP or AA analysis. The aim of the sampling was to characterise the rock succession, allowing better correlation between units, and to find indications of mineralisation by sampling the BIF and other exhalites along strike (using the principle of 'vectors' to mineralisation). The location of the samples is shown in Figure 5 and the results are described for each tectono-stratigraphic unit.

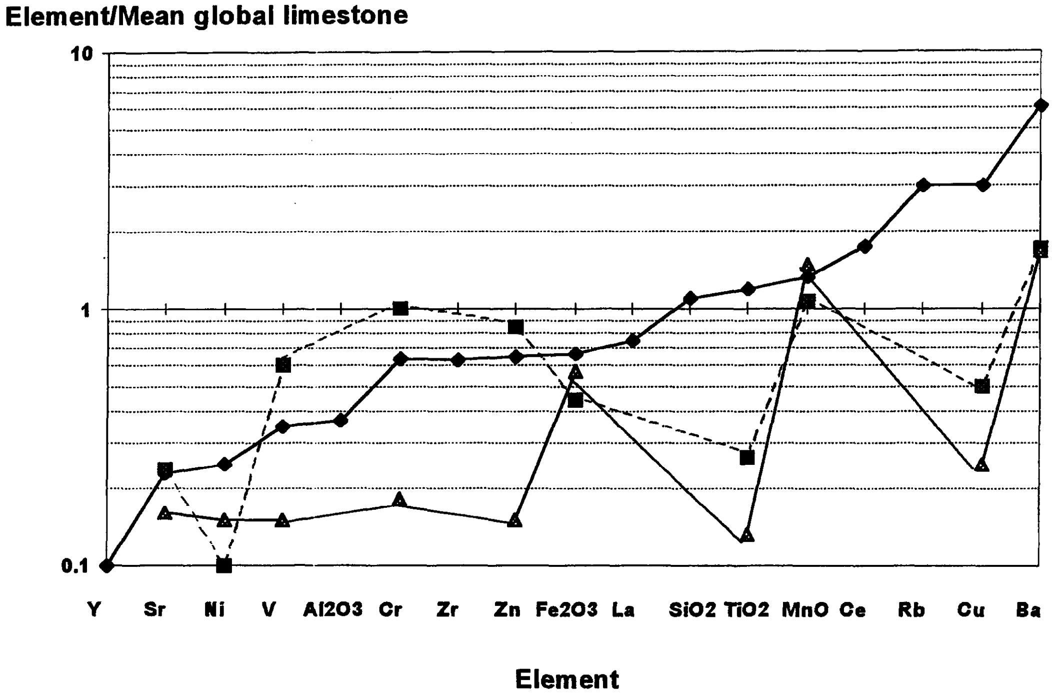

Figure 6 Spidergram of median compositions of Strathanmore (▪), Letterewe (▲) marbles and Lewisian dolostones (♦) (Rock, 1987) normalised to mean global limestone.

Strathanmore Marble

Samples were collected of the marble (KLR 4543, 4544, and 4547), calc-quartzite (KLR 4464), black schist (KLR 4456, 4462, 4463, 4465, 4476, 4545) and quartz and mica schist (KLR 4461, 4540, 4541, 4542, 4546 and 4548). The marble has a calcium content (median c. 24% Ca) which is typical of Lewisian dolostones (Rock, 1987), and most of the trace element values are comparable to the average global limestone (Figure 6). The Strathanmore Marble has higher values of V, Cr and Zn than the average Lewisian dolostone, but lower Ni, Fe, Ti, Mn, Cu and Ba. The median Ba content is 86 ppm but one sample (KLR 4544) contains the exceptional level of 1.44% Ba. Rock (1987) also found one very high Ba level in his dataset (S35264) with 1.06% Ba, and this sample was collected from the Letterewe Marble at Allt Folais (NGR not given by Rock, 1983 and 1987). Rock used this high value in calculating his arithmetic average composition (898 ppm Ba) for the Loch Maree Group dolostones (Rock, 1987) but, if the median is used, the typical Ba content comes down to 30 ppm, much closer to the global mean of 50 ppm. A similar strongly skewed distribution is seen for Cu. In summary, the Strathanmore marble shows low values of Sr and Ni compared to the global average, a feature which it shares with most Lewisian dolostones, but also lower levels of Fe and Ti.

Table 6 Median compositions of pelitic schists in the Loch Maree area compared to the average shale (Taylor and MacLennan, 1985)

	SM Graphitic Schist	SM Mica Schist	BACMS	RMS	IMS	T & M (1985)
No. of samples	6	6	5	17	4	
As	<1	1.5				
Au	0.0035	0.0045				
Ba	672	389	24	231	560	650
Ca	7750	10700	11000	21800	13350	9300
Cr	224	127	140	188	155	110
Cu	239	112	36	123	29	50
Fe	72300	54650	68000	62600	45400	51000
Mn	365	390	370	670	490	850
Ni	90	32	9	55	46	55
Pb	34	21	4	15	19	20
Sb	<1	<1	2.5	1	1	
Sr	118	66	228	90	181	200
Ti	6910	4945	2240	4340	3905	6000
V	315	155	59	246	98	150
Zn	230	51	33	194	78	85

Notes: All elements in ppm

SM = Strathanmore, BACMS = Beinn Airigh Charr Mica Schist, RMS = Rusty Mica Schist, IMS = Inishglass Mica Schist

Strathanmore graphitic and mica schists

Summary statistics for the six samples of the graphitic schist are presented in Table 6. Compared with the average shale (Taylor and MacLennan, 1985) the unit shows elevated levels (by a factor of 2 or more) of Cr, Cu, V and Zn and low levels of Mn, Ca and Sr (Figure 7). One sample of the graphitic schist was analysed for S and C. The carbon content is low, at 1000 ppm, but the rock has a high sulphur content of 5.53%. The unit therefore shows features of a black shale, enriched in mafic and chalcophile elements, probably through biogenic processes (Vine and Tourtelot, 1970), along with a low carbonate fraction. The mica schists have average levels of most trace elements and only Cu exceeds the average shale by a factor of 2. Mn and Sr have slightly lower levels than average, like the graphitic schists reflecting a lower carbonate content.

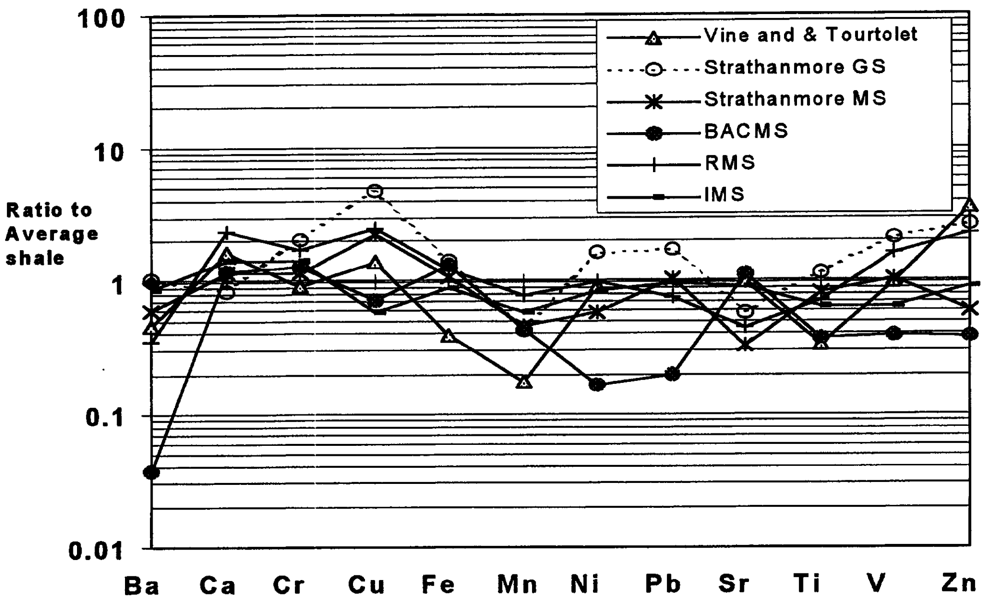

Figure 7 Spidergram of Loch Maree Group mica schists normalised to average shale (Taylor and MacLennan, 1985). Average black shale compositions from Vine and Tourtelot (1970) and median concentrations of Strathanmore graphitic (GS) and mica schists (MS), Beinn Airigh Charr Mica Schist (BACMS), Rusty Mica Schist (RMS) and Inishglass Mica Schist (IMS) from this study.

Table 7 Summary statistics of the Ben Lair and Creag Dharaich Hornblende Schist Units

	Ben Lair HS	Creag Dharaich HS	Aundrary Basite	MORB
Statistic (No. of samples)	Median (13)	Median (10)	Mean (44)	Mean
Au	0.002	0.002		
Ba	98	151	54	12
Ca	48500	45800	72400	
Cr	128	120	174	290
Cu	106	81	95	
Fe	93300	99350	93900	
Mn	1600	1600	1400	
Ni	50	56	100	138
Pb	6	9	0.6	
Sr	108	109	134	136
Ti	5750	5185	6115	9000
V	273	236	300	
Zn	119	115	98	

Notes: All elements in ppm
As, Bi and Sb medians below detection limit (1 ppm)
Aundrary Basite analyses from Johnson et al. (1987), MORB basalt average from Rollinson (1993)

Ben Lair Hornblende Schist

This thick unit was sampled extensively over its outcrop and a total of 31 samples were collected of the main lithology along with representatives of the stratiform pyritic bands. The medians for the unit, excluding the altered rocks and pyritic bands, are given in Table 7 and are compared with the means for the Aundrary Basite (Johnson et al., 1987) and MORB basalt (Rollinson, 1993).

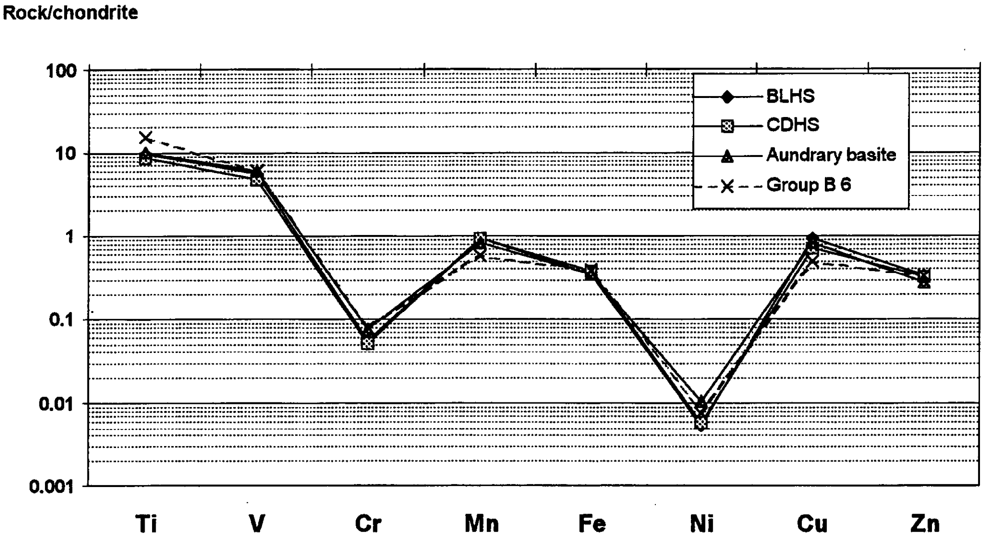

Figure 8 Spidergram of transitional metals in Loch Maree Group metabasic rocks, chondrite-normalised, showing the median compositions of the Ben Lair (BLHS) and Creag Dharaich Hornblende Schists (CDHS), and the mean compositions of the Aundrary Basite and the Group B6 from (Johnson et al., 1987).

The chemistry of the metabasites in the Loch Maree Group is comparable to tholeiitic basalts (Johnson et al., 1987, Cattell and Williams 1988), and the Ben Lair and Creag Dharaich Hornblende Schists are closely comparable to the Aundrary Basite and Group B6 basite (Johnson et al., 1987) with only a few minor differences (Table 7 and Figure 8).

Four groups of samples can be recognised from their chemistry and field observations: unaltered, mylonised, stratiform pyritic bands and pyrite veins. The unaltered group of 13 samples shows igneous trends on plots such as Ti vs V (Figure 9), Ba vs Sr (Figure 10) and Ca vs Sr (not shown) and only very limited variation in bivariate plots of elements such as Fe, Cu, Zn, Ni, Cr and Pb. The Aundrary Basite also shows a very limited variation in most of the bivariate plots given by Johnson et al. (1987), indicating that the magma came from a single source and was rapidly erupted (or intruded) with little high-level crystal fractionation.

A second group of samples can be distinguished on the basis of their mylonised texture in the field. These are hard, flinty rocks with some evidence of silicification, and their chemistry reflects this with much higher levels of Ba (400–1250 ppm compared to the normal range of 35–250 ppm), Sr (220–310 ppm, normal range 0–180 ppm Sr) and Pb (16–64 ppm, normal range 5–14 ppm Pb). Other elements that are slightly higher in the mylonised samples are Ca, Cr and Au. The mylonised rocks have slightly lower levels of the mafic elements Fe, Mn, Ti and V. Rocks of this group have probably undergone metasomatism during the processes of brittle-ductile shear at mid-crustal depths where Ba, Sr, Pb and, possibly, K and Si have been added to the rock. The Lewisian crust as a whole is known to be depleted in these elements (Holland and Lambert, 1973) and the chemical data here suggests a mechanism for their removal and subsequent fixation. K-feldspar breakdown takes place during granulite-facies metamorphism at low crustal levels, releasing large lithophile elements which are transported upwards in a fluid medium and cause a metasomatic reaction in mylonised zones at higher levels in the crust. The mafic elements are slightly depleted because of the metasomatic addition and the breakdown of mafic minerals.

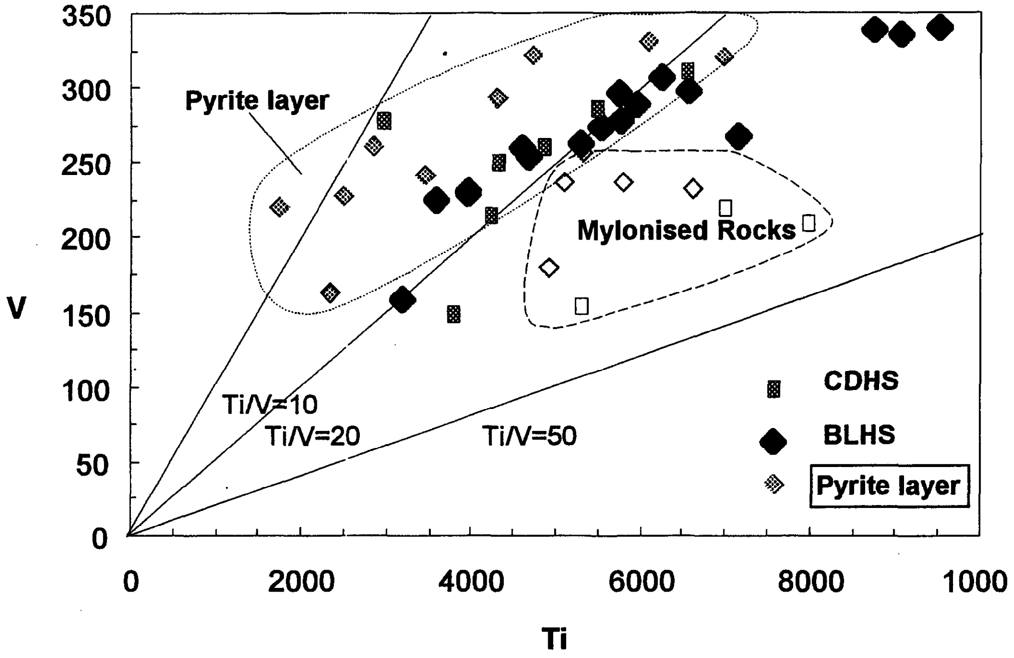

Figure 9 Ti vs V variation in Ben Lair (BLHS) and Creag Dharaich Hornblende Schists (CDHS). Open symbols indicate that the sample shows mylonitic textures.

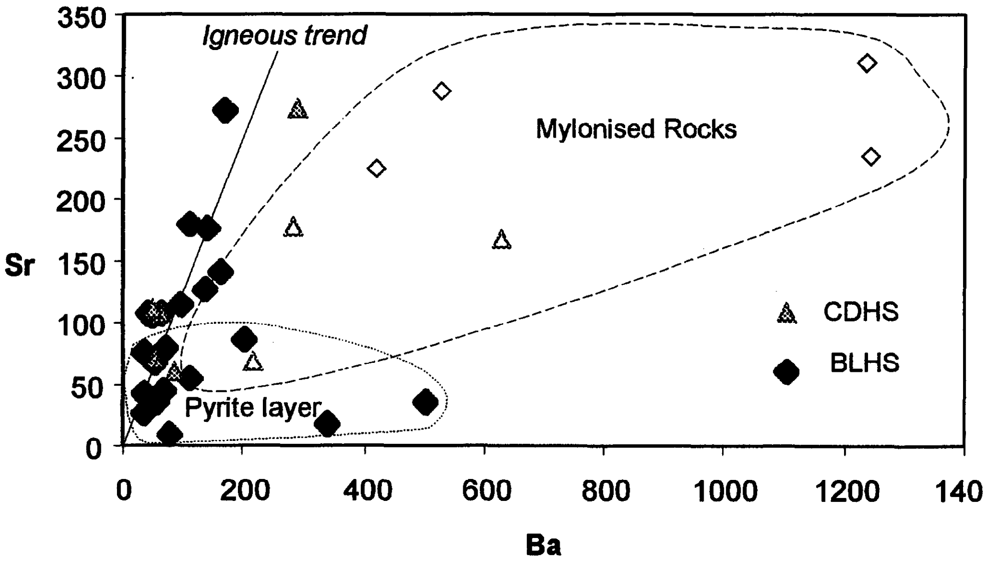

Figure 10 Ba vs Sr variation in Ben Lair and Creag Dharaich Hornblende Schists. Mylonised rocks shown in open symbols.

Two groups of pyrite-bearing rocks can be distinguished in the Ben Lair Hornblende Schist, stratiform pyritic bands (Pyrite layer in Figure 9–11) and pyritic veins. Stratiform pyritic bands occur at the following locations: in the headwaters of Allt Airigh a'Char; north-west of Meall Chnaimhean at

[19132 87633], [19165 87605] and [19165 876170]; and as a loose block south of Meall Mheinnidh at [19539 87405]. Whilst these bands are often highly deformed and brecciated in places, it can be seen that they forms bands 0.1–1.0 m thick parallel to the earlier foliation and are thus stratiform. The sulphide content is variable between 10 and 90%, and thin section examination shows that the rocks have a cataclastic deformation fabric of massive sulphide rock with subordinate felsic silicate clasts (descriptions of KLR 4589, 4592 and 4618, Fortey, 1993). The sulphide is dominantly pyrite with accessory chalcopyrite, except in KLR 4592 where pyrrhotite is dominant. The silicate layers and clasts are composed of quartz, microcline and actinolite. A pale felsic layer above the massive sulphide band (KLR 4596) contains cummingtonite (Fortey, op. cit.). The chemistry of the stratiform pyritic bands differs from the host hornblende schist in that they are enriched in Fe and Cu, as expected, reaching a maximum of 24% Fe and 655 ppm Cu, but are also enriched in Zn (maximum 1120 ppm) (Figure 11) and Ni (maximum 540 ppm). Some of the samples have high Pb (up to 70 ppm) but generally background levels of Ba and Sr and low levels of Ca. They also have low Ti/V ratios (Figure 9). The Aundrary Basite in the Gairloch area also contains stratiform sulphide bands, most notably at Sidhean Mor (Jones at al., 1987), and these have a comparable chemistry to the stratiform pyritic bands (e.g. Sidhean Mor: Cu 300 ppm and Zn 600 ppm; Loch Maree: Cu 523 ppm and Zn 504 ppm). Another similarity is the lack of quartz-magnetite schists associated with the sulphide bands in both areas (but see discussion later on this point).

The samples of the pyritic veins in the Ben Lair Hornblende Schist have a different chemistry to the stratiform rocks. They are enriched in Cu but show little enrichment in Fe or Zn (Figure 11). Other elements such as Ca, Sr, Cr Mn, Ni and Ti have slightly lower concentrations than the unaltered Ben Lair Hornblende Schist.

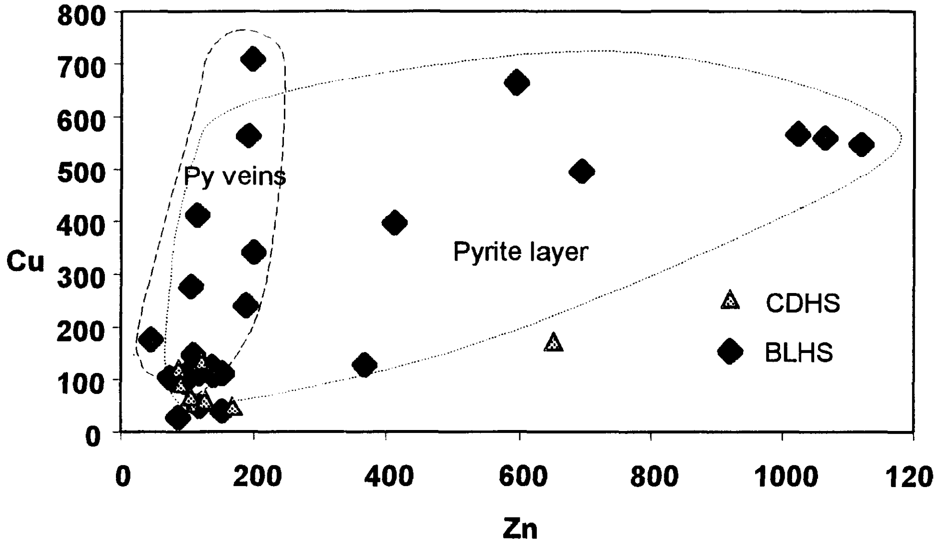

Figure 11 Cu vs Zn variation in Ben Lair (BLHS) and Creag Dharaich Hornblende Schists (CDHS). The fields for the pyrite layer and pyritic veins are shown by the broken lines.

Exhalite bands

Two narrow bands containing meta-exhalative and sedimentary lithologies are present near the tectonically upper part of the Ben Lair Hornblende Schist (Figure 4). These were mapped by Peach et al. (1907) and marked schematically on the published 1:63360 geological map. The Lower (northern) exhalite band (Ex1 on Figure 4) is composed of the following lithologies: quartz-magnetite schist, quartz ± biotite schist, garnetiferous metaquartzite and garnet-amphibole-magnetite schists. The typical thickness of the band is about 3 m but, in places such as near Loch Garbhaig, it reaches 7 m thick. The band can be traced along strike for 6 km, some 2 km further north-west than shown on the original geological map. The magnetic susceptibility of these rocks is easily distinguished in the field with the use of a kappameter, and the outcrop of the band was mapped largely using this instrument. Magnetic susceptibilities vary markedly between adjacent bands and some of the black, glassy-looking quartz schists give readings between <1 to >500 $\times 10^{-3}$ SI depending on the magnetite content. The Upper exhalite band is mainly composed of dark grey graphitic schists and with lesser quantities of the lithologies described above. It extends for about 4.5 km westwards from Loch Garbhaig.

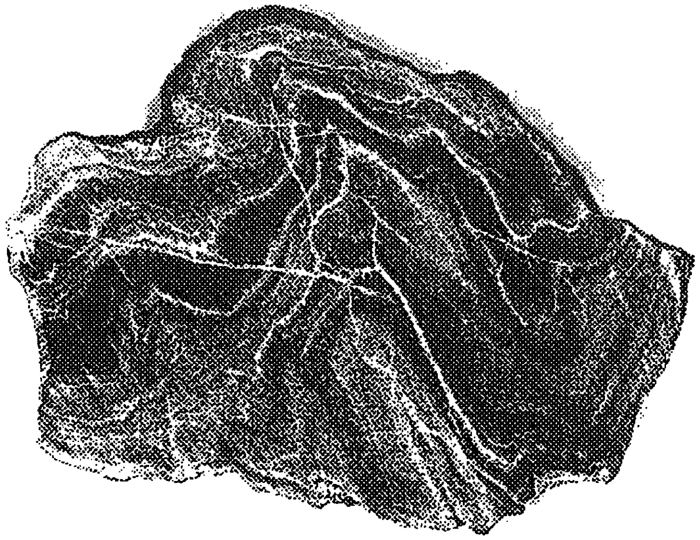

Figure 12 Banded quartz-magnetite rock from the Lower exhalite band, Loch Maree area, showing alternating quartz- and magnetite-rich bands. Specimen is 13 cm across.

Microscopic examination of seven thin sections from the Lower band show that quartz and magnetite/hematite are ubiquitous, and garnet, pale amphibole and biotite are present in most samples in varying proportions, even in rocks showing alternating dark black and white banding of a typical banded iron formation (Figure 12). The garnetiferous metaquartzite is a salmon-pink coloured rock and is a typical example of a 'coticule' (Kennan, 1986). Detailed microprobe anaysis of the garnet in one quartz-magnetite schist sample (KLR 4627) shows it to be a ferroan spessartine ($Pyr_4Alm_{35}Spess_{47}Gro_{10}And_4$). The accompanying amphibole is either grunerite or cummingtonite, (grunerite is the iron-rich end member of the cummingtonite series).

The exhalite bands vary quite widely in composition. The Lower band is mainly composed of lithologies such as quartz-magnetite schists and garnetiferous quartzites (coticules) which have an exhalative origin, whereas the Upper band also contains rocks of sedimentary origin. Iron, the most distinctive element of the exhalites, varies widely from <1 to >30% Fe. The quartz-magnetite schists vary widely from essentially low-Fe quartz schists (metamorphosed cherts) to ironstones containing c. 25% Fe. The rocks are mineralogically complex, and the sample with the highest Fe content (KLR 4469 with 34% Fe) contains garnet, amphibole and magnetite.

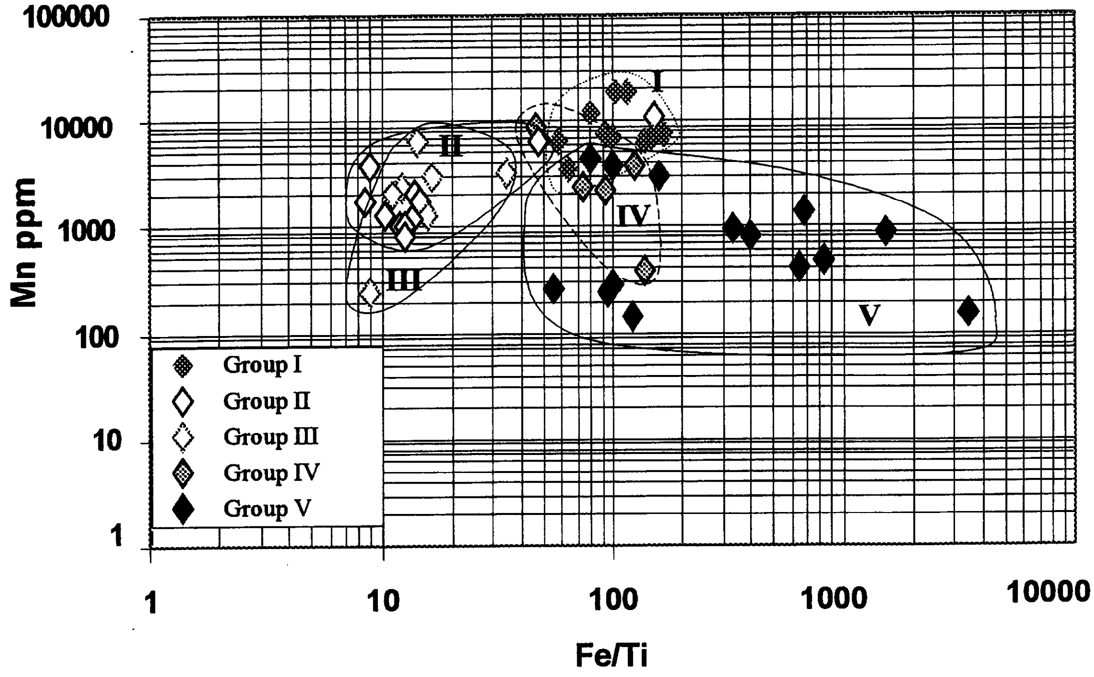

Figure 13 Fe/Ti vs Mn plot for exhalite bands from Loch Maree. Groups I-V derived by cluster analysis of the chemical data.

Inter-element relationships show significant positive correlations between Ba, Ca, Ni, Sr, Ti, V, and Zn (Table 8). Iron is normally correlated with this group in sedimentary rocks but behaves independently in this dataset. Closer examination of the chemical data using cluster analysis (FASTCLUS procedure, SAS, 1985) enables five groupings to be identified (labelled I–V on Figures 13 and 14).

The easiest group to separate is the metasediments (Group III), which occur mainly in the Upper band, and were described in the field as graphitic schist and garnet-mica schist. Their range of composition is usually small and on all the bivariate plots they form a coherent group without outliers. For example, on the Fe/Ti vs Mn plot (Figure 13) the Fe/Ti ratio varies between 9 and 17, and Mn between 240 and 6220 ppm. Similarly, Fe varies in the range 5–10%, Ca 0.4–1.6%, Cr 150–300 ppm.

Another coherent group (Group II) is composed of garnet-amphibole-magnetite and garnetiferous schists. These are found in close association with the quartz-magnetite schists and garnetiferous quartzites in the Lower band, most notably near Allt na Ciad Eilig at [199640 871030]. Rocks of this group overlap the metasediments on the Fe/Ti vs Mn plot, but are distinguished by having higher Ca values (1.4–4.2%). On the Ca vs Ti plot (Figure 14) this overlap can been seen and the group of four samples (KLR 4516, 4602, 4605, and 4650) with high Ti values c. 1% Ti are easily identified. The range of composition is typical of metabasic rocks and the group probably represents metamorphosed pyroclastics. The igneous and sedimentary groups overlap, and some rocks which were described in the field as graphitic schists may be meta-igneous in origin (for example, KLR 4607 which on petrographic study was shown to be a pyritic biotite-amphibole schist).

Table 8 Spearman correlation coefficients for exhalite band samples (N = 51, $r_{99} = 0.36$)

	As	Au	Ba	Ca	Cr	Cu	Fe	Mn	Ni	Pb	Sb	Sr	Ti	V	Zn
As	1	-0.01	0.34	-0.03	0.07	0.24	0.19	-0.01	0.44	0.43	0.11	0.20	0.45	0.34	0.25
Au		1	-0.30	-0.22	-0.03	0.19	-0.33	0.13	-0.21	0.16	0.04	-0.35	-0.24	-0.30	-0.23
Ba			1	0.36	-0.20	0.34	0.26	0.33	0.68	0.52	-0.21	0.70	0.78	0.70	0.65
Ca				1	-0.36	-0.06	0.04	0.18	0.31	0.02	-0.01	0.66	0.45	0.50	0.61
Cr					1	-0.12	0.01	-0.28	-0.01	-0.16	0.09	-0.28	-0.19	-0.15	-0.21
Cu						1	-0.16	0.36	0.50	0.52	-0.11	0.10	0.37	0.31	0.32
Fe							1	-0.16	0.14	-0.16	-0.05	0.34	0.32	0.26	0.19
Mn								1	0.18	0.45	-0.29	0.03	0.33	0.17	0.24
Ni									1	0.48	-0.17	0.55	0.65	0.70	0.74
Pb										1	-0.19	0.23	0.48	0.25	0.39
Sb											1	0.01	-0.33	-0.26	-0.07
Sr												1	0.59	0.72	0.71
Ti													1	0.79	0.70
V														1	0.77
Zn															1

Group V contains the largest number of samples and these are dominantly banded quartz-magnetite and quartz schists. These typically have fine, mm-scale bands, which exhibit delicate folding. Their magnetic susceptibility varies in the range <1 to 500 x 10^{-3} SI, and their Fe content also varies widely from 1 to 25%. On the Fe/Ti vs Mn plot (Figure 13) this group occupies a broad area of relatively normal Mn values in the range 100–400 ppm Mn and a wide range of Fe/Ti values, indicating increasing enrichment in Fe without Ti. This is seen in the Fe vs Ti plot (not shown) where the Ti content is less than 2000 ppm (lower than other groups) but the Fe varies from 1 to 25%. Other characteristics of this group are lack of a positive correlation between Ca and Ti (Figure 14), high Cr relative to Fe and low Sr and Ba.

One sample of quartz-magnetite schist (KLR 4600) from [197550 872120] contains 740 ppb Au, which is the highest value from the Loch Maree area and only exceeded by one sample from the Flowerdale area. Sample KLR 4600 also contains the highest Ca content (7%), but there is a negative correlation between Ca and Au in other samples of the exhalite bands. Most of the other elements in this sample are at levels typical of the quartz-magnetite schists. The exact correlation of this quartz-magnetite schist with the Lower exhalite band is not clear, as the outcrop is isolated from the mapped position of the band. It may be a folded repetition or an entirely separate band.

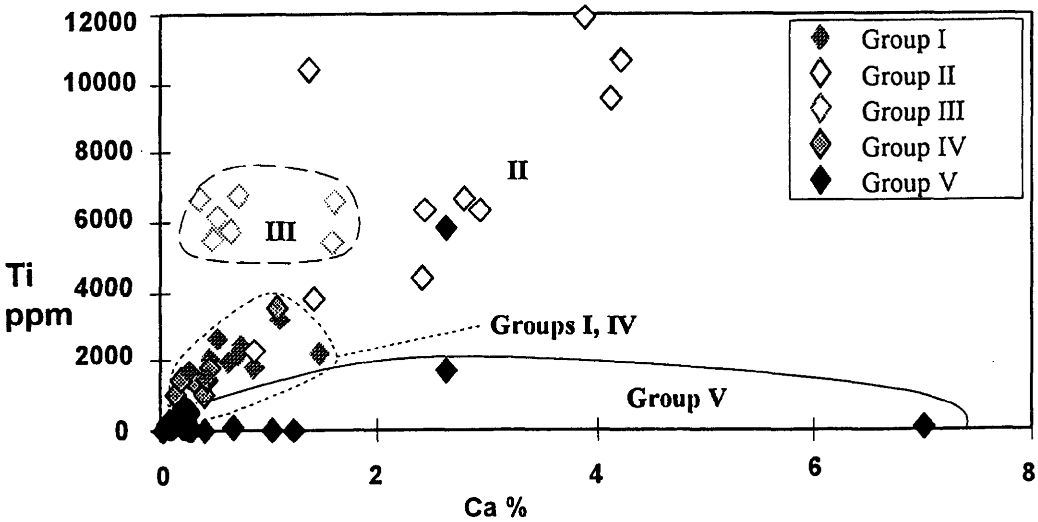

Figure 14 Ca vs Ti plot for exhalite bands from Loch Maree. Groups I-V derived by cluster analysis of the chemical data.

Group I samples have higher levels of Mn than the other groups (0.6–7% Mn) and this is shown on the Fe/Ti vs Mn plot. Iron is also high in these samples, at 10–25% Fe. Both Ca (<1.5%) and Ti (<0.4%) are lower than Groups II and III indicating that sedimentary and igneous input was low to these rocks. The Fe/Ti ratio ranges from 100–3000 in this Group which is typical of modern sea floor metalliferous sediements (Wonder et al., 1988). The rocks in Group I are also enriched in Ba (100–400 ppm) relative to Sr, which is a common feature in Mn deposits.

Group IV samples (KLR 4515, 4517, 4518, 4519 and 4521) all come from the Lower band in a restricted part of the area north of Loch Garbhaig, from [199285 871600] to [199899 870915]. All the samples contain pyrite (5–10% estimated in the field) and are quartz-magnetite schists or garnet-quartz schists. Chemically this group has enhanced levels of Cu (200–700 ppm), Cr (200–400 ppm), Fe and Fe/Ti, but most of the other elements have values similar to Groups I and V. This Group is probably a sulphide-bearing facies of the Group V quartz-magnetite schists.

The chemistry of the exhalite bands shows that they contain both sedimentary and igneous components, but their major distinguishing feature is the abundance of Fe and Mn-rich variants. These rocks show many features typical of exhalative or chemical sediments; fine alternations of contrasting composition, juxtaposition of quartz-, Fe- and Mn-rich rocks, and low contents of elements typical of terrigenous sediments, Ba, Ni, Pb, Sr, Ti, V and Zn.

Correlation with exhalite bands in the Loch Maree Group at Gairloch is not easy, as all the quartz-magnetite schists mapped at Gairloch by Jones et al. (1987) occur above the Flowerdale schists, at the margins of or within the Kerrysdale basite group, not within the Aundrary Basite(equivalent to the Ben Lair Hornblende Schist) which is tectonically lower in the succession. An alternative explanation is that the exhalite bands are the oxide facies equivalent of the stratiform pyritic band in the Ben Lair Hornblende Schist, which can be correlated with the Sidhean Mor stratiform sulphides (Jones at al., 1987).

Beinn Airigh Charr and Furnace Mica Schists

Five samples were collected from the Beinn Airigh Charr Mica Schist (BACMS), 17 of the Rusty Mica Schist (RMS) and 4 of the Inishglass Mica Schist (IMS). No samples were taken from the Interbanded Schist (Figure 4). The median chemical compositions of the different schist bands, including those of the schists associated with the Strathanmore Marble (SM), are given in Table 6.

The RMS samples show trends typical of normal pelitic sediments, for example on the Fe vs Ti plot (Figure 15) and Fe vs Mn (Figure 16). Compared to the average shale (Taylor and MacLennan, 1985) the RMS has low levels of Ba, Sr and Pb and high levels of Ca, Cr, Cu, V, and Zn. This chemistry is a reflection of their generally calcareous and pyritic nature and the lower level of elements associated with clay minerals and detrital feldspar. The samples with the highest Ca contents are hornblende-schists, and mineralogical examination of KLR 4632 shows the rock to be a banded pyritic hornblende-andesine-quartz schist (Fortey, 1993). The amphibole was identified as actinolite to actinolitic hornblende in composition, and the precursor rock may have been an impure, ferruginous dolomitic mudrock or, possibly, a tuffaceous sediment. Examination of the Ti vs Ni and Cr diagrams, however, shows that all the samples plot within the pelite field of Leake (1964). Interbanded with the hornblende-bearing schists are more psammitic rocks, quartz, biotite and lesser graphitic mica schists and these rocks represent more silt and clay-rich beds. The observed wide variation in chemistry is the result of sampling this variety of interbedded lithologies.

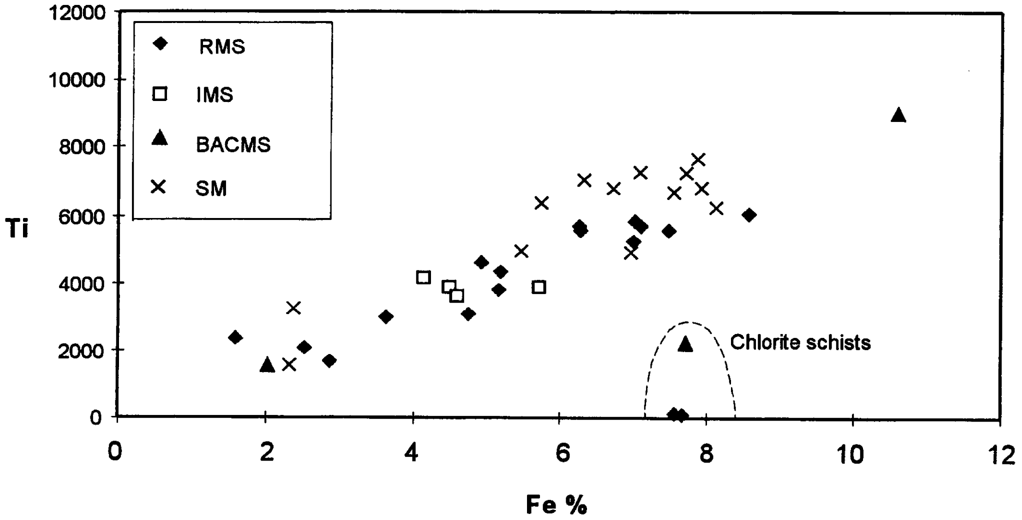

Figure 15 Fe vs Ti plot for metasediments from the Loch Maree area. (SM=Strathanmore Marble schists, BACMS=Beinn Airigh Charr Mica Schist, IMS= Inishglass Mica Schist, RMS=Rusty Mica Schist).

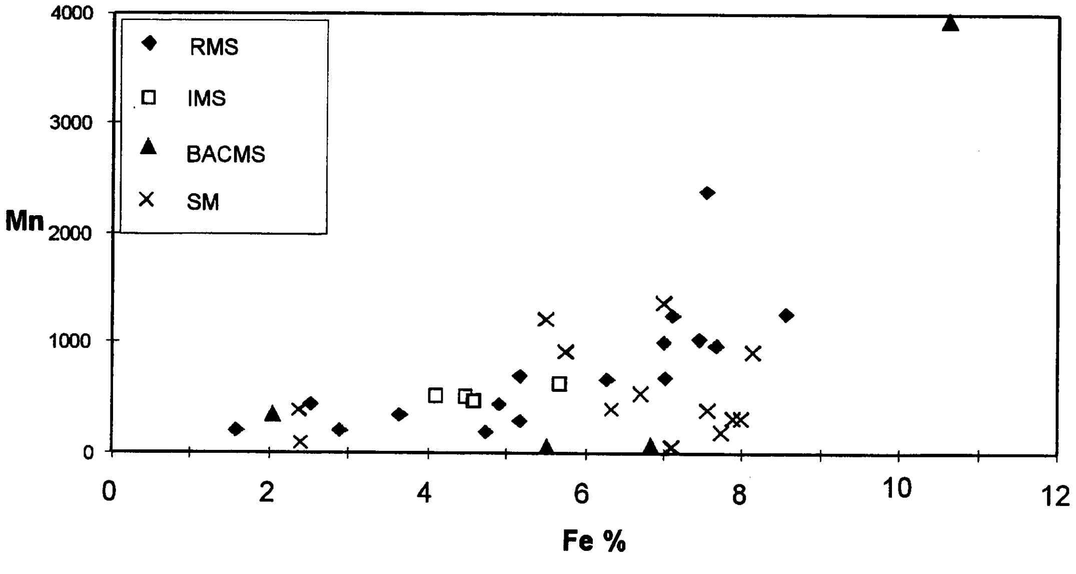

Figure 16 Fe vs Mn plot for metasediments from the Loch Maree area. Symbols as in Figure 15.

The Beinn Airigh Charr Mica Schist samples (BACMS) generally plot within the large field of the RMS on bivariate element plots (Figures 15 and 16) but there are two samples (KLR 4451 and 4649), which plot outside these fields. KLR 4451 from [193960 874990] is a garnetiferous quartzite which has high Ti (0.9%), Fe (10.58%) and Mn (3940 ppm). Other elements, such as Ba and Ca, are present in fairly usual levels. Plotting on a Fe/Ti vs Mn diagram (not shown) that the sample falls within the metasediment field and does not contain a significantly higher concentration of Fe or Mn relative to Ti. The rock is thus a metamorphosed Fe-Mn-Ti-rich sediment and not a chemical exhalite. The other sample, KLR 4649 from [195520 872980], is a chlorite schist and closely resembles quartz-chlorite schists, KLR 4512 and 4513, from the RMS at [196285 870710]. These samples have high levels of Ca, Fe, and Mn, but low levels of Ti, V, Ba, Sr. This is best illustrated by the Fe vs Ti plot (Figure 15), where the three samples form a small group below the main trend. The high Ni and Cr in sample KLR 4649 indicate some ultramafic parentage. Chlorite schists are recorded from the Gairloch area (Jones et al., 1987) and the compositions are compared in Table 9. Whilst the chemistry is not identical, the Gairloch rocks do plot in the same areas on the bivariate element plots (e.g. Ca vs Sr) and their orgin must be similar. The chlorite schist is an important component of the footwall to the Kerry Road sulphide deposit and may represent the hydrothermally altered zone beneath the deposit (Jones et al., op. cit.). At Loch Maree, these samples are located near to major thrust zones such as that near Abhainn na Fuirneis [196285 870710], where the Letterewe Gneiss is thrust against a thin slice of RMS. The importance of these chlorite schists was not recognised during the field investigations, and further exploration in the Loch Maree area should concentrate in more detail on these rocks and their stratigraphic horizon. The main sulphide orebody at Kerry Road is strongly deformed and the focus of an extensive shear/thrust zone. Perhaps similar thrusting has removed the surface expression of sulphide mineralisation at Loch Maree.

Table 9 Comparison of chlorite schist analyses from the Loch Maree and Gairloch areas

	Loch Maree (this study)			Gairloch (Jones et al., 1987)		
	KLR 4512	KLR 4513	KLR 4649	5	6	7
Ba	18	18	24			
Ca%	2.18	7.35	5.25	1.25	2.00	5.00
Cr	54	155	1802	78	40	75
Cu	11	168	37	121	10	57
Fe%	7.66	7.55	7.71	11.55	11.20	8.76
Mn	980	2380	1370	1780	2170	1160
Ni	5	67	600			
Pb	2	11	0			
Sb	0	0	3			
Sr	5	12	15	30	30	59
Ti	100	130	2240	3297	5995	3357
V	21	21	160			
Zn	171	194	68	186	310	60

Note: All values in ppm except where indicated

Inishglass Mica Schist

The Inishglass Mica Schist (IMS) is a pale-grey siliceous mica schist (Fernandez, 1987, Peach et al., 1907) which is relatively uniform in appearance and is similarly so in its chemistry. On all the bivariate plots (e.g. Figures 15 and 16) it occupies a very restricted field with a very small range for the major elements Ca, Fe, Mn and Ti. Some of the trace elements are more variable and, for example, Sr varies between 100 and 250 ppm, a higher range than the RMS. High Sr is a feature of the Basement Gneiss (Winchester et al., 1980), which may have been a contributor to this sediment. The precursor of the IMS was an impure sandstone, perhaps turbiditic and rapidly deposited as beds of uniform composition.

Creag Dharaich Hornblende Schist

The median composition of the Creag Dharaich Hornblende Schist is given in Table 7, and it can be seen that compared to the BLHS the CDHS has higher values of Ba, Fe and Pb and lower values of Ca, Cr, Ti and V. However, detailed examination of the data shows that Ba, Pb and Sr are enriched in samples which are mylonised and silicified, and a similar process of enrichment of these elements must have taken place as in the mylonised samples of the BLHS. Examination of the Ti - V variation indicates that Ti is slightly lower but V is significantly lower in the CDHS. Fe and Cr are negatively correlated in the CDHS, indicating high-level fractionation of olivine and spinel, leading to Fe enrichment and Cr depletion in the more differentiated samples. This is in contrast to the more uniform composition of the much thicker BLHS. Despite pyrite being recorded in many samples of the CDHS, up to a maximum of 10%, there is no indication of base-metal or gold enrichment, either in veins or in stratiform bands.

Letterewe Marble

Detailed descriptions of the marble can be found in Peach et al., (1907, 1913). Five samples were collected from the Letterewe Marble band during this study. The Ca content varies from 21 to 32%, a range typical of Lewisian dolostones (median 22% Ca) and marbles (median 33% Ca) (Rock, 1987). The median content of trace elements again is lower than most Lewisian dolostones (Figure 6) indicating that there was little pelitic or igneous input into the original carbonate rock. This is in contrast to the Gairloch area where Rock (op. cit.) states that the Flowerdale marble belt shows not only higher metallic trace elements but also higher contents of Rb, Sr, Y Zr and Ba. One Letterewe Marble sample (KLR 4640) has 5775 ppm Sr, which is exceptionally high for an Archaean marble and exceeds even the normally higher values for Dalradian marbles (Rock 1983). One of Rock's samples from 'Allt Folais' contains 10620 ppm Ba, and must have contained baryte, but none of the samples collected in this study show a similar feature. The Letterewe Marble is therefore composed of relatively pure dolostone and limestone with lower than average content of trace elements.

Letterewe Gneiss

The Letterewe Gneiss is composed of coarse quartz-feldspar gneisses containing bands of amphibolite, which, as previously discussed, were originally Scourian dykes. The Kerry Road mineralisation is hosted by the supracrustal Loch Maree Group so that the Letterewe Gneiss is not a highly prospective host for mineralisation. However, on the original 1:10560 geological field slips magnetite-rich rocks are marked at one location in Allt na Leth Chreige at [197070 870965]. These are not described in the Survey memoirs (Peach et al., 1907, 1913), although the magnetite is considerably coarser grained and in greater abundance than in the quartz-magnetite schists, which were described. There is also evidence of old workings and it is likely that the outcrop was trialled for the nearby Furnace iron smelter. The location of this smelter was probably chosen in the seventeenth century for the ready availability of wood along the shores of Loch Maree, limestone and also water from the Abhainn na Fuirneis.

The rocks exposed along the Allt na Leth Chreige are mainly grey and pink quartz-feldspar gneiss with bands of amphibolite between 0.2 and 1.0 m thick occurring every 5–10 m. At [196990 870950] a coarse amphibolite band, c. 6 m thick (KLR 4566) contains a cm-scale, semi-massive magnetite band accompanied by pyrite. Most of the rock is composed of green hornblende, magnetite, pyrite and accessory chalcopyrite and hematite (Fortey, 1993). The Fe content of this rock is 19.7% and the magnetic susceptibility ranges from 30–400 x 10^{-3} SI.

Further upstream, at [197070 870965], a 1 m thick band of massive amphibolite (KLR 4572 and 4574) occurs next to a 1.0–1.6 m band of coarse tremolite-chlorite schist containing coarse granular magnetite (KLR 4568 and 4573). Layers within this schist are more magnetite-rich and a 0.2–1.1 m thick pod of magnetite-rock (KLR 4569, 4570 and 4571) occurs just upstream. Above the magnetite rock a further >1 m thick unit of tremolite-carbonate-magnetite schist is seen. A number of short magnetometer and SP traverses were surveyed across the magnetite rock but it could not be traced for more than 10 m either side of the outcrops in the stream. Thin section examination of the magnetite rock showed it to be dominantly magnetite with lesser quantities (30–40%) of chlorite, carbonate and muscovite with minor pyrite, hematite and trace chalcopyrite. The Fe content of these rocks ranges from 3–9% in the tremolite schists up to 58% in the magnetite rock. The magnetite rock contains variable levels of sulphide interstitial to the coarse magnetite, and one sample has 0.47% Cu, which is probably contained in chalcopyrite.

The Letterewe Gneiss has a very restricted range of Fe/Ti values (10–20), but a wide range of Mn levels from 100–1500 ppm. In the amphibolite bands the Fe/Ti ratio varies in the range 15–60 and this increases through the actinolite schists (40–200) to the magnetite rocks with up to 1000. Throughout this sequence the Mn content is relatively constant from 400 ppm to 1300 ppm. This indicates that hydrogenous processes which involve the separation of Mn from Fe by their differing oxidation potential, have not taken place. There is also a broad correlation between Fe and Au, Cu, Ni and V (Spearman coefficients r = +0.72, 0.72, 0.87 and 0.79 respectively). Cr is negatively correlated with Fe (r = -0.53) indicating that the process of Fe enrichment was a relatively late stage igneous or skarn type mineralisation, not an early magmatic chrome-spinel accumulation. The former conclusion is supported by the relatively high Ca content of some of the tremolite schists (reaching 8.1% Ca in KLR 4573). The chalcophile elements Cu and Ni are highest in sample KLR 4731, with 4731 ppm Cu and 108 ppm Ni, but KLR 4569 has the highest Au of 35 ppb.

Table 10 Comparison between the median compositions of the amphibolites in the Letterewe Gneiss, Scourie and Tollie dykes, and the Ben Lair Hornblende Schist

Median	Amphibolite dykes in Letterewe Gneiss (this study)	Scourie dolerite dykes (Weaver and Tarney, 1981)	Tollie dykes (Johnson et al. 1987)	Ben Lair Hornblende Schist (this study)
No. of samples	4	7	7	13
Ba	196	261	179	98
Ca	51400	62500	62200	48500
Cr	78.5	67	94	128
Cu	30.5	–	20	116
Fe	89700	104500	107500	93300
Mn	1355	1626	1626	1600
Ni	28	41	87	50
Pb	5.5	–	0.4	6
Sr	199.5	167	207	108
Ti	5045	13010	8810	5750
V	247	–	342	273
Zn	124	117	114	119

Notes: All elements in ppm. – = absent data

Similar magnetite-rich rocks have not been recorded elsewhere in the Lewisian, and it is possible that a basic dyke was intruded (the coarse amphibolites closely resemble Scourie dykes in other areas) in a marble horizon. The magnetite-rich rocks could therefore be a metasomatic skarn rather than an igneous accumulation. Such skarns typically have minor sulphides associated with them, as in these rocks. Low Cr levels indicate that the protolith was not a carbonated ultramafic rock. Comparison between the composition of the amphibolites in the Letterewe Gneiss with Scourian dolerite dykes (Weaver and Tarney, 1981) and similar dykes from Tollie (Johnson et al., 1987) shows them to have very similar Ba and Sr levels, and much higher then the median for the BLHS (Table 10). Similarly low levels of Cr and Cu are distinctive features of the Scourie dykes.

Mineralised veins

A number of small mineralised veins are found cutting rocks in the Loch Maree area and two of these, near Loch Garbhaig [199590 871020] and north-north east of Letterewe House [195905 872440], are mentioned by Wilson and Flett (1921), after Peach et al. (1913). The pyrite-bearing veins within the BLHS have been described earlier, but the veins discussed here are all coarse-grained, carbonate veins carrying pyrite and base-metal sulphides. The veins are narrow, most being only 10–20 cm in width, and normally occupy breccia zones within north-easterly trending faults. These faults and an associated north-north-east set can be seen on the published 1:63360 geological map, and are also followed by many of the streams draining south-west into Loch Maree. One of the veins on the shore of Loch Maree at [193360 872680] was worked as a 'gold mine' according to local legend, but this locality is strangely omitted from the Wilson and Flett compilation (1921) even though marked on the 6-inch field sheet. The Geological Survey field sheets record "Level driven in 7–8 yds along Ca strings usual hade S average direct WSW or so", but at present only a small trial excavation is visible driven about 1 m into the rock face. The carbonate strings are about 15–20 cm thick and contain galena, sphalerite and chalcopyrite. Base-metal contents are low, ranging up to 0.19% Pb, 0.03% Zn and 0.08% Cu. The Au content is only 1–2 ppb. It is likely that the trial was for base metals, or perhaps silver, rather than gold. Other small discordant veins in the Loch Maree succession are of similar mineralogy and locally exceed 1 m in width at the Loch Garbhaig locality [199590 871020], with 1% Pb, 1% Zn and 0.7% Cu in a grab sample (KLR 4466).

One other vein sample is worthy of mention, KLR 4537 from [198758 871420]. The narrow 2 cm vein is very weathered and only altered material could be collected. Thin section examination (Fortey, 1993) could only identify pyrite as a primary opaque mineral. The sample contains 1356 ppm Ag, 3989 ppm As, 1.33% Cu, 1849 ppm Ni, 9.25% Pb, 142 ppm Sb, 3199 ppm U and 2031 ppm Zn. Whilst these grades are enhanced by secondary weathering, they demonstrate the polymetallic nature of the mineralisation. However, the Au content is only 1 ppb and there is no evidence therefore for hydrothermal concentration of Au in these late cross-cutting veins. The age of the mineralisation is unknown but the fault zones may be related to movement along the Loch Maree fault or Mesozoic extension parallel to the Minch fault (Figure 1).

The mineralised veins are of little economic importance and show no signs of gold enrichment. There is little evidence for epigenetic upgrading of gold from slightly higher background levels within the exhalite bands and supracrustals into the later cross-cutting veins. The 'gold' trial on the shores of Loch Maree may have been an attempt to locate gold with the base-metal sulphides but was clearly abortive.

Geophysics

Mineralised horizons in the Loch Maree Group at Gairloch provide a strong geophysical response (Bowker and Hill, 1987), with techniques such as detailed magnetic, VLF and self potential (SP). Similar geophysical responses might be expected over mineralised outcrops of the group to the north of Loch Maree (Figure 4). Because of the known association of mineralisation with magnetic lithologies, and because of time constraints and the nature of the terrain north of Loch Maree, it was decided to concentrate on reconnaissance surveying of the total magnetic field with supplementary VLF observations where appropriate.

Over 20 traverses of total-field magnetic data, with a few lines of VLF data, were surveyed across the Ardlair and Letterewe Forests north of Loch Maree (Figure 17). Data were collected at a nominal separation of 12.5 m along line-of-sight traverses with a general north-east orientation. Paced distances were adjusted to map navigation points. Traverses were concentrated in the region between Furnace and Loch Gharbaig, with other lines north of Letterewe and Ardlair. In this project area the background field is in the region of 49850 nT.

Observed total-field magnetic data (Figure 17) indicate several zones with anomalous fields in excess of 51000 nT, although anomalies were difficult to trace between lines. The most prominent anomaly occurs about 1.5 km north-east of Furnace with anomalous field values above 58000 nT (Figure 18). Susceptibility sampling along the traverses identified several horizons of highly magnetic schists, with local horizons of almost pure magnetite. Other less prominent magnetic anomalies were associated with interbedded amphibolites, with susceptibilities locally up to 30×10^{-3} SI. The massive amphibolite of Ben Lair has a very low bulk susceptibility ($<5 \times 10^{-3}$ SI). The discontinuous zones of exhalites occurring within the main Ben Lair Hornblende Schist have been locally identified by the magnetic and susceptibility sampling between Loch Gharbaig and Meall Mheinnidh.

Detailed magnetic observations over the magnetite-rich bands identified in the exposures of the Alt na Leth Chreige were supplemented by SP and VLF surveys. About 200 m upstream from the path from Letterewe a strong anomaly with amplitudes above 5000 nT was identified on four traverses. However the anomaly is not traceable across lines about 100 m north-west or 150 m south-east of the stream, suggesting that the source is a cross-cutting north-easterly trending feature. The source might be a Scourie-type dyke carrying a high proportion of magnetite. A less significant anomaly sub-parallel to the path can be traced to the south-east and is associated with a magnetic amphibolite layer within the Letterewe Gneiss.

The regional aeromagnetic data (described earlier) suggests some continuity of the Srath Lungard anomaly northwards to the Loch Maree fault with a significant anomaly on one of the easterly flight lines crossing Loch Maree, although non-magnetic Torridonian rocks occur on all the islands of Loch Maree. Two magnetic traverses were surveyed across the loch in the region of Eilean Rhuairidh Mor (Figure 17) to confirm the regional data. One of the profiles shows an anomaly of about 200 nT which can be interpreted by Werner deconvolution techniques to suggest a source depth of about 200 m.

A few of the regional lines were also surveyed using the VLF technique, and significant VLF anomalies (>50% in phase) were observed on a some of these lines (Figure 19). In detail, many of the VLF anomalies are associated with thin bands of mica schist intercalated with the Ben Lair Hornblende Schist, or else minor faults.

Conclusions

Reconnaissance lithogeochemical and geophysical surveys of the Loch Maree Group, on the north side of Loch Maree, have permitted the detailed delineation of extensive exhalative horizons, including both quartz-magnetite schists and coticules. Minor occurrences of stratiform sulphide bodies have also been located in the Ben Lair Hornblende Schist. The presence of enhanced levels of Au (790 ppb) in one sample of quartz-magnetite schist is encouraging, but apart from this sample none of the mineralisation is directly economic. These observations are not surprising as the level of bedrock exposure is so high that directly outcropping mineralisation, like that occurring at the Kerry Road site, should have been recorded by the initial geological survey (Peach et al., 1907). However, the stratigraphy of the Loch Maree area is now better understood and correlated with the Gairloch area,

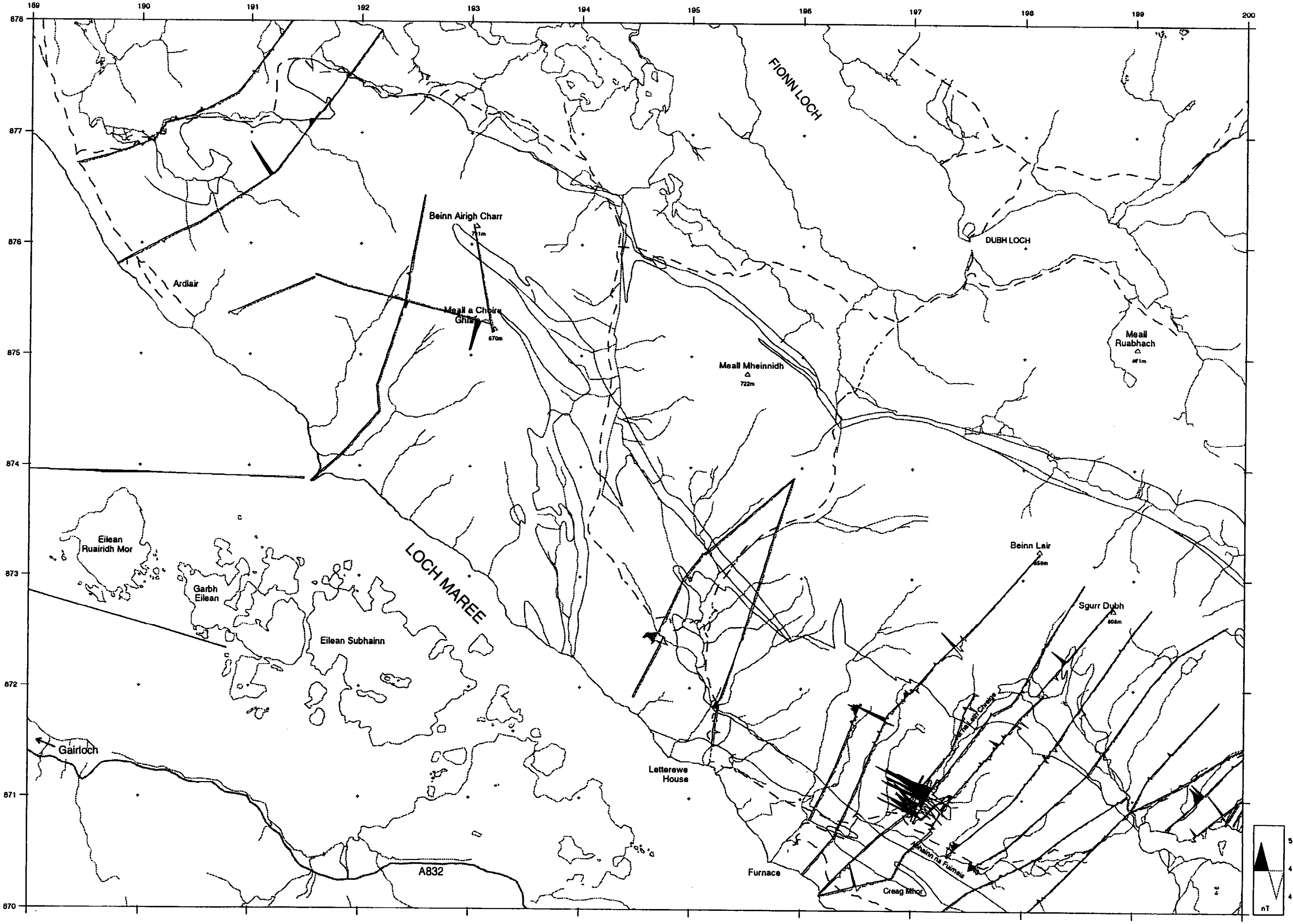

Figure 17 Loch Maree area: ground magnetic data. Total field anomaly relative to a datum of 49850 nT. Geological line work as for Figure 4.

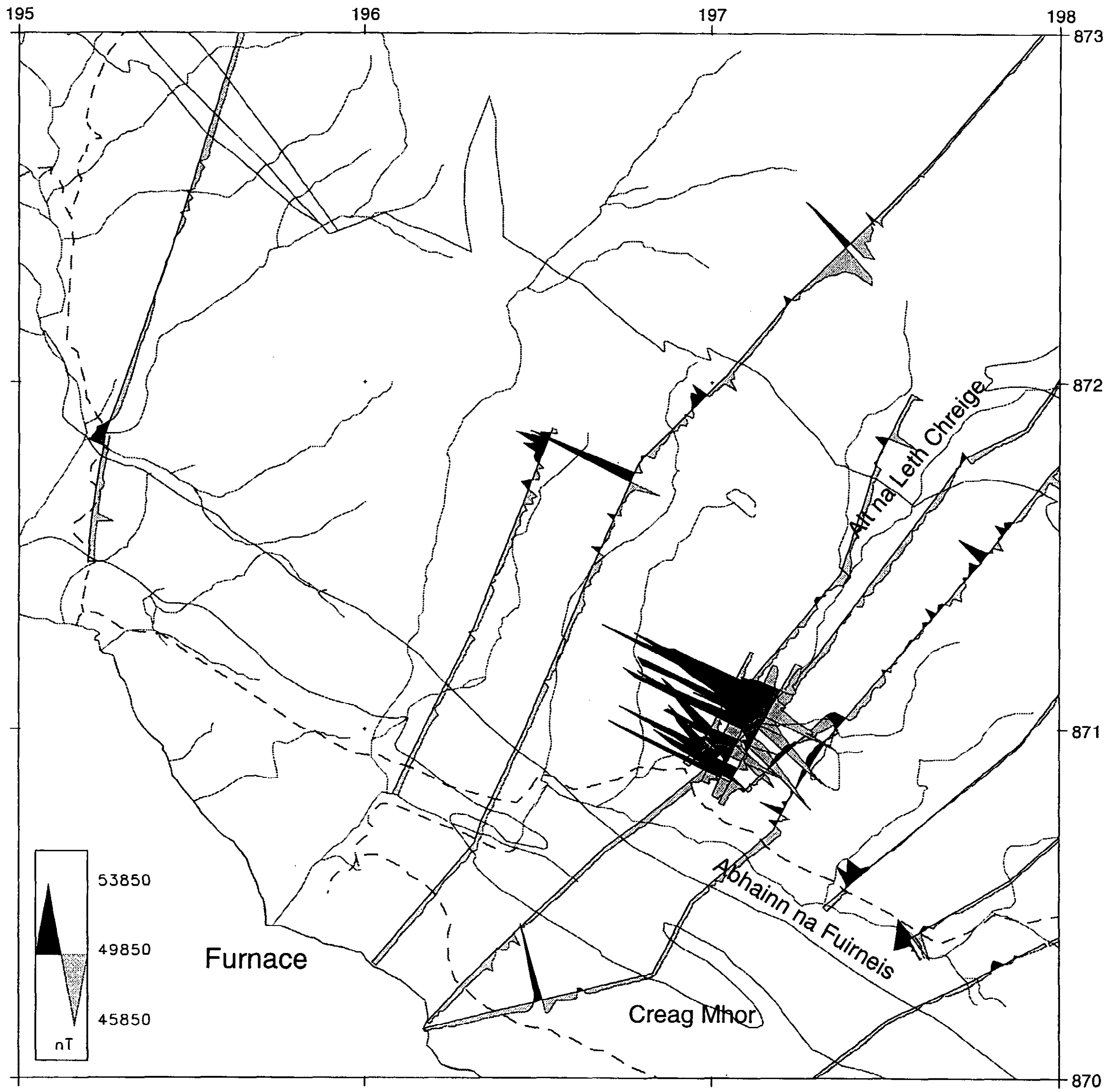

Figure 18 Loch Maree area: ground magnetic data. Detail of the anomaly north-east of Furnace.

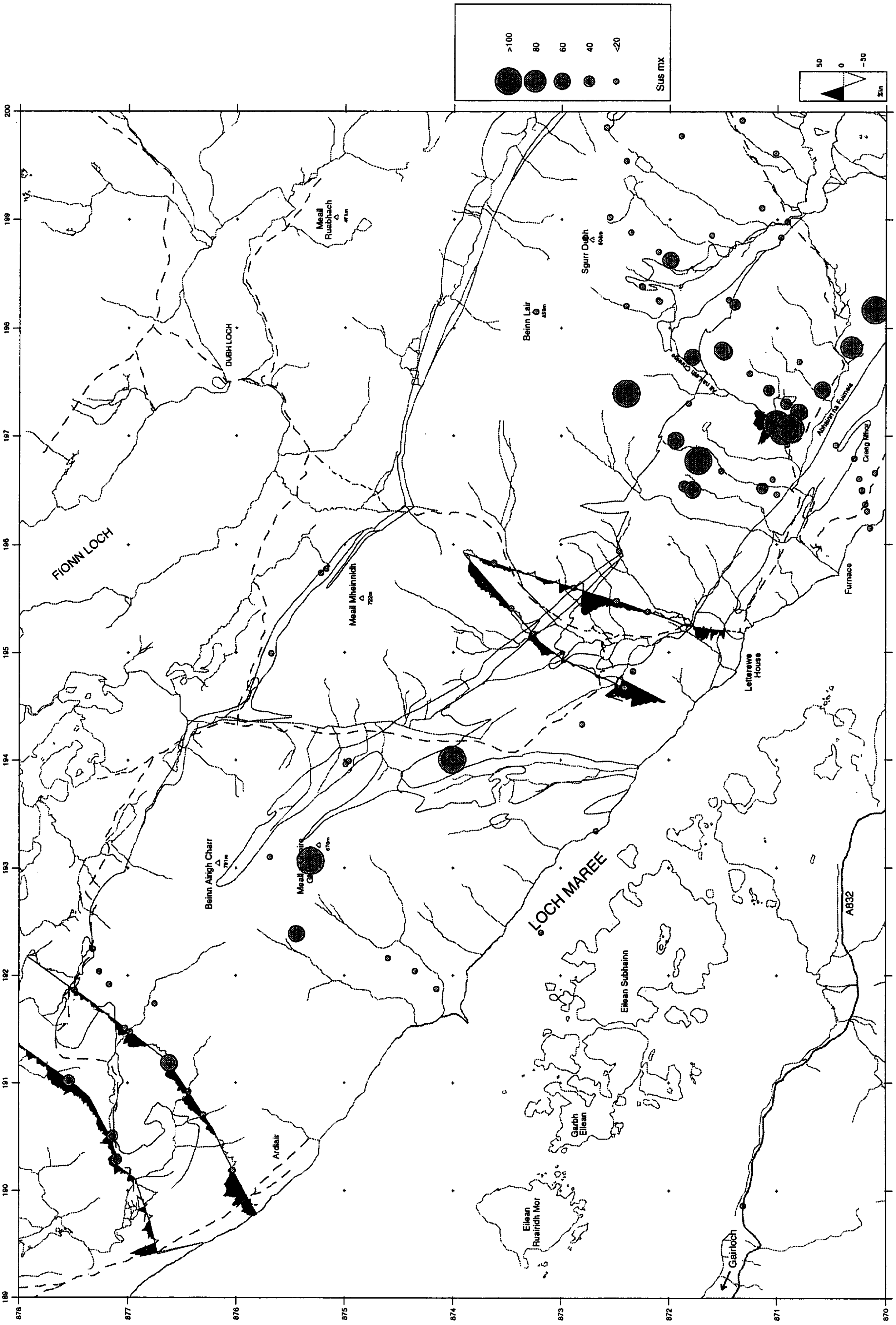

Figure 19 Loch Maree area: ground VLF-M field data. In-phase component of the VLF magnetic field. Scaled symbols are the maximum susceptibility observed at outcrop (x 10^{-3} SI).

enabling further work to be concentrated on the chlorite schists within the Rusty Mica Schist and Creag Dharaich Hornblende Schist.

FLOWERDALE FOREST

Geology

The main Gairloch outcrop of the Loch Maree Group supracrustals terminates just south-east of Dubh Loch [185 869], where Jones et al. (1987) record copper-bearing siliceous pebbles in the locally derived Torridonian basal conglomerate at Allt na Cosaig [185 870] (Figure 20). To the east of this locality, sporadic outcrops of migmatite are found on the Meall Garbhaig ridge [1904 8693], and on the east side of the River Talladale on the western flank of Creag Ghaineamhaich [1928 8684] (shown as CG Inlier on Figure 20). South of this, in the Flowerdale Forest, the Lewisian is increasingly masked by superficial cover in the valley areas, or else overlain by significant thicknesses of Torridonian sandstone, which form impressive, steep-sided hill ridges of 600–800 m elevation. In the lower ground a number of small Lewisian inliers protrude (Figure 20 Area C). The geology and structure of these rocks is described by Elliott (1964).

Within the supracrustal succession, outcrops of hornblende schist are readily identified and form good lithogeochemical markers. They are characterised by a strong north-west deformation fabric. The hornblende schists extend eastwards as far as An Lungard [1914 8638] on the western flanks of the main north-trending Srath Lungard valley, where an extensive, 1 km long exposure of relatively massive hornblende schist with fine streaks of plagioclase, closely resembling the Aundrary Basite and the Ben Lair Hornblende Schist, is situated. The northern part of the Srath Lungard valley is underlain by Torridonian conglomerates, which cover the Basement Gneiss, whereas the central part of the valley is floored by flaggy sandstones of unknown thickness which represent a higher part of the Torridonian succession. The Torridonian sandstones in the vicinity of the An Lungard inlier are relatively coarse grained and probably reflect the basal part of the overlying sequence.

Three further supracrustal inliers are found in the Flowerdale Forest area, namely at Loch na Beinne [1903 8634], north of Loch na Cabhaig [1894 8629] (Figure 21) and on the northern side of Loch a' Bhealaich [1870 8644]. A brief examination of all the inliers was made in 1993 and, following these appraisals, work was concentrated on the Loch na Beinne inlier. The Loch na Beinne inlier comprises a mixed sedimentary, chemical and volcanic facies including quartz-magnetite schists (Table 11), similar to those found around the Kerry Road mineralised locality. The Loch a' Bhealaich inlier comprises a layered mafic-ultramafic suite (actinolite schists) and falls within the mapped basement succession. It is probable that it is part of a dismembered layered intrusive body similar to those found in the Central Lewisian Belt and North Uist. The Loch na Cabhaig inlier is comprised dominantly of massive to weakly foliated olivine-rich ultramafic rocks. Contacts with other rocks at this locality are not exposed and it is not possible to correlate between this and the Loch a' Bhealaich or Loch na Beinne areas.

The Loch na Beinne inlier (Figure 21), is located 1 km south-south-east of the southern end of Loch na Oidche where it is sporadically exposed over an area of approximately 10 hectares. A well-exposed metabasic unit forms the dominant lithology on 'Loch na Beinne Hillock', south of the western end of Gorm Loch na Beinne (Figure 22). This lithology, hereafter known as the Loch na Beinne Hornblende Schist, shows close similarities to the Kerrysdale basite (Jones et al., 1987), and gives median magnetic susceptibility readings of c. 0.55×10^{-3} SI.

Within the Loch na Beinne Hornblende Schist narrow bands of quartz-magnetite schist and weakly magnetic quartz schist occur. They are generally <1.5 m wide but can be traced for tens of metres

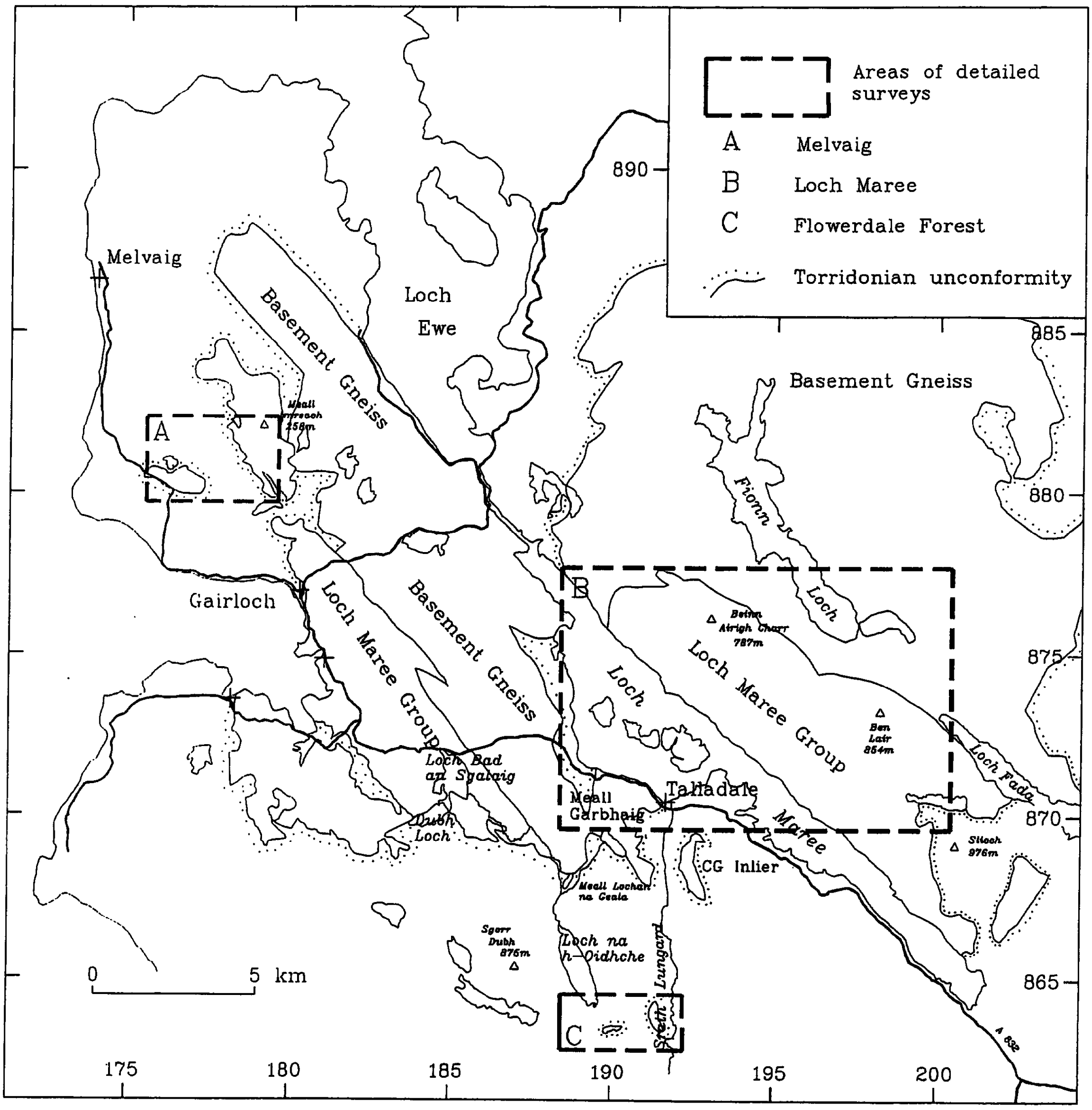

Figure 20 Location map of the Melvaig, Loch Maree and Flowerdale Forest areas.

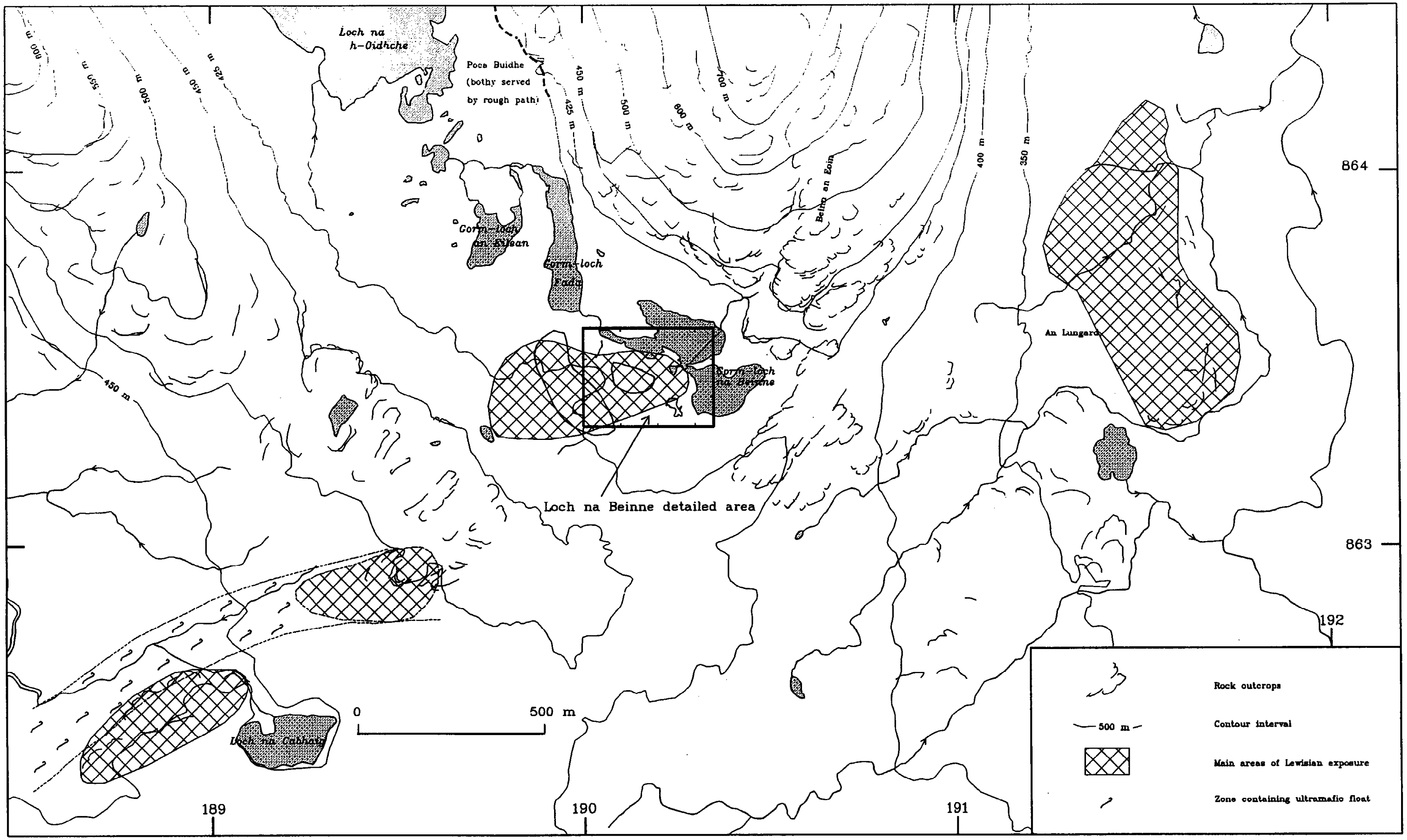

Figure 21 Flowerdale Forest showing location of Loch na Beinne Inlier.

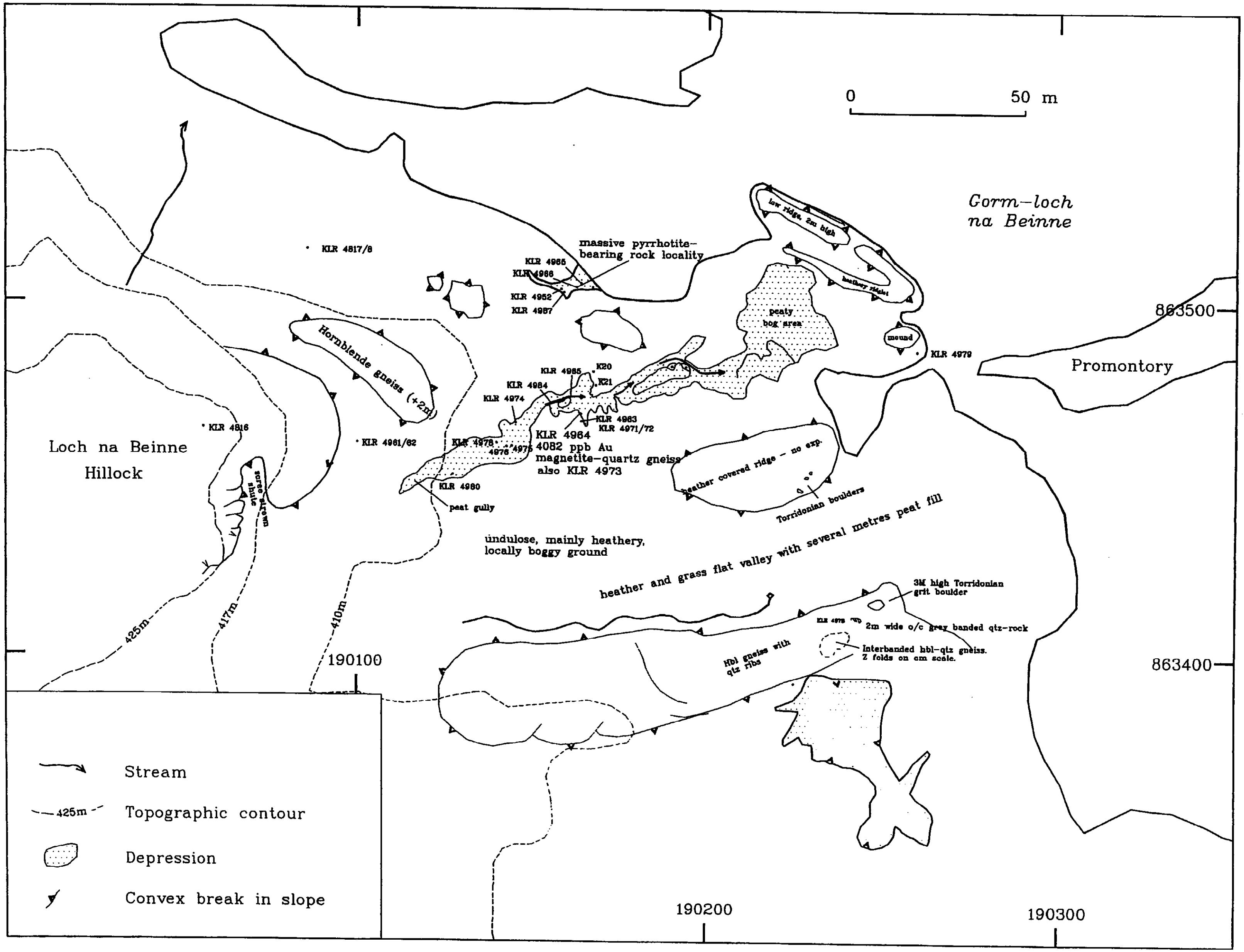

Figure 22 Loch na Beinne area: detailed topography and rock sample locations.

where exposure is good. Boudinaging and folding of the bands is common and they are indistinctly banded on a centimetric scale. Occasional float of similar type occurs in bouldery Torridonian ground approximately 30 m south-west of the conspicuous scree chute on the south side of the hillock [1900 8634], indicating that bands of similar type are concealed beneath the thin cover of till. Susceptibility readings vary markedly within and between these quartz-magnetite units. The bands are occasionally moderately magnetic, for example a 0.5 m thick band at [189845 863405] giving a median value of 65 x 10^{-3} SI. Although similar in appearance the weakly magnetic variants give low susceptibility values, generally in the range 0.1 and >0.5 x 10^{-3} SI.

The Loch na Beinne Hornblende Schist is unconformably overlain to the west and south by shallow-dipping Torridonian grits, although the unconformity is seldom exposed due to the thin covering of peaty soil and vegetation. Approximately 150 m east-south-east of the main exposure a 30 m wide low-lying ridge of c. 2 m maximum elevation provides exposure of the hornblende schist, again interbanded with quartz-magnetite schist. To the north-east of this shallow mounds of bouldery till and extensive peat cover mask the adjacent supracrustals.

To the north of Loch na Beinne Hillock as far as the shore of Gorm Loch na Beinne a variety of unusual clasts are present in poorly exposed ground. These lithologies are mainly located in the main peat hollow and adjacent ground to the north-east of Loch na Beinne hillock (Figure 22). Although exposures of rock in the peat gully appear to be absent, the distribution of clasts of particular type provide an approximate stratigraphy. Manual digging at two localities confirmed the presence of irregular subcrops or possible outcrops of sulphide and oxide-facies exhalites. The positions of these exposures, together with the float mapping, suggest the presence of sulphide facies exhalites immediately south of the loch, with banded oxide facies rocks sandwiched between metasediments to the south-west, obliquely transecting the central part of the gully. Two distinctive elongate outcrops of coarse hornblendite occupy slightly elevated positions immediately west of the gully (Figure 22). Due to the limited amount of exposure in this area it is not possible to determine the contact relations between the metavolcanic and metasedimentary facies.

Within the exhalite zone the dominant lithology comprises micro- to meso-banded quartz-magnetite (oxide-facies) exhalites, with alternating iron and cherty quartz bands generally 1–8 mm in thickness, which exhibit fabrics ranging from planar to tightly folded. The quartz matrix of these rocks is generally fine-grained, although the less deformed variants occasionally display a slightly coarser texture. In oxide-facies rocks, pervasive alteration of the magnetite bands is apparent as persistent reddening, which may the result of Torridonian weathering.

Table 11 Proposed Loch na Beinne succession, west to east

Loch na Beinne Hornblende Schist (interbanded hornblende and felsic schists)
Mica schist
Amphibolite
Quartz-magnetite schist (oxide facies BIF)
Amphibolite
Quartz-magnetite schist
Sulphide facies exhalite

Float mapping of the east side of Gorm Loch na Beinne reveals a range of metasedimentary and exhalative clasts similar to those on the west side of the loch. However, only one subcrop on this side of the lake is of sufficient size to be identifiable as possible subcrop. This large boulder of sulphide-bearing quartz schist (KLR 4981) occurs on the north side of the main promontory, at [190350 863500], (just to the east of Figure 22), and contains the highest level of As of any sample collected (233 ppm) and low enrichment in Au (17 ppb) and Cu (99 ppm). In terms of its high As and sulphide content it is possible that this forms a part of the sulphide facies, as present on the southern shore of the loch, and that therefore sulphide facies rocks also underly all or part of Gorm Loch na Beinne between these two occurrences.

Small float fragments of metasediments stretch as a narrow ribbon east-north-eastwards and upslope to approximately [190600 863600]. Although this elevation is >10 m higher than the main lochside outcrop it is possible that this material might have been glacially transported upslope as a dispersion train from the main mineralised locality. Alternatively, the clasts may be dispersed downslope from an undiscovered occurrence of the Loch na Beinne succession.

Lithogeochemistry

A total of 49 rock samples were collected from the Loch na Beinne area. Representative samples of float material or outcrop, weighing c. 2 kg, were prepared by jaw crushing and tema milling. 12 g sub-samples of milled powder were analysed by XRF on pressed powder pellets by the Analytical Geochemistry Group of BGS for Ca, Fe, Mn, Cr, Ni, V, Ba, Sr, Ti, Cu, Pb and Zn on all samples. Additionally, a small suite of samples were analysed for Ag, As and Sb by XRF and Pt and by fire assay followed by ICP. Separate 30 g splits were submitted for Au analysis to Acme Analytical Pd Laboratories, Vancouver, Canada. Because of the wide variety of lithologies sampled and the relatively small numbers of each, sample statistics are only presented for the Loch na Beinne Hornblende Schist (Table 12).

Table 12 Summary statistics of the Loch na Beinne, Ben Lair and Creag Dharaich Hornblende Schist Units and the Aundrary Basite

	Loch na Beinne HS	Ben Lair HS	Creag Dharaich HS	Aundrary Basite (Jones et al., 1987)
Statistic (No. of samples)	Median (8)	Median (13)	Median (10)	Mean (44)
Au	0.004	0.002	0.002	
Ba	73	98	151	54
Ca	34160	48500	45800	72400
Cr	197	128	120	174
Cu	187	106	81	95
Fe	96450	93300	99350	93900
Mn	1688	1600	1600	1400
Ni	71	50	56	100
Pb	16	6	9	0.6
Sr	75	108	109	134
Ti	7020	5750	5185	6115
V	447	273	236	300
Zn	254	119	115	98

Loch na Beinne Hornblende Schist

Eight samples of this rock type were collected, together with four samples of intercalated quartz-magnetite schist. Median levels of Ca are 3.4% and Fe 9.6%. Compared with the Aundrary Basite and

Ben Lair Hornblende Schist, the Loch na Beinne Hornblende Schist contains slightly higher Ti (median 7020 ppm) and V (447 ppm). The Ti (c. 6000–12000 ppm), and Fe (8.6–17.5%) values fall within narrow ranges and consequently cluster closely on a bivariate plot. Compared with the other hornblende schists, magnetic susceptibility readings are low, with median values from outcrops ranging from 0.3 to 0.4 x 10^{-3} SI, suggesting a greater abundance of ilmenite compared with magnetite in this lithology .

Within a c.10 m wide zone along the northern flank of the hillock the hornblende schist contains up to 10% pyrite occurring as thin, foliation parallel streaks (KLR 44818, 44826). These pyrite-enriched variants contain slightly elevated levels of Fe (12.4 and 17.5%), but otherwise show little difference to the non-sulphidic hornblende schists. However, one of the two samples collected (KLR 44826) was slightly enriched in Au (37 ppb) but not in base metals. Pyrite was the only sulphide observed in these samples at outcrop. Magnetic susceptibility values are slightly higher than in the non-pyritic zone, with a median value of 0.5 x 10^{-3} SI and occasional values over 1.0 x 10^{-3} SI. The pyritic zone dips steeply, striking parallel to the general north-west regional trend, and appears to form the lowest part of the Loch na Beinne Hornblende Schist.

The samples of quartz-magnetite schist from within the hornblende schist showed no significant enrichment in Au or base metals. They are characteristically low in Ti, with values ranging from 84 to 186 ppm. Both Cr (16–65 ppm) and Ni (3–16 ppm) are also markedly lower than in the hornblende schist, indicating that these are essentially exhalative sediments. The rocks lack visible sulphides, and both base metal and Au values are low.

Metasediments

A total of 10 metasediments, largely of float material, were collected from the main peat gully (Figure 22). The lithologies are dominantly mica schists, frequently garnet-bearing. These rocks contain highly variable Ti, with high Ti relative to Fe, resulting in Fe/Ti ratios ranging from 5 to 36. These variations probably represent mixing between the sediments and the local basic volcanics, as suggested by Floyd et al. (1989).

Most of the samples show slight enrichment in Au, with a maximum value of 62 ppb. The metasediments also show slight enrichment in Cu relative to the exhalites, and two samples (KLR 4984 and 44813) contained over 1000 ppm Cu. The highest Au value is from a sample of mica schist float from the main peat gully (KLR 4975), which also contained slightly elevated Cu (300 ppm). A semi-pelitic schist, also from the gully, again shows minor enrichment in Au (19 ppb) and Zn (1153 ppm), but low Cu (58 ppm) and Pb (19 ppm).

As enrichment occurs in all metasedimentary and exhalative lithologies present, with background enrichment within the range 10–20 ppm and a maximum value of 233 ppm. This suggests a close association between As and Au, with samples containing the highest levels of Au (> 50 ppb) all containing elevated As.

Exhalites

The range of exhalites sampled include massive oxide and sulphide facies rocks and interbanded silicate/oxide facies. Their general composition is closely comparable with exhalites from the Loch Maree area, with low levels of those elements associated with terrigenous sediments, Ba, Ni, Pb, Sr, Ti, V and Zn. However, a small number of both silicate (Fe-garnet, Fe-hornblende) and magnetite-bearing rocks contain elevated V and Ti levels, suggesting possibly that these are hybrids containing volcaniclastic debris.

The six main groups can be distinguished on the Fe/Ti vs Mn diagram (Figure 23). Quartz-magnetite schists (QMS) have high Fe/Ti ratios and Mn values are associated with oxide facies rocks, with

>25% Fe and Ti <200 ppm. The highest values of Au were encountered in this group with samples KLR 4964, KLR 4973 and KLR 4983 containing 4 ppm, 0.6 ppm and 0.4 ppm Au respectively. These samples have Fe/Ti ratios ranging from 200 to 500 and Mn ranging from 3000 to 6000 ppm. The QMS group includes magnetite-rich samples from within the exhalative/metasedimentary suite, which contain 11–12 ppb Au and also a few sulphide-facies samples. The most sulphidic sample (KLR 4966) and its adjacent oxide facies sample (KLR 4987) both show enrichment in V, Ti and Zn. In KLR 4966 sulphides make up c. 30% of the total and this sample contains the highest Cu level of all those from the Loch na Beinne area (483 ppm). The quartz-magnetite schists are comparable with similar rocks from the Loch Maree area (Figure 13) but most contain higher levels of Mn (>1000 ppm).

The Loch na Beinne Hornblende Schist (LnB) forms a very tight group on the diagram with Fe/Ti between 9 and 20 and 900 to 4000 ppm Mn. A third group of samples of banded hornblende-quartz schists (HS) forms an intermediate group between the Loch na Beinne Hornblende Schist and the QMS, and probably represent volcaniclastic sediments. The mica schists (MS) have low Fe/Ti ratios from 5 to 40 and are similar to those from the Loch Maree area (Figure 13). A small group of siliceous schists (SIL) can be distinguished, with widely varying Mn contents and these resemble siliceous sinters. The ultramafic rocks (UM) plot in the central area of Figure 23 with levels of Mn between 500 and 1600 ppm. However, they can be readily distinguished on the basis of their Cr and Ni contents.

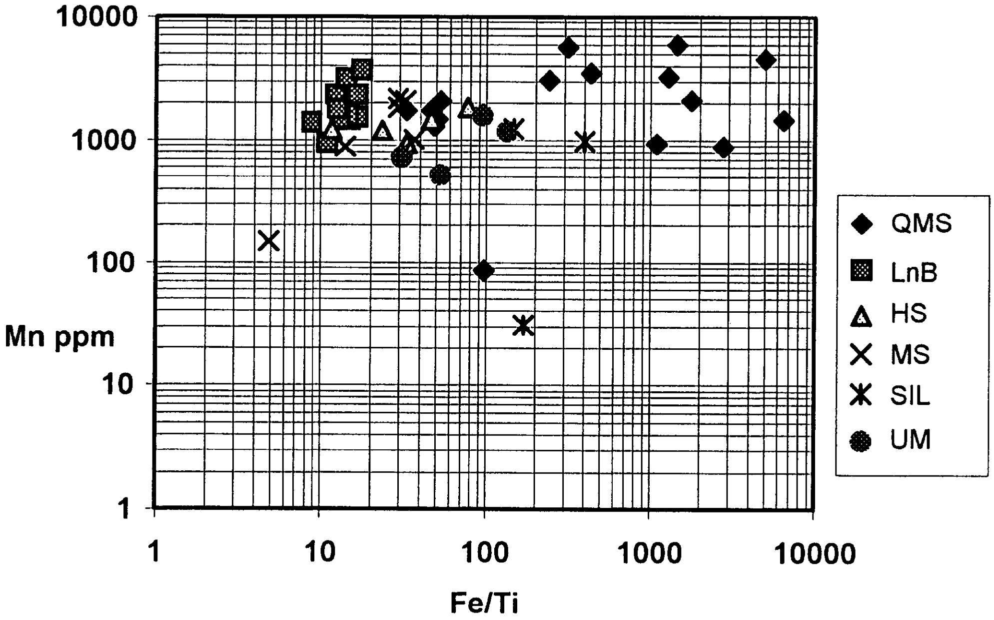

Figure 23 Fe/Ti vs Mn plot for Flowerdale samples. (QMS = quartz-magnetite schist, LnB = Loch na Beinne Hornblende schist, HS = banded hornblende-quartz schist, MS = mica schist SIL = siliceous schist, UM = ultramafic rocks).

The highest values of Au are found in quartz-magnetite schists in the central gully area. The highest value, 4 ppm (KLR 4964), was from a <0.5 m subcrop or boulder protruding through peat on the southern margin of the main peat valley [190160 863480]. The rock, red-brown weathered on its surface, but showing conspicuous, tightly folded mesobanding of quartz and magnetite-rich bands in fresh specimen, gave highly variable magnetic susceptibility readings of <1 for the quartz-rich bands to >100 for the magnetite-rich bands. The sample was selected specifically from the magnetite-rich material. The second highest Au value, KLR 4973, (574 ppb) is from a more quartzose sample from the same outcrop.

Geophysics

Detailed geophysical observations were concentrated in the Loch na Beinne area where lithogeochemical sampling had proved anomalous Au concentrations associated with banded iron formation. The aim was to identify any banded iron lithologies, suggest possible strike direction and extent and to explore for any associated sulphide-facies exhalites. Over 20 km of combined total magnetic field and VLF data were collected, with readings taken at a data spacing of between 10 and 20 m (predominantly 12.5 m), using a Scintrex IGS-2 module (Figure 24).

Lines were surveyed in greatest detail around Gorm Loch na Beinne, with line orientations of 255° or 165° magnetic. Diurnal corrections were made for the magnetic data, based on periodic observations at a field base close to Gorm Loch na Beinne, and all observations referenced to a common epoch. VLF observations used the transmitters at Rugby, England (GBR 16 kHz), at Carlisle (19 kHz) and occasionally in the USA (NAA 24 kHz). Additional magnetic data were collected over the Lewisian inliers on the north side of Loch a Bhealaich [187 864], Loch na Cabhaig [189 862] and across the upper parts of Srath Lungard [191 864]. The locations of the traverses and field susceptibility sites are shown in Figure 24.

The main features of the magnetic data around Loch na Beinne are two sub-parallel anomalies with a general north-west trend of limited strike extent (Figures 25, 26). The largest anomaly is over Loch na Beinne hillock, where total field values exceed 55000 nT and a prominent anomaly can be traced for approximately 300 m. A secondary anomaly, closer to the southern shore of Gorm Loch na Beinne, has positive amplitudes of between 1000 and 2000 nT and extends for about 200 m, with a pronounced negative anomaly on the north-east side. Local field gradients were in excess of 5000 nT, so that the field could not be measured. This means that the positive component of the smaller anomaly might not be fully represented in the data. The overall shape of both magnetic anomalies suggests source structures dipping to the south-east, assuming induced magnetisation.

A feature of the larger magnetic anomaly is the abrupt termination to the north-west. The two profiles between Loch na Beinne and Gorm loch Fada show a pattern dissimilar from those lines further south-east. Lines intersecting Gorm loch Fada do however show two anomalous zones with anomalies several hundred nT above background. On the east side of Loch na Beinne there are minor anomalies, suggesting magnetic lithologies very close to the outcrop of the Torridonian. Werner deconvolution and straight slope depth estimates for the main anomaly over Loch na Beinne hillock suggest a source within about 20–40 m of the surface. Field susceptibility observations on the hillock indicate a generally low level for the hornblende schists, with the intercalated quartz-magnetite schists giving much higher values (locally 50–60 $\times 10^{-3}$ SI). However, these magnetic horizons form less than 10% of the outcrop and are not considered responsible for the magnitude of the 5000 nT anomaly (Figure 27). It is therefore probable that a larger body of magnetite schist underlies the hillock. Simple modelling of the magnetic anomaly on line M101 (Figure 28), suggests that this magnetic zone lies within 20 m of the surface beneath much of the hillock, possibly in a synclinal structure with an axial plane dipping south-west at about 50°.

The pattern of VLF-M field anomalies (Figures 29, 30) is more complicated but shows a strong localised VLF anomaly located in the peaty ground adjacent to Loch na Beinne, with in-phase values often above 25% and locally down to -70%. These are comparable to the Kerry Road geophysical responses (Bowker and Hill, 1987) over mineralised sulphide horizons. This zone is immediately adjacent to the localised magnetic anomaly with a strike of approximately 120° grid. As with the magnetic anomaly, the VLF anomaly is terminated to the south-east within 200 m.

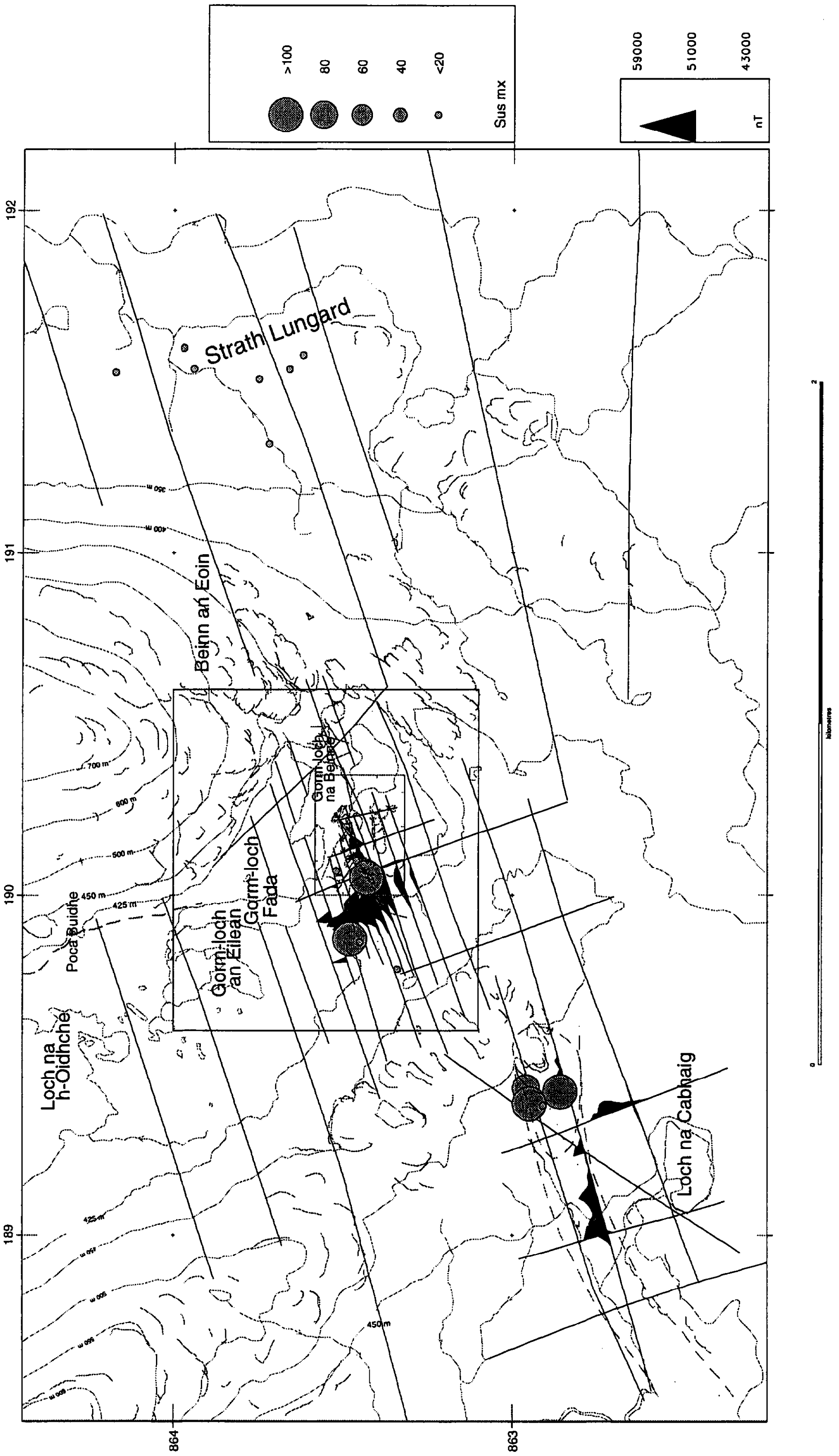

Figure 24 Flowerdale Forest: location of geophysical (MAG-VLF) traverse lines. Locations where the total field exceeds 51000 nT are shown to indicate the main magnetic anomalies. Scaled symbols are the maximum susceptibility observed at outcrop (x 10^{-3} SI).

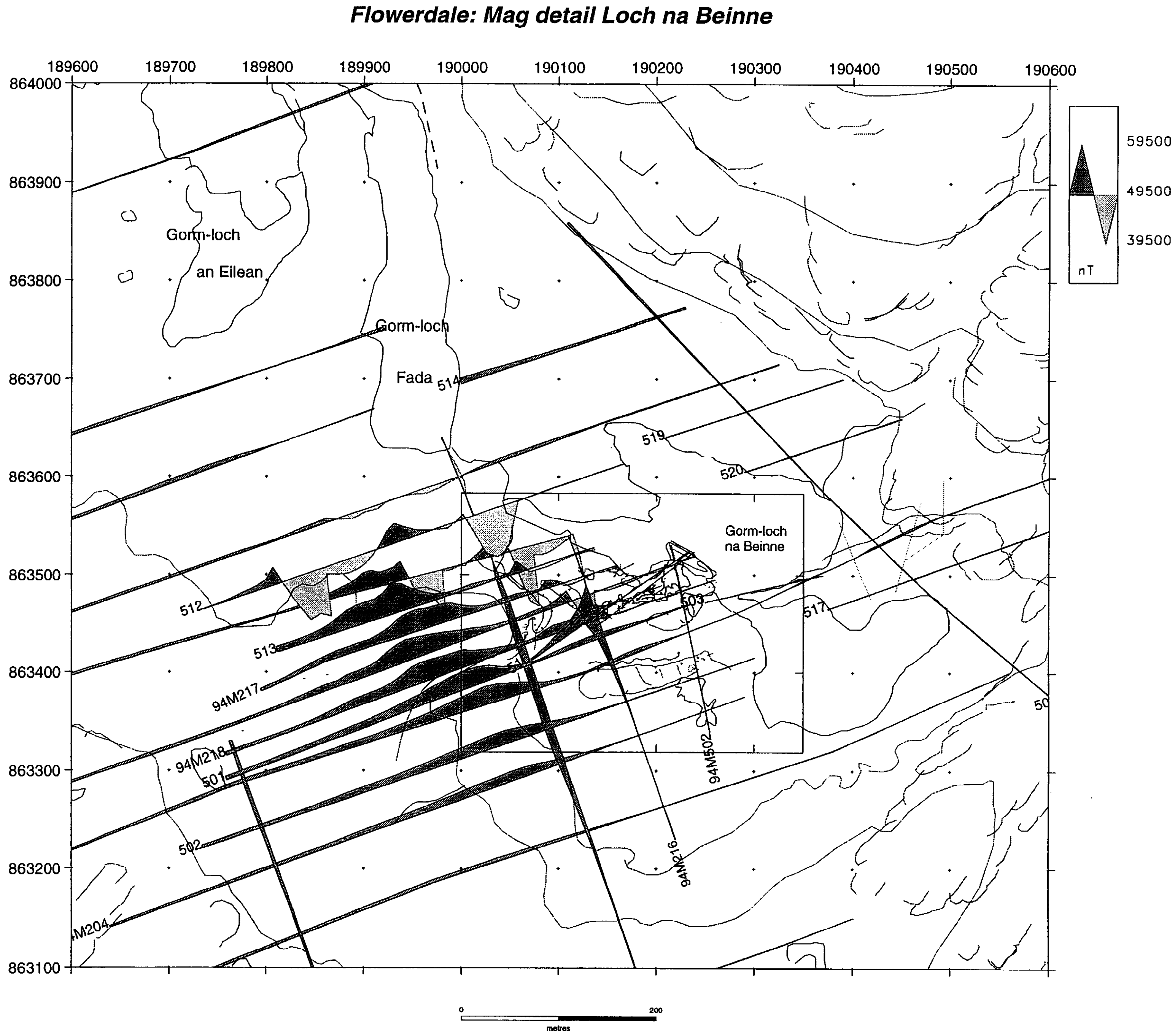

Figure 25 Flowerdale Forest: ground magnetic data around Gorm-loch na Beinne. Total field anomaly relative to a datum of 49500 nT.

Figure 26 Flowerdale Forest: ground magnetic data, detail on west side Gorm-loch na Beinne. Total field anomaly relative to a datum of 49500 nT.

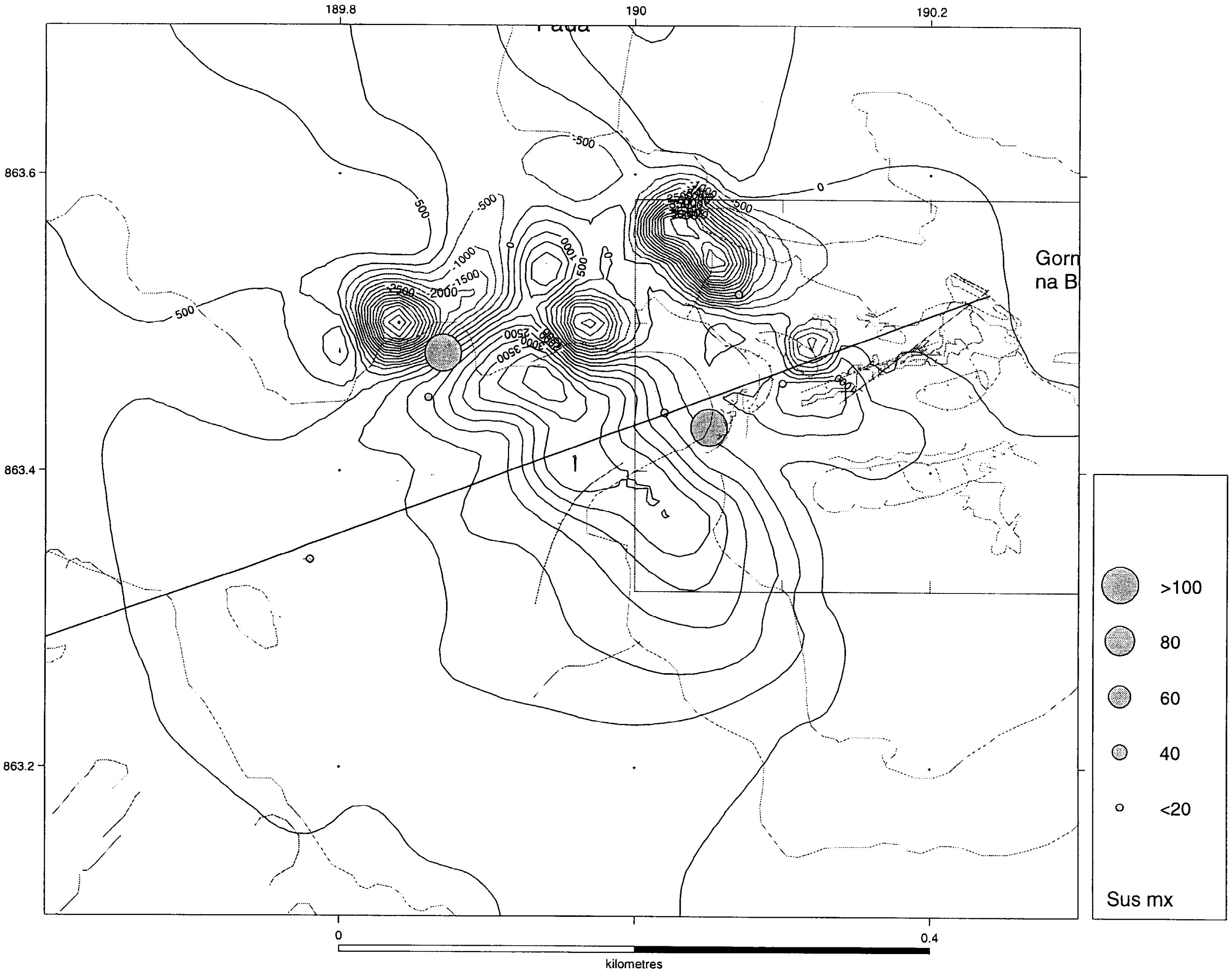

Figure 27 Flowerdale Forest: contour map of ground magnetic data over Gorm-loch na Beinne area. Contours at 500 nT. Thicker line is traverse M101 shown modelled in Figure 28.

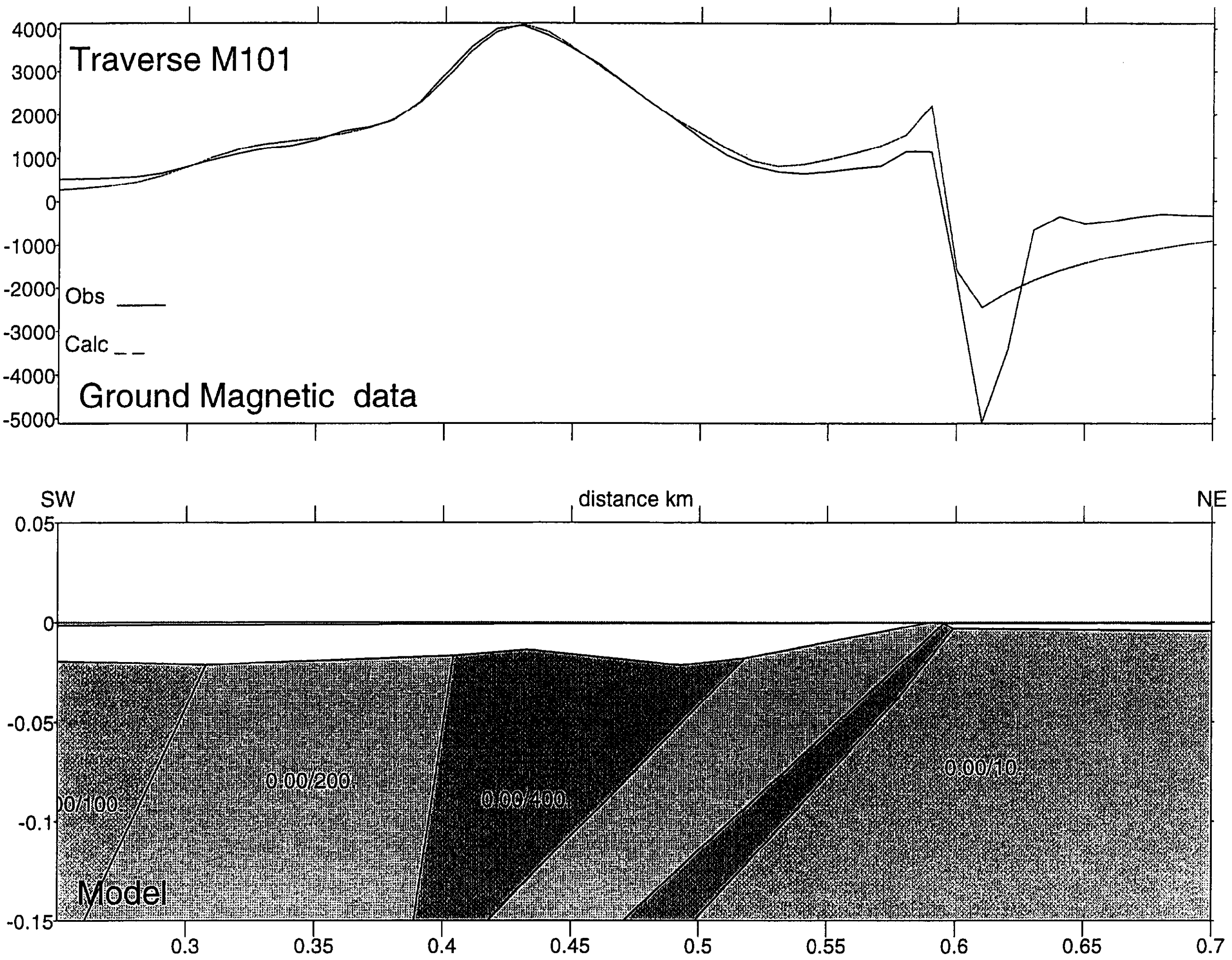

Figure 28 Flowerdale Forest: 2D model across Gorm-loch na Beinne hillock. Magnetic anomalies have been modelled as magnetic layers dipping south-west at 50°. Model annotation shows polygon density/susceptibility (x 10^{-3} SI).

Near Loch na Cabhaig [189 862] ground magnetic data (Figure 24) indicate that magnetite-bearing ultramafic rocks extend to the west of the mapped exposure. A general east-west orientation seems probable, although the anomaly is terminated immediately east of the mapped exposure. The anomaly therefore appears unlikely to extend as far east as the Loch na Beinne locality.

A series of traverses were surveyed across Srath Lungard to explore the regional aeromagnetic anomaly running north-north-west into Loch Maree (Figure 31). Methods concentrated on total magnetic field with VLF-M field observations on five of the lines (Figure 32). The magnetic data trace a discontinuous zone approximately 4 km in length, from east of Loch Garbhaig to east of Loch na h-Oidhche. Maximum amplitudes are approximately 1000 nT, with the highest frequencies in the vicinity of [191 868]. Werner deconvolution solutions of the magnetic data suggest sources at around 50 m depth in this region. The source material was not identified and is likely to be concealed beneath Torridonian cover, most likely related to a change of magnetic property within the Basement Gneiss. The VLF anomaly on the eastern side of the Loch Garbhaig Lewisian inlier is possibly related to faulting of the Lewisian - Torridonian contact.

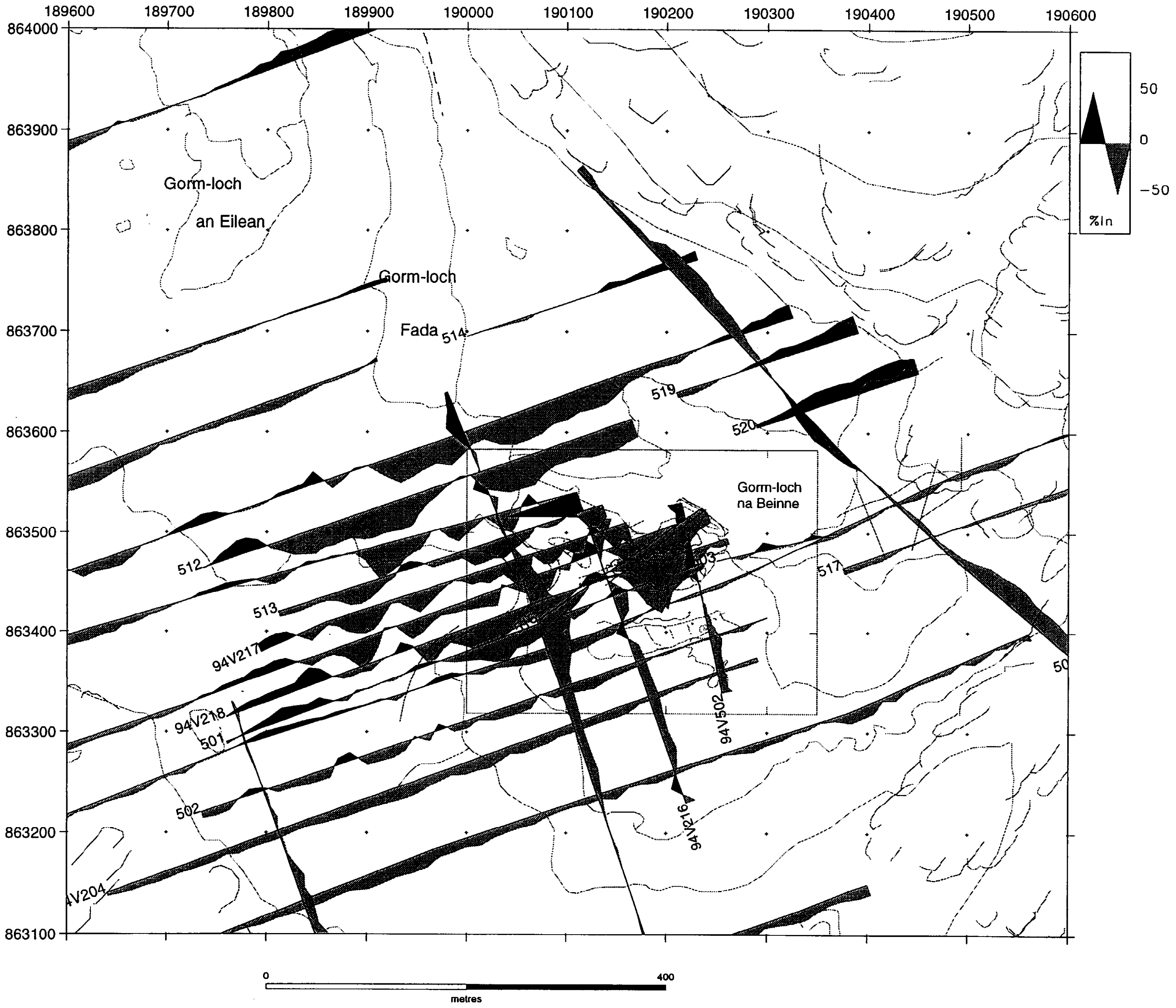

Figure 29 Flowerdale Forest: ground VLF-M field around Gorm-loch na Beinne. In-phase component of the VLF magnetic field.

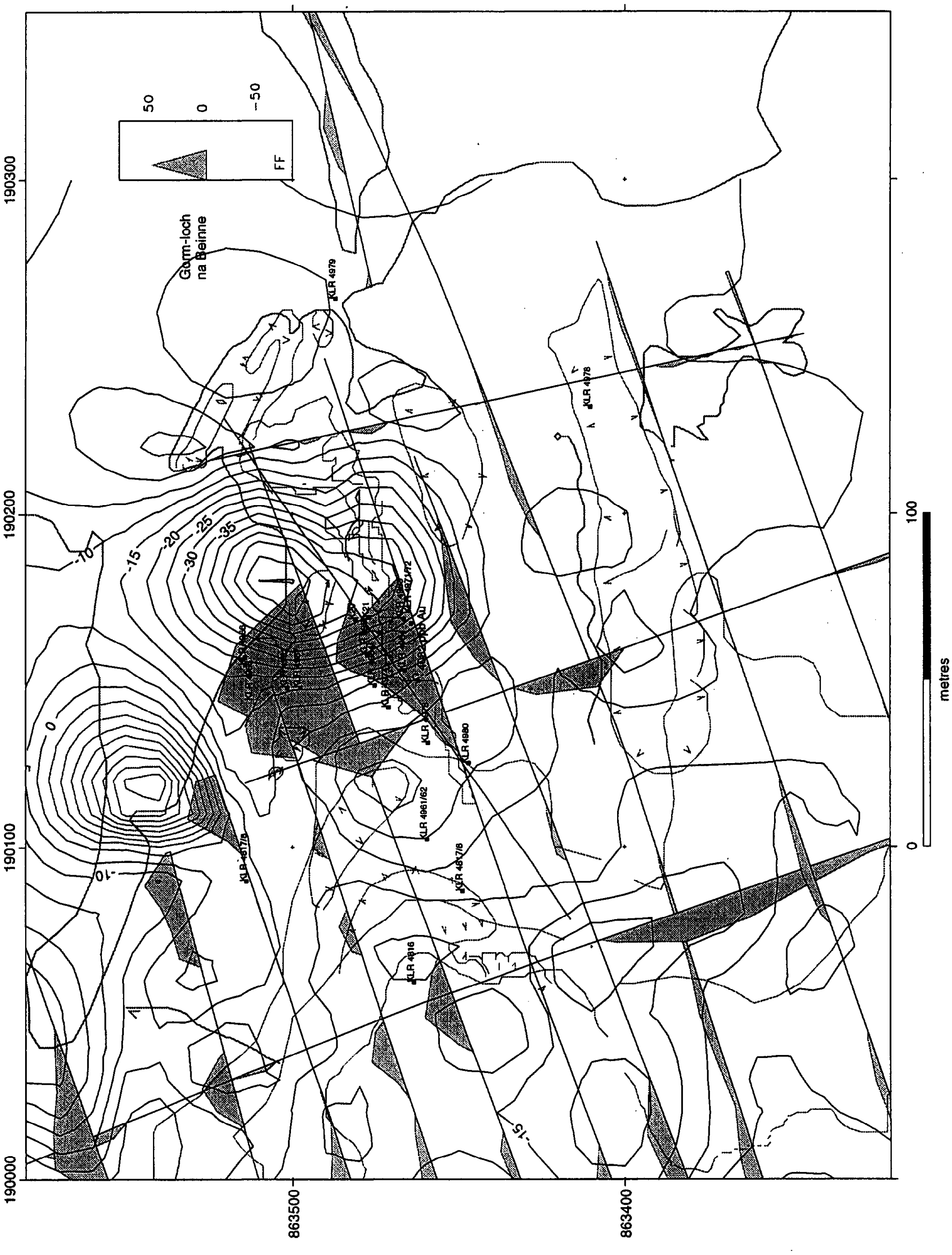

Figure 30 Flowerdale Forest: ground VLF-M field data, detail on west side of Gorm-loch na Beinne. In-phase component of the VLF magnetic field shown as contours, positive Fraser-filtered (FF) anomaly shaded.

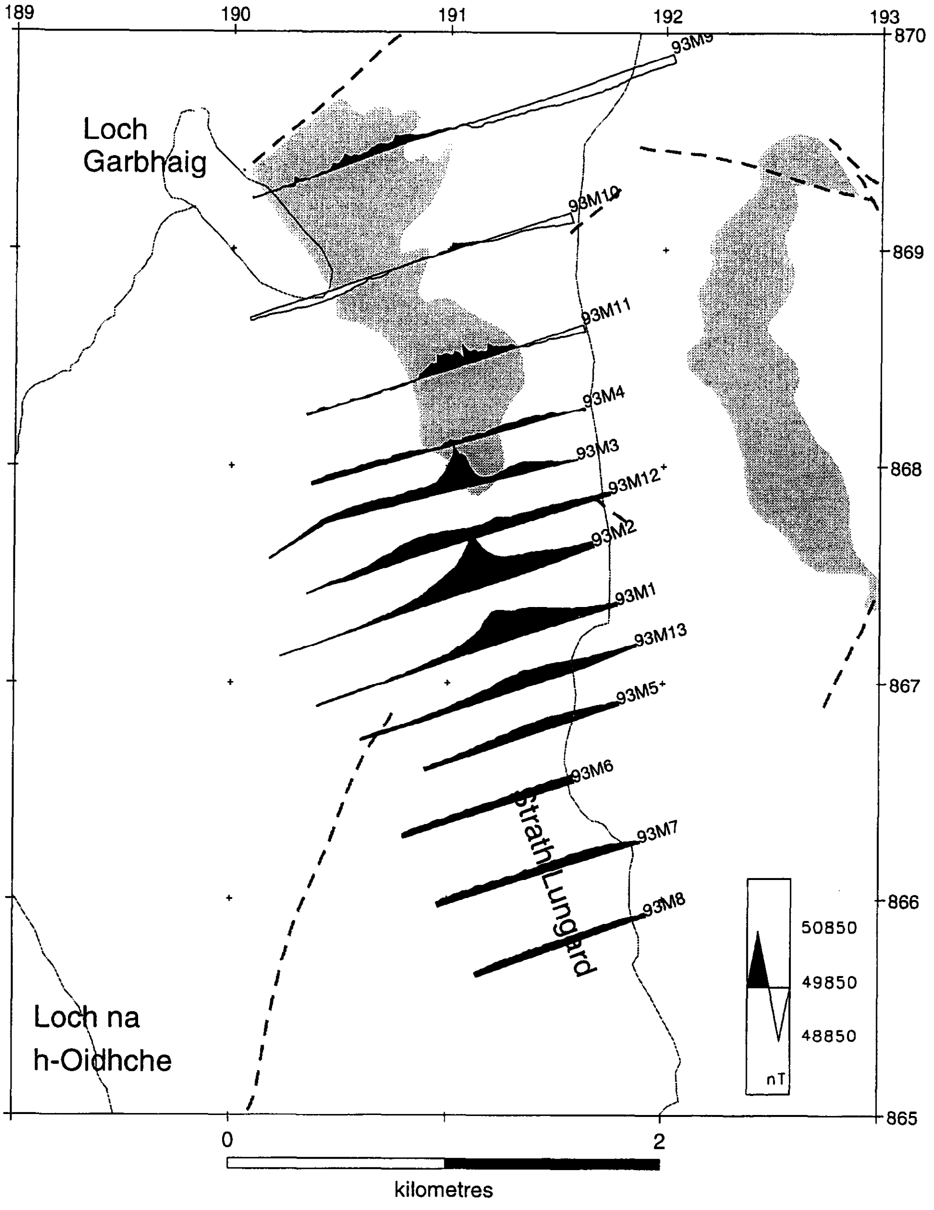

Figure 31 Srath Lungard: ground magnetic data. Total field anomaly relative to a datum of 49850 nT. Shaded regions are outcrops of Lewisian rocks south of the Talladale fault. Dashed lines are the main faults.

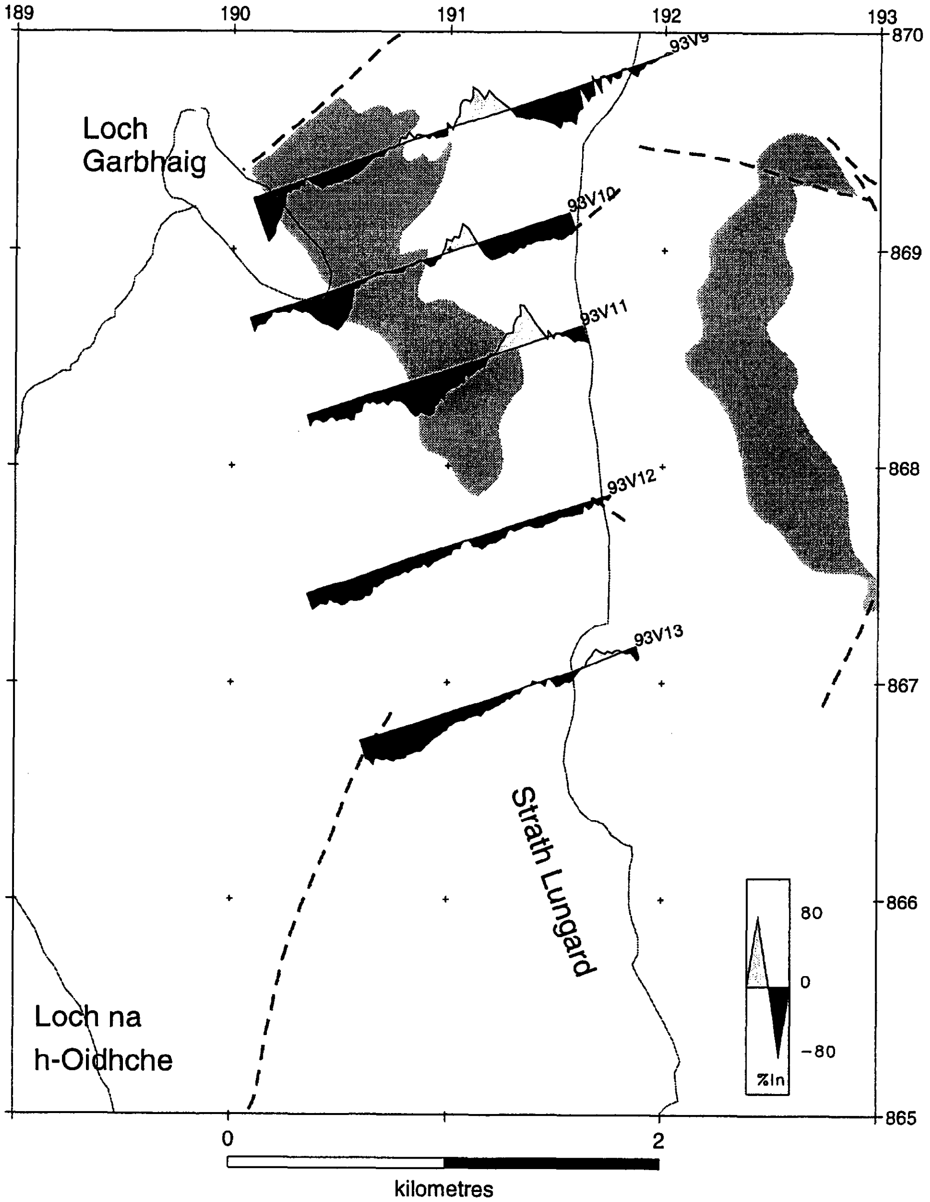

Figure 32 Srath Lungard: ground VLF-M field data. In-phase component of the VLF magnetic field. Scaled symbols are the maximum field susceptibility observed at outcrop.

Mineralogy and petrography

Geochemical assays of a suite of bedrock samples had proven the presence of anomalous Au concentrations in rock. Out of sixteen bedrock samples analysed, the four highest Au concentrations were 4082 ppb, 574 ppb, 535 ppb and 165 ppb, all the others being <100 ppb. The suite of samples selected for petrography and mineralogical examination were chosen to investigate the lithologies in the survey area, in particular those containing anomalous Au values (Fortey and Styles, 1995).

Polished thin sections were prepared by the BGS thin section laboratory and were examined under a Zeiss Universal petrological microscope in transmitted and reflected light. The four sections which represent the highest Au assay values were also examined by electron-microprobe (BGS Cameca SX50 microprobe) using 'TurboScan' software which searches the backscattered electron image of the thin section for high mean atomic number ('density' sensu lato) mineral grains at a spatial resolution of 1 micron. Grains identified by this means were then analysed to determine the composition of the minerals.

KLR 4963: 165 ppb Au: [190150 863460].

Gneiss which has undergone late-stage deformation and alteration. The rock is essentially composed of quartz and garnet, much of it with significant amounts of microgranular opaque inclusions. Mylonite texture is present in quartz bands and patches, and is also expressed in intense micro-fracturing of the c. 6 mm sized garnet crystals. However, amongst the coarse garnet crystals are areas which appear to preserve an early-metamorphic fine-grained quartz-garnet fabric. Post-mylonite alteration has taken place pervasively, on micro-fractures and grain boundaries, together with an example of a cross-cutting planar fracture veinlet. Alteration minerals are fine-grained, including opaque material, iron-stained "clay" and minor amounts of probable white mica and possible chalcedony.

Most of the opaque component consists of non-reflective, probably carbonaceous microgranules, but plates and ovoid patches of probable hematite (or ilmenite), up to 200 by 50 microns in size, occur in quartz charged with these microgranules. In addition, a small number of isolated <=10 micron blebs of probable pyrite occur armoured within areas of quartz.

The rock probably originated as a terriginous sedimentary rock containing carbonaceous material of presumed biogenic origin. Only traces of Fe-sulphide are present, and the gold may occur in association with the post-metamorphic micro-fracturing and poorly crystalline ferruginous cement.

KLR 4964: 4082 ppb Au: [190164 863468]

Deformed, hematite-impregnated gneiss which appears texturally disordered under the microscope. It is a garnet-quartz gneiss which has undergone intense crushing and granulation. Areas preserving earlier texture display a mylonitic fabric, in some places with fine-scale alternation of quartz and garnet bands. Other areas consist of fine dismembered granules of quartz and garnet in an opaque matrix. These areas run throughout the thin section and link with discontinuous fracture veins also of opaque material.

The opaque component is mostly made up of very fine-grained non-reflective material (possibly carbonaceous) and areas of massive fine-grained hematite. Within the latter are mm-scale patches of well crystalline hematite. Blebs of yellow-white, strongly reflective material are widespread, ranging from <10 microns up to about 100 microns in size. They are probably of chalcopyrite, although it is recognised that some may be, or contain inclusions of, native gold. Though most are spatially associated with the hematitic alteration, some occur in areas with little hematite and their genetic association is not established.

There is some uncertainty regarding the origin of the sulphide grains, since the rock has evidently undergone regional metamorphism, mylonitic shear deformation and late-stage micro-fracturing with cementation by poorly crystalline hematitic material.

KLR 4965: 10 ppb Au:[190164 863480]
Finely laminated grey schistose rock with about 5% of disseminated brassy sulphide grains. Quartz (c. 15%) and albite (c. 20%) form a mylonitic fabric enclosing porphyroblasts of garnet (c. 10%). This fabric is overgrown by coarse crystals of probable cummingtonite (c. 30%) together with grains of phlogopite (<5%) and chlorite (<10%). The cummingtonite, together with the presence of phlogopite rather than biotite, indicates a Mg-rich lithology. Microgranules of ilmenite and probable carbonaceous material suggest that it originated as a dolomitic marl.

Tabular ilmenite grains c. 0.1 mm long are a common accessory mineral, sited especially within amphibole-rich areas but oriented parallel to the overall schistosity. However, pyrite is the major opaque mineral present, occurring as irregular grains in quartz and quartz-amphibole rich bands, and as elongated tabular grains associated with ilmenite. Trace amounts of chalcopyrite are also present as blebs in fractured garnet, at grain boundaries, in micro-fissures in quartz-amphibole bands and in association with pyrite and arsenopyrite. Microgranules of probable carbonaceous material are also very common.

KLR 4966: 51 ppb Au: [190563 863504]
Finely banded contorted gneiss consisting of fine-grained quartz (c. 40%), fine-grained carbonate (c. 20%), fine-grained iron-stained biotite (c. 5%), pale amphibole (c. 2%), poikiloblastic garnet (c. 3%), opaque grains (c. 30%) and accessory apatite.

Pyrite is abundant, as grains of 0.1–0.3 mm size, mostly coalescing to form continuous bands and areas with a network-like fabric. Associated trace constituents include granules of chalcopyrite and an isolated c. 150 micron grain of arsenopyrite. Magnetite forms < 5% of the rock and occurs as ovoid 0.5–1.0 mm porphyroblasts enclosed in the spaces in the network areas of pyrite. The magnetite itself contains trace minute blebs of pyrrhotite. Most of the pyrite is unaltered, but locally contains lamellae in which the sulphide is altered to a non-reflecting micro-porous material.

The lithology is similar to that of KLR 4965 (see above) in the apparent Mg-rich character, and can be interpreted as having originated as a sulphidic dolomitic marl.

KLR 4967: 86 ppb Au: [190170 863495]
Porphyroblastic garnet-biotite-schist in which sub-equant garnet crystals c. 5 mm wide host arrays of quartz inclusions strongly aligned along a pre-existing fabric. Surrounding the garnet crystals is a fine-grained schist composed of biotite, quartz, feldspar, muscovite, minute crystals of probable andalusite and accessory ilmenite.

Most of the opaque fraction (< 5%) is made up of tabular microgranules of altered ilmenite and subordinate unaltered ilmenite. The opaque constituents also include an accessory amount of pyrite and traces of chalcopyrite and pyrrhotite (rare). The sulphides occur as fine-grained irregular grains at garnet-biotite grain boundaries and within the biotitic schist fabric. Minute non-reflecting probably carbonaceous granules occur throughout the thin section.

The thin section can be interpreted as a metasedimentary rock, possibly originally a siltstone.

KLR 4973: 574 ppb Au: [190164 863467]
Gneiss in which plastic deformation of earlier-formed banding has resulted in formation of leucocratic, lenticular bands up to 10 mm thick, forming > 50% of the rock, separated by brown mafic bands of comparable thickness. The lenticles consist of quartz mylonite, and the mafic bands consist

of similar mylonite but with abundant laminae of dark to opaque minerals. Garnet porphyroblasts form c.15% of the rock. In many cases, these have been fractured and dismembered, resulting in trails of c. 0.1 mm garnet granules extending along the shear fabric.

Abundant opaque granules in the dark bands are non-reflective, probably carbonaceous. Also present are isolated 10–50 micron blebs of pyrite and probable chalcopyrite. These occur armoured in quartz and garnet grains, in some cases conspicuously associated with fabric-parallel trails of carbonaceous granules. The rock is a metamorphosed quartzose siltstone with carbonaceous material of probable biogenic origin. Regional metamorphism was followed by intense shear deformation.

KLR 4975: 62 ppb Au: [190143 863459]
Leucocratic quartz mylonite in which the colourless patches are lenses of coarse-grained, highly strained quartz within a pale grey matrix of fine-grained quartz mosaic. Minor opaque and goethitic microgranules occur within a band. Traces of hornblende are also present. A small number of late-formed hairline brittle fractures are coated and cemented by goethitic material.

The principle opaque mineral is magnetite, present as ovoid porphyroblasts < 1 mm. The magnetite crystals, appearing deformed and partially dismembered, occur along the mafic band described above, and also singly in the remainder of the thin section. Minute non-reflecting probably carbonaceous micro-granules occur throughout, but especially in the mafic band. Traces of chalcopyrite occur as rare granules c. 50 microns in size.

The origin of this rock is uncertain in view of the degree of shear deformation it appears to have suffered. However, its characteristics are consistent with the precurser having been a ferruginous chert.

KLR 4976: 24 ppb Au: [190142 863459]
Finely laminated, contorted graphitic schist with a cluster of pale pink, 3–8 mm garnet porphyroblasts. The porphyroblasts are strongly fractured and cemented by seams of opaque material. The quartzose host contains abundant opaque microgranules and minor biotite as isolated c. 0.2 mm sized porphyroblasts which cross-cut the laminar fabric. The rock is cut by an interconnecting network of close-spaced planar and convoluted hairline fractures, coated and/or cemented by goethitic material.

The abundant opaque seams consist of massive, very fine-grained hematite, some showing clear reflectance indicating high crystallinity. In addition, ilmenite is a common accessory mineral, as tabular grains up to 200 microns long. Non-reflecting probable carbonaceous micro-granules are abundant throughout the thin section. No sulphide minerals were observed. The sample strongly suggests a metamorphosed carbonaceous quartz-siltstone or chert.

KLR 4977: 535 ppb Au: [190139 863486]
Graphitic schist with a set of parallel leucocratic bands 0.5 to 3 mm thick and isolated garnet porphyroblasts 2–5 mm wide. The main constituents seen in thin section are quartz, opaque microgranules (probably carbonaceous), garnet (>10% by volume) and discrete patches of brown goethitic material after biotite or some other mafic silicate. Tabular crystals of probable pyrrhotite are significant in some dark bands. Traces of pyrite occur as isolated blebs less than 50 microns in size, armoured within quartz grains. The sample strongly suggests a carbonaceous siltstone or chert.

KLR 4980: 54 ppb Au: [190127 863451]
Pale graphitic quartz schist displaying tight isoclinal folding of dark grey layers in one part of the thin section. The texture is that of a quartz mylonite accompanied by opaque (carbonaceous) microgranules and local fine-grained clusters of accessory garnet. Minor late fractures, mostly parallel to the mylonite fabric, are lined and sealed by semi-opaque goethitic material. Opaque granules and minute

patches present abundantly throughout the thin section are all of non-reflecting probable carbonaceous material. No other opaque minerals were recorded. The sample strongly suggests a carbonaceous siltstone or chert. The rock has undergone regional metamorphism and later mylonitic alteration.

'TurboScan' rare phase searching for gold grains
A Cameca SX50 electron microprobe was used to make automated searches for gold grains on the polished thin sections cut from the samples with the highest gold assays, KLR 4963, 4964, 4973 and 4977.

These searches confirmed the presence of gold in only one section, KLR 4963. Rather surprisingly the section with gold is from the sample with the lowest bulk assay. This probably reflects the 'nugget effect', which is often experienced with precious metals where the thin section represents a much smaller sample than the bulk sample and will have more erratic gold contents.

Gold was found in two locations in the section, KLR4963. The larger grain, about 5 microns wide, is located at the boundary between a quartz grain and the brown phyllosilicate described previously (showing a marked cleavage). This grain appears to be partly sitting on the sample rather than in the section. It cannot therefore be ruled out that this grain is not in-situ and was introduced during sample preparation. A semi-quantitative analysis of this grain shows it to be a copper-rich gold-copper alloy with the approximate composition Cu_3Au. The gold at the second location proved on close examination to be a cluster of three grains, each around 1 micron in diameter. These minute grains are located inside a quartz grain, and there was no indication that they were not in-situ. Attempts at further analysis of these grains suggest that they are also a copper-gold alloy similar to the previous grain. This suggests that the larger grain may well be part of this sample but may have undergone slight local movement during polishing. The composition of the copper-gold grain is unusual and has not been recorded previously in Britain (R C Leake, personal communication). The only similar copper-gold alloys, but with a composition of Au_3Cu and AuCu, are recorded from the Permian Mauchline basin (Leake et al., 1997).

Conclusions

The metasedimentary and exhalative succession at Loch na Beinne is comparable to the main mineralised zone described by Jones et al. (1987) and Williams (1986), although exact stratigraphic correlation between the two areas is not possible. The An Lungard Hornblende Schist is lithologically and chemically similar to the Aundrary Basite and occupies an analogous structural situation. Its position constrains any extension of the Loch na Beinne mineralisation to the north of An Lungard, beneath Torridonian cover. The succession displays many of the characteristics which typify volcanic-associated massive sulphides in a mixed volcano-sedimentary succession, which are usually regarded as being attributable to arc-related environments. These include the distinctive layering of the exhalative and volcaniclastic succession, the dominance of pelitic metasediments and oxide facies iron-formation forming the hanging wall to the sulphidic zone. However, base-metal values at this locality are low, so that the occurrence cannot be classified as typical of "Besshi-style" mineralisation, as in the case of the Kerry Road occurrence.

The Loch na Beinne supracrustals are characterised by a variety of fabrics. They have been subjected to amphibolite facies regional deformation, some of which has been overprinted by mylonitisation. Some samples also display evidence of late-stage brittle micro-fracturing. The original lithologies are quite variable, ranging from siltstones, through possible Mg-rich marls, Fe-rich exhalative rocks and volcanic rocks, both lavas and tuffs.

The Gorm Loch na Beinne Au mineralisation is concentrated in banded oxide and sulphide-facies exhalates. Lesser amounts of Au are also present within oxide facies lithologies and in intercalated metasediments. Due to the minimal amount of exposure, stratigraphic and structural assessment of the Au-mineralised lithologies was not possible, nor was any evaluation of the possible disposition or extent of the mineralisation. Mineralogical evaluation of selected Au-enriched rock samples confirms the late hematitic alteration and indicates that mylonitisation of some of the sedimentary facies has taken place. The relevance that these observations might have to ductile-brittle deformation and the possible secondary remobilisation of Au has not, as yet, been established. The highest Au values come from a sample with disseminated chalcopyrite, suggesting a spatial and paragenetic association between Au and Cu. However, it is not clear whether the sulphides and/or the gold were original or introduced during metamorphism or the subsequent episodes of deformation which the rocks have suffered.

MELVAIG AREA

Geology

A reconnaissance phase of sampling was carried out in the Melvaig area, to the north-west of Gairloch (Area A Figure 20). The aim of this work was to find exhalative rocks, which might be indicative of mineralisation buried under the thin Torridonian cover. The structural geology of the area has been mapped by Bhattacharjee (1963, 1968) who gives a generalised map of the distribution of the Lewisian rocks (Figure 33). Basement gneiss of the Creag Mhor Thollaidh block forms the north-eastern part of the area and is deformed by the D3 Tollie antiform (Shihe and Park, 1993). To the south-west, the junction between the Basement gneisses and the Loch Maree Group is obscured by Torridonian sediments. Where the elevated ridge between Meall Mor and Meall Imireach is reached, the exposed lithology is a fairly massive amphibolite or hornblende schist, which closely resembles the Aundrary Basite. The unconformity between the Lewisian and basal angular breccia is locally exposed as at [178610 881200], where the bulk of clasts in the breccia are of hornblende schist. Only limited exposures of the supracrustal suite are exposed to the south-west of the ridge, and the outcrop of the succession thins from about 500 m east of the A832 road to zero at Lochan Sgeireach, over a strike length of < 5 km. It is possible that this thinning is the result of tectonic attenuation, as a shear zone has been mapped along the eastern margin of the succession. To the west of the metasediments the metabasic rocks are well exposed.

Within the supracrustals no exhalative rocks are seen in outcrop, in contrast to the Gairloch area and Flowerdale Forest. However, the presence of exhalites in the Melvaig area is indicated by angular clasts of banded quartz-magnetite rocks in basal Torridonian diamictites. At a location 300 m east-north-east of Larach Tigh Thionail [178 881] the hornblende schist is overlain by Torridonian grit containing angular fragments of banded slightly magnetic quartz-magnetite schists, up to 10 x 5 cm in size, of the type found in the Kerrysdale and Loch na Beinne hornblende schists A local source is indicated by the relatively large size of these clasts.

To the west of Lochan Sgeireach the Lewisian succession is largely concealed by Torridonian cover, drift and vegetation. Two small areas of hornblende schist are exposed within the Allt Mor catchment (Figure 33), but otherwise there is no Lewisian exposure for about 1 km until the conspicuous ridge formed by the Little Sand diorite is reached. The geology of the diorite has been described by Bhattacharjee (1964) who showed that the diorite has been metamorphosed to amphibolite-grade. The relationship between this deformed intrusion and the Loch Maree Group is obscure. It may represent a small subvolcanic intrusion related to the metabasic sills which intrude the metasediments.

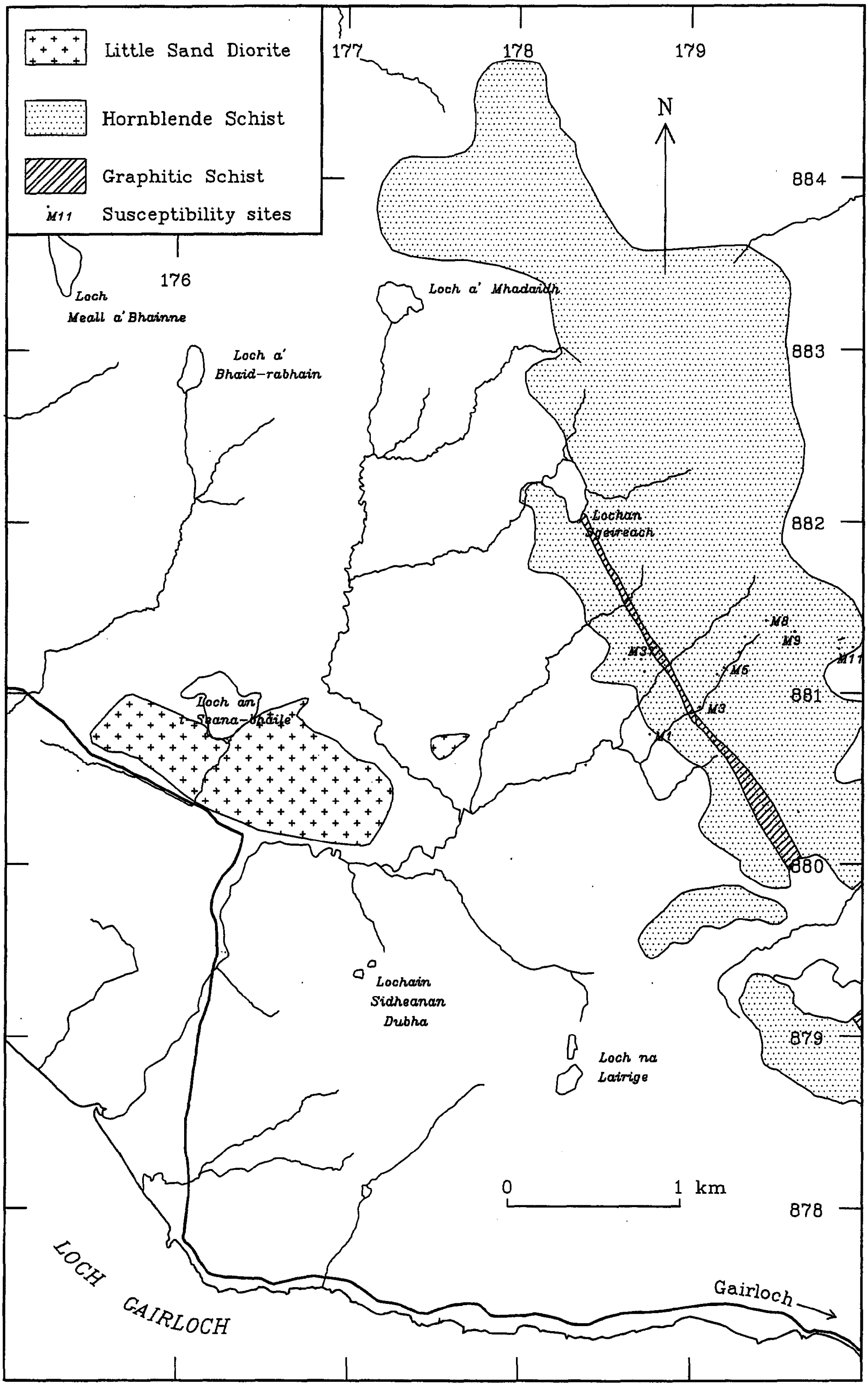

Figure 33 Location map of the Melvaig area. Geology from Bhattacharjee (1968). Torridonian rocks left blank.

Lithogeochemistry

A single sample of quartz-magnetite schist from a clast within the Torridonian (KLR 44810) was collected at [178580 881280]. The clast was only weakly magnetic, with susceptibility values up to 6 x 10^{-3} SI. Its chemistry indicates a quartz-rich lithology (Fe < 8%), but with an extremely high Fe/Mn ratio of 209, low Ti (72 ppm) and low Au, Bi, Cu, Ni, Pb, Sr, Sr and Zn. It is probable that this clast is comparable to the 'low magnetic' banded quartz rocks as found in the Loch na Beinne Hornblende Schist.

Two samples of hornblende schist (KLR 44801 and 44809) were collected. This limited sampling indicates that the hornblende schist is similar to the Aundrary Basite (Table 13). One sample contained patchy, rusty weathering with minor 2–3 mm elongate blebs of pyrite running parallel to the main foliation of the rock. Chemical analyses show that base-metal levels in these samples are low.

Table 13 Comparison between the Aundrary Basite, Melvaig and Ben Lair Hornblende Schist Units

	Aundrary Basite (Jones et al., 1987)	Melvaig Hornblende Schist	Ben Lair Hornblende Schist
Statistic (No. of samples)	Mean (44)	Mean (2)	Median (13)
Au		0.001	0.002
Ba	54	60	98
Ca	72400	61285	48500
Cr	174	89.5	128
Cu	95	114	106
Fe	93900	103965	93300
Mn	1400	1603	1600
Ni	100	72.5	50
Pb	0.6	1	6
Sr	134	137	108
Ti	6115	6828	5750
V	300	360	273
Zn	98	106	119

Note: All elements in ppm

Geophysics

A series of geophysical traverses were made across the western part of the inlier. Methods used were total-field magnetic data and VLF (magnetic field). The most prominent magnetic anomalies, with values above 50000 nT, are around and just to the south-west of Lochan Sgeireach (Figure 34). There are at least two zones of magnetic rocks striking north-west. The pattern of anomalies at the southern margin of the lochan can be recognised on the two adjacent lines to the south and possibly on the line north of the Lochan. The largest anomaly, just to the south-west of the mapped Torridonian outcrop, is less continuous. The shape and pattern of this anomaly is typical of the quartz-magnetite schist bodies in other parts of the Loch Maree Group, and observation of local quartz-magnetite clasts support this interpretation. A prominent negative anomaly 800 m east of Lochan Sgeireach is also probably associated with a magnetite schist.

There is also a strong VLF in-phase anomaly in this zone with continuity of strike for over 1 km (Figure 35) trending north-west. This anomaly can be traced along all three lines south of Lochan Sgeireach, over mapped Lewisian rocks, and probably extends south of the lochan over mapped

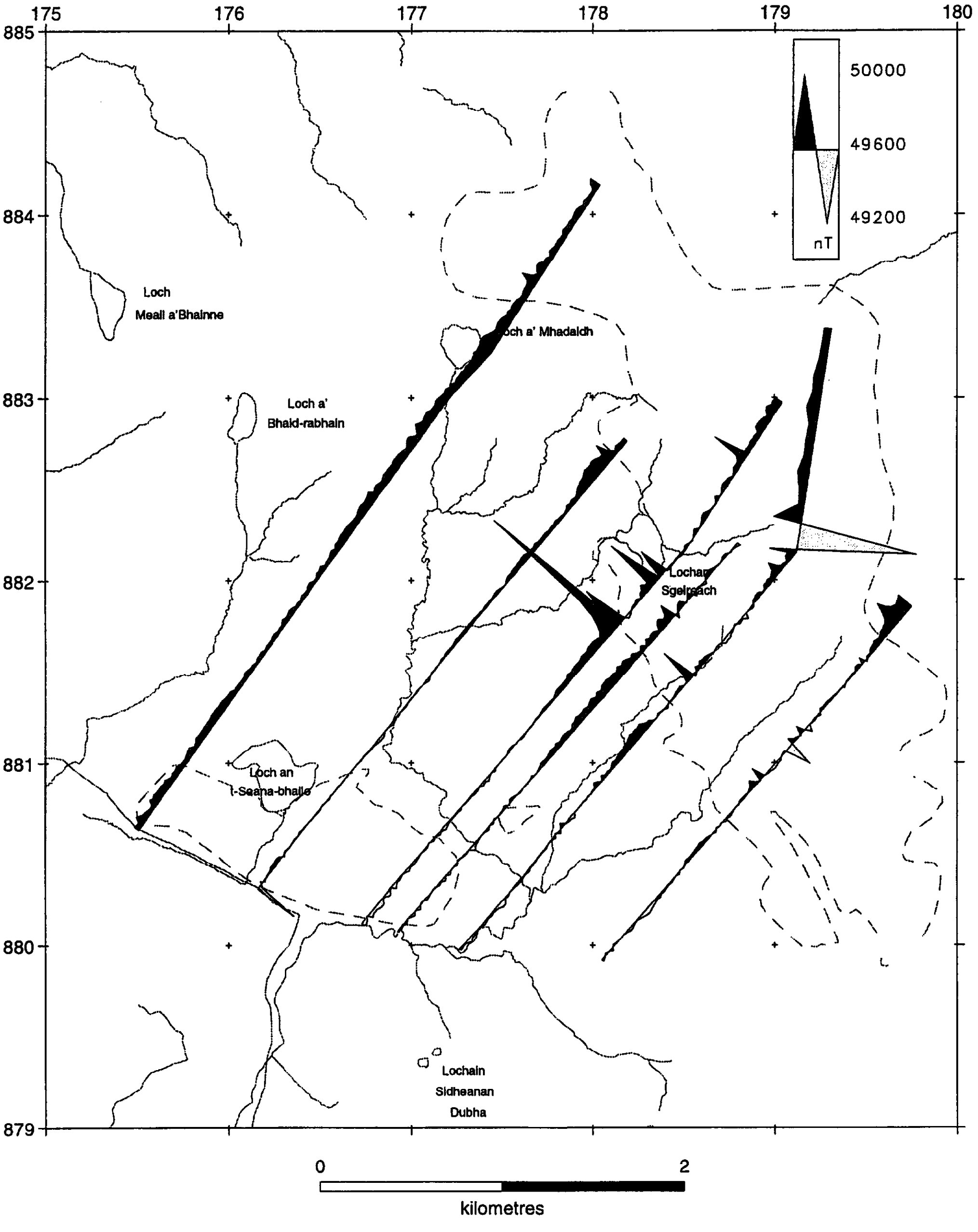

Figure 34 Melvaig area: ground magnetic data. Total field anomaly relative to a datum of 49600 nT. Dashed line is the outcrop of the Lewisian inlier.

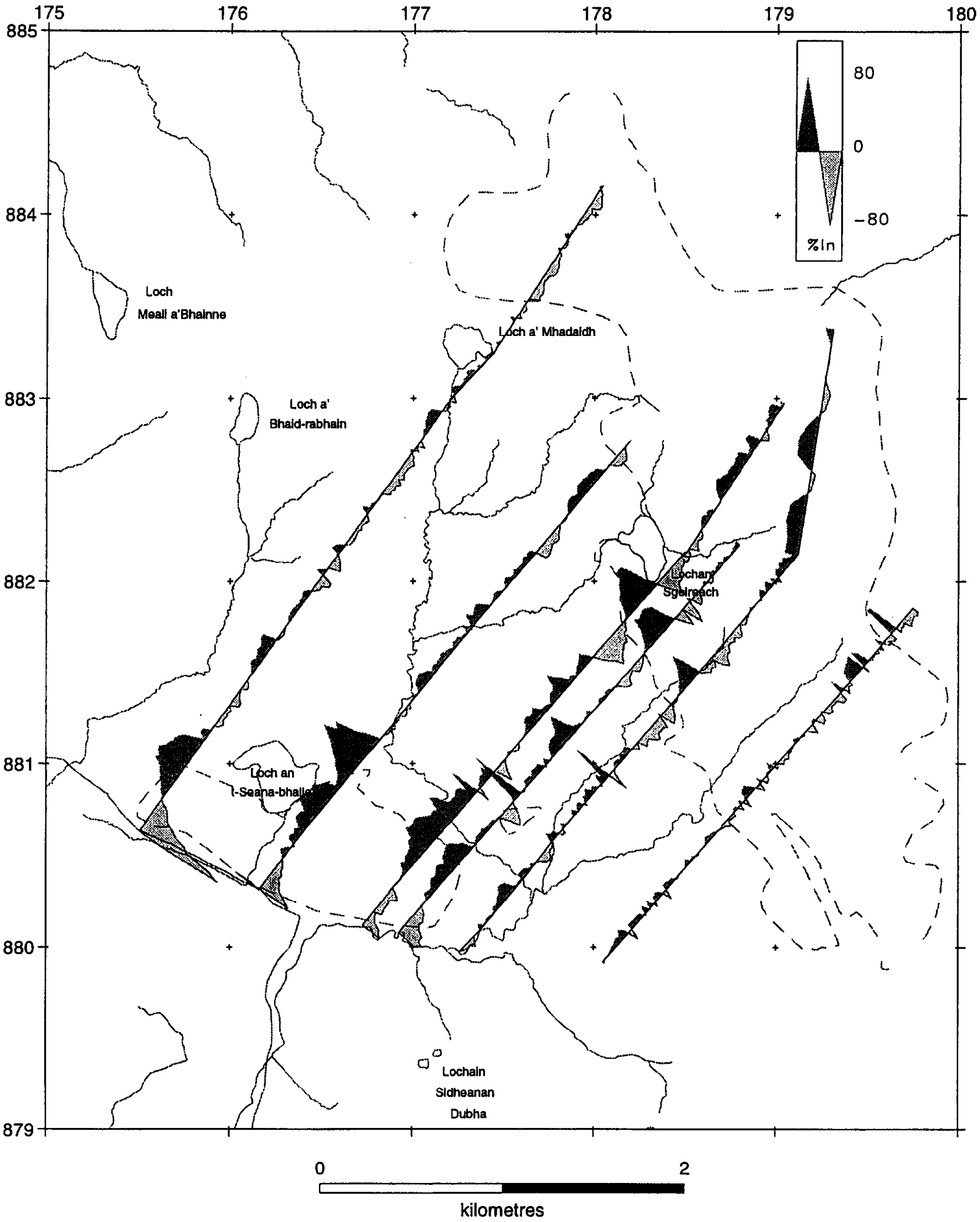

Figure 35 Melvaig area: ground VLF-M field data. In-phase component of the VLF magnetic field. Scaled symbols are the maximum field susceptibility observed at outcrop.

Torridonian rocks just east of the inlier. These combined magnetic and magnetic/VLF features are similar to patterns observed over other parts of the Loch Maree Group with banded oxide and sulphide facies mineralisation. However, it is possible that the VLF anomaly is related to the band of graphitic schist which widens south-east from Lochan Sgeireach.

Conclusions

There is little direct evidence for stratabound mineralisation in the Melvaig area. Due to the very limited exposure of the potentially mineralised zone only one sample of quartz-magnetite rock was collected, and results indicate that this, and similar clasts within the basal Torridonian breccia, is the sulphide-poor quartz-magnetite variety. However, geophysical data indicate a pronounced high amplitude magnetic response to the south-west of Lochan Sgeireach, in a position analogous to the Kerry Road and Loch na Beinne magnetic anomalies. This is flanked on its north-east side by a moderate VLF-M field response, which extends for at least 500 m. The position of these anomalies corresponds to the projected position of magnetite and graphite-bearing lithologies, possibly associated with a separate metabasic unit along the south-western flank of the main Lewisian exposure.

TIREE

Geology

With the exception of the small island of Iona, the islands of Tiree and Coll form the southernmost expression of the Lewisian Complex. Like their counterparts on the mainland and in the Outer Hebrides they are composed dominantly of a basement of granulite and amphibolite facies gneisses of tonalitic composition, within which are found enclaves or belts of mafic igneous and metasedimentary supracrustal material (Drury, 1973). A number of intrusions also occur locally, and are comparable to the mainland Scourie dyke swarm.

The basement rocks of Tiree are divided into two terrains of differing metamorphic grade - namely the western granulite facies terrain and the eastern amphibolite facies terrain (Whitehouse and Robertson, 1995). Good exposures of each occur along rocky coastal headlands and on elevated ground inland. The boundary between the two terrains is concealed by raised beach deposits, within a belt of low-lying ground through the centre of the island (Figure 36).

The basement rocks of western Tiree comprise dominantly ultramafic and mafic orthogranulite and granofels, together with subordinate felsic granulites which were subjected to peak metamorphism between 2900 and 2600 Ma (Drury, 1973). Isotopic dating of the western granulite facies gneisses using Sm-Nd and Pb isotope data provides evidence of a late Archaean protolith reworked at around 2.8 Ga. (Whitehouse and Robertson, 1995). In the western half of the island the basement rocks are mainly mafic (hornblende-biotite-pyroxene dominated), and commonly show a variable, low to moderate, magnetic susceptibility (<2–>30 x 10^{-3} SI) due to the presence of accessory magnetite. Rarer acid variants (granitic gneisses) have median susceptibility values of <1 x 10^{-3} SI. In the east of the island amphibolite facies (mainly hornblende-biotite) migmatites dominate.

Rare zones of supracrustals, including metasediments and exhalites, also occur within the basement-dominated terrain (Whitehouse and Robertson, 1995). Overlying the basement gneisses, or tectonically incorporated within them, these supracrustals form three main belts, which may be defined as the western, central and eastern belts. Within these metasedimentary lithologies, comprising semi-pelites (biotite gneisses), subordinate psammitic and calcareous lithologies are dominant over metavolcanic rocks. The western belt also contains a suite of exhalative rocks which

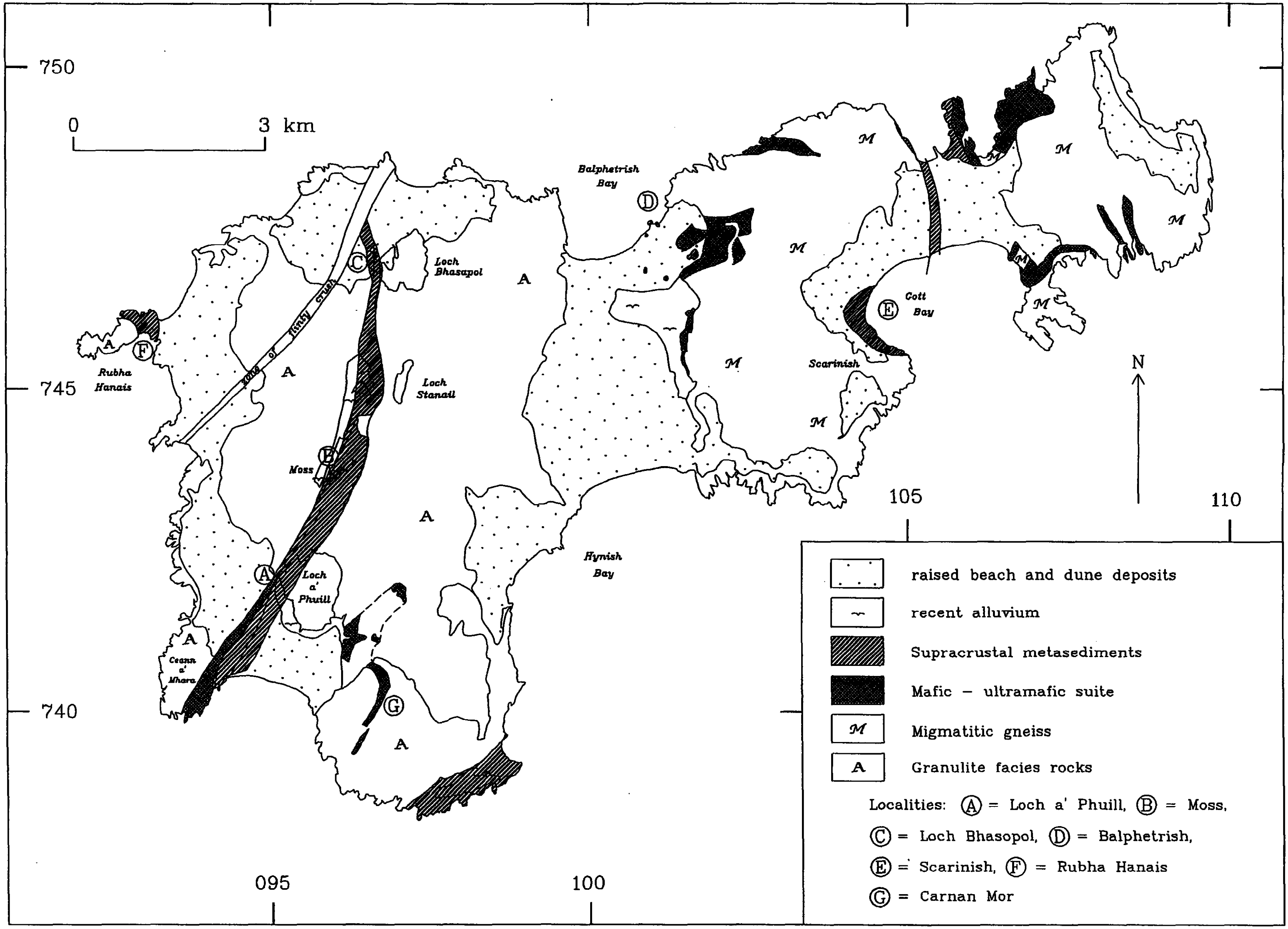

Figure 36 Geology map of Tiree.

are described in the section below. Exposure of the supracrustals is poor due to extensive coverings of raised beach and wind-blown sand.

Previous work

The regional aeromagnetic map defines the Tiree/Coll province as a magnetic high relative to the mainland and Hebridean series. In particular, the western part of Tiree foms part of a distinctive magnetic high, which reflects the basic chemistry of the basement rocks as described above.

The supracrustals became the subject of strategic interest in April 1941 when the Geological Survey drew the attention of the government Home Ore Department to the existence of an extensive belt of magnetite-rich pyroxene gneiss, which had first been excavated by Dr J B Simpson of the Geological Survey in 1922. Further investigations were commissioned by the firm of Wilkins and Devereux. A combination of geological and geophysical surveying, together with shallow core drilling was employed to substantiate the continuity of the iron-bearing lithologies. The work included ground total-field magnetics and subsequent trenching. At the Loch a' Phuill locality [095 742] trenching revealed the presence of three magnetic horizons, a major one flanked by two subsidiary horizons, bounded to the west by graphitic schists (Whetton and Myers, 1949). The trenching operations established that the magnetite-rich gneisses were masked by relatively shallow overburden of raised beach material and wind-blown sand. Excavations in the nearby Moss area [096 743] had to be abandoned due to waterlogging in the wet, peaty soil.

In 1958–9 Colvilles Ltd reassessed these magnetite-rich orthogneisses with a view to possible development. A combination of geological and geophysical surveying, together with shallow core drilling (unpublished data in BGS National Geological Records Centre) was employed to substantiate the continuity of the iron-bearing lithologies. Their conclusion, mainly based on more detailed evaluation of the magnetic data, was that only the highest amplitude anomalies from the original magnetic survey could be attributed to magnetite-rich exhalites. Other, lower-amplitude anomalies in the belt were attributable to mafic rocks. On the basis of trenching results a series of 17 vertical and inclined boreholes were sunk. The best intersections were average concentrations of c. 30% Fe across a steeply inclined zone, with intersections of 7.58 m and 21.23 m true thickness in two borehole sections 1B and 2, (Figure 37). However, correlation of these detailed investigations with the magnetic data indicated that only the highest-amplitude magnetic anomalies could be attributed to magnetite gneisses. As a consequence no further commercial assessment was carried out.

The Colvilles drill-core material, which is housed at the BGS Edinburgh Core Repository, became the subject for detailed geochemical and petrological studies for an MSc thesis by Stocks (1994). The chemical analysis of carefully selected sections established that the gneisses had been little modified from their protoliths. The lithologies identified were mafic pyroxenites of mid-ocean-ridge affinity, together with a succession of relatively thin units of pelite, semipelite and manganese-rich banded-iron formation. According to Stocks the 'magnetite zone' occurs in part at a contact of paragneiss (garnet-biotite granulite) and the aforementioned orthogneiss (hornblende and hornblende-garnet gneiss and schist) and is partly or wholly enclosed within the latter. This is a similar situation to the exhalite horizon at Loch Maree.

Stocks also identified a trace amount of a PGE-bearing mineral (Pd, Pt, Ni + Te), present as micron-scale inclusions within chalcopyrite, intergrown with pyrite, in a sample of hornblende schist from Borehole 3 (Figure 37).

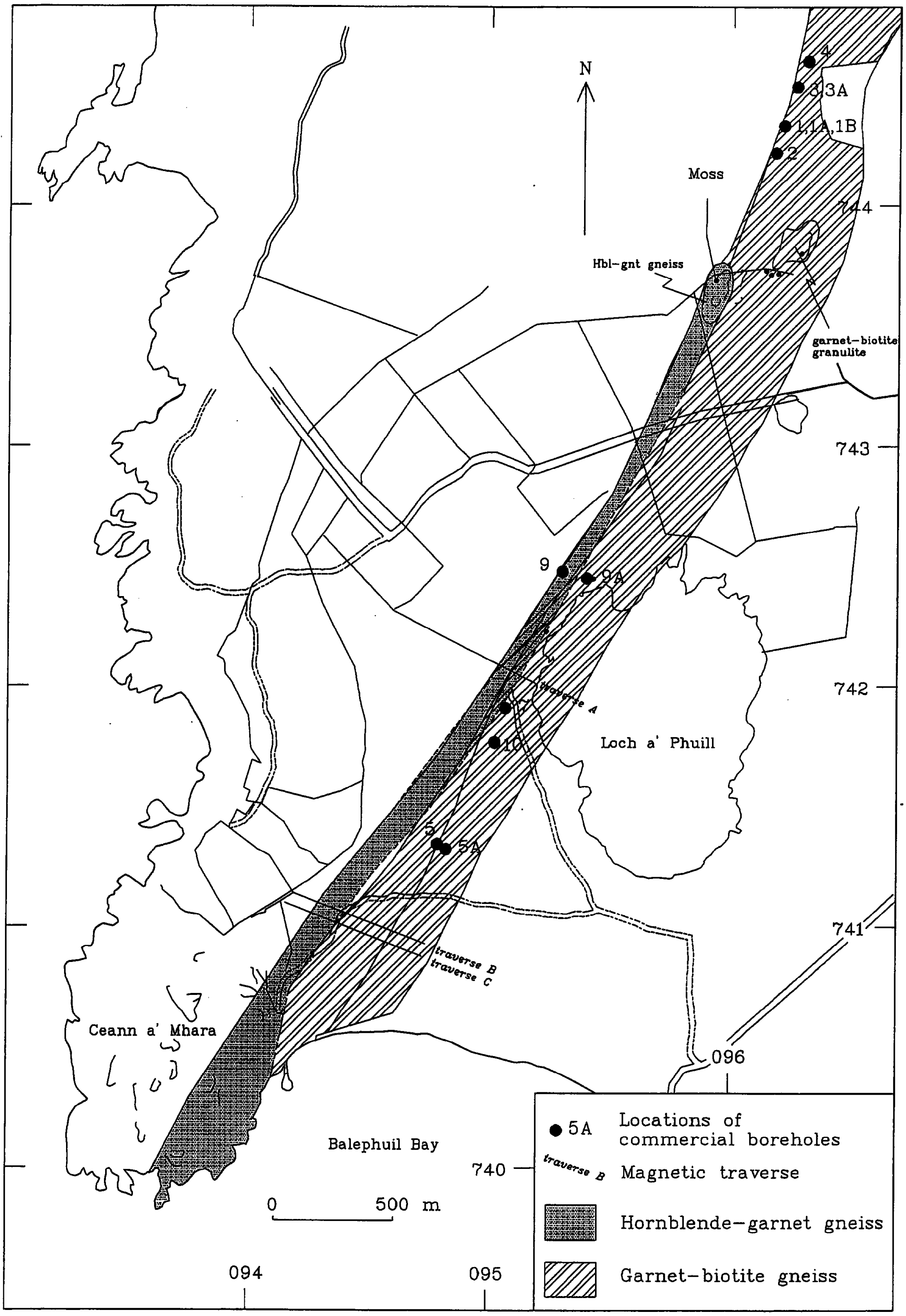

Figure 37 Map of south-west Tiree showing location of commercial boreholes.

Lithogeochemistry

The Tiree supracrustals outcrop within three northerly trending belts, each in the order of several hundred metres in width (Figure 36). The western belt is distinguished by the presence of iron-oxide-rich gneisses within the metasedimentary succession, together with garnet-bearing coticules of probable exhalative origin. Outcrops of these rocks (Figure 36 localities A-C), are minimal over the 8 km length although extensions of the magnetite-bearing horizons were identified by ground magnetics during the original commercial surveys. The central and eastern belts are composed mainly of clastic metasediments, but contain subordinate graphitic, semipelitic and pelitic lithologies bearing small amounts of sulphide.

Lithogeochemical sampling was carried out at the localities defined in Figure 36 and samples are described below.

Western Belt

At Loch a' Phuill (Figure 36, Locality A) supracrustals are exposed at a lochside locality [095220 742205]. The main exposure is of banded quartz-magnetite gneiss (KLR 4844), which are poorly exposed over c. 3 m strike width. The bands of magnetite and quartz alternate on a generally sub-centimetric scale. Locally, strain dilation has produced pods of magnetite up to 10 cm across. Magnetic susceptibility varies from <100 x10^{-3} SI, in quartz-dominated bands, to >600 x 10^{-3} SI for the magnetite bands. This sample containselevated Fe (33%), Mn (1.6%), V (790 ppm) and Ti (23000 ppm). The low Fe/Ti ratio of 14 indicates a predominantly basic igneous source rather than a chemical exhalite. The low Cr and Ni levels in this sample confirm minimum input from an ultramafic source. Although Zn was also slightly elevated (248 ppm), the other base-metal and Au values are low. Ten metres to the east of the quartz-magnetite gneiss a massive coarse quartz-garnet gneiss (coticule), is exposed over c. 8 m strike length. The rock comprises garnet-rich bands of 10–15 cm width with euhedral garnets generally 3–8 mm in diameter, interbanded with minor cm-sized quartz bands. The rocks therefore show similarities with the eulysites seen at Glenelg (Coats et al. 1996). Susceptibility values range from 6–55 x 10^{-3} SI, with a median value of 12 x 10^{-3} SI. This lithology shows minor enrichment in Cu (188 ppm), but not in the other base metals or Au.

The exhalites are flanked to the west by a 6 m thick medium-grained quartz-hornblende-garnet gneiss, with susceptibility values ranging from 15 to >100 x 10^{-3} SI (median 47.1 x 10^{-3} SI). Although this lithology was not sampled it is probably the same as at Ceann a' Mhara (KLR 4842).

At the northern end of Loch a' Phuill [095440 74245] a small boulder of coarse grained quartz-orthoclase-muscovite granulite was sampled (KLR 4846). This lithology is unusual for the Loch a' Phuill area but similar float occurs at Moss [096160 743725].

To the west of Locality A sand dunes form continuous cover over bedrock. The next exposure of the supracrustal succession is at Ceann a' Mhara (KLR 4842 and 4843), where a succession of amphibolites are well exposed along the shoreline. It is probable that these lithologies immediately underly the exhalative package. The two samples collected from this locality show markedly differing magnetic properties, with median values of 99 x 10^{-3} SI.

At Moss (Locality B) the central and western parts of the supracrustal belt are exposed or occur as float in a ditch between the main rock outcrops at [095900 743600] and [096300 743800]. Five rock samples were collected (KLR 4857–4861). The lithological succession, from west to east, comprises interbanded plagioclase-hornblende and quartz-biotite gneiss, with a moderate magnetic response (median susceptibility value 30.1 x 10^{-3} SI) and extends over a cross-strike width of 70 m on Sruthan ridge. This rock is similar to the Ceann a Mhara banded hornblende gneiss. The supracrustals comprise dominantly biotite-quartz schist, locally weakly garnetiferous, e.g. KLR 4857

[096290 743795], which interfingers with narrower bands of hornblende gneiss, e.g. KLR 4858, [096270 743840]. Coarse pyroxenite float, containing c. 2% pyrite as fine crystal aggregates, also occurs in a ditch at [096160 743720] (KLR 4860). The trench also contains a variety of pegmatitic quartz-rich lithologies, KLR 4859, possibly representing metamorphosed psammites. KLR 4861 is of similar composition but is more Fe-rich. A 15 m wide unit (KLR 4857) comprises garnet-quartz-biotite gneiss, with median susceptibility value of 0.3 x 10^{-3} SI. Although traces of interstitial pyrite are seen in several of these lithologies both base metal and Fe concentrations are low.

Samples collected at Loch Bhasopol (Locality C, Figure 36) represent the northernmost parts of the western belt. Outcrops occur c. 100 m west of Loch Bhasopol [099650 747110] as two conspicuous rocky knolls on otherwise flat-lying ground. The main lithology is a garnet-biotite granulite (KLR 4864) which in places is coarser grained, with minerals forming aggregates. Locally garnets occur in clots or impersistent ribs, and are up to 1 cm size. Small clots and streaks of magnetite are also present and give rise to moderately high susceptibility readings, locally in the region of 40 x 10^{-3} SI. The four samples of this lithology collected show little variation in Fe (15–16%), Ti (1.1–1.3%) and V (326–384 ppm). Unusually, the samples are also moderately enriched in Cr (>400 ppm). Maximum values for the base metals are Cu (35 ppm), Pb (5 ppm) and Zn (144 ppm). The Fe/Ti ratio of 13 indicates an igneous or sedimentary origin, rather than a chemical exhalite.

On the east side of the main outcrop an unusual rock, about 10 cm maximum dimension, with an irregular, cavernous, weathered surface was sampled (KLR 4865). The fresh core of the specimen comprises dark brown, homogeneous, microcrystalline hematite, with common sub-millimetric spherical cavities. This sample contains the highest Fe and Mn levels of any sample on the island (46% and 2.4% respectively) and Ba (3643 ppm). Base-metal and Au values for this sample are also low (1 ppb Au, 70 ppm Cu, 0 ppm Pb and 13 ppm Zn). The composition indicates that it is a bog iron ore (or possibly a gossan), which was derived from the iron-rich rocks. Its position close to the main magnetic anomaly in this area suggests the presence of such rocks immediately west of Loch Bhasopol (Figure 36). An adjacent outcrop of banded hornblende-quartz-plagioclase gneiss, 23 m in length, was slightly enriched in Cu (447 ppm). On the shore of Loch Bhasopol, 200 m south-east of the main knoll outcrop, a more magnetic variant of this lithology outcrops, with susceptibility values in excess of 200 x 10^{-3} SI. This is probably the source of the magnetic anomaly in the original commercial magnetic survey.

Central Belt

At Balphetrish (Locality D) the contact between basement and supracrustal marbles is locally exposed along the shoreline and particularly at the Natural Arches [101005 747505]. Contacts vary from sharp to gradational, and are commonly marked by secondary mineral growth in the form of pyroxene and scapolite by related to metasomatism (Coomaraswamy, 1903). With the exception of the marble and its metasomatic derivatives, the lithologies sampled are probably modified basement or, alternatively, parts of an intrusive dyke suite as described elsewhere on the island (Muir et al., 1993). Brecciated and interfingered within the basement gneiss are zones of highly magnetic, very fine-grained hornblendite (median 89.4 x10^{-3} SI) (KLR 4847). No significant elevations in base metals or Au are present in the marble or any of the 'modified' contact lithologies. Rock (1983), however, records 258 ppm Cu from a marble at Balephetrish, and this is the highest Cu content in his dataset of Lewisian marbles.

The Hynish succession (Locality G) is dominated by garnet-bearing biotite gneisses which are best exposed on the Am Barradhu headland [0988 7392]. The biotite gneisses are similar in appearance to those at Loch Bhasopol, Moss and Loch a Phuill, although unlike these other localities there is no evidence of an intimate association with banded Fe-rocks. Significantly perhaps, they also have a lower Fe content than their equivalents in the western belt (<7%) and have lower magnetic susceptibility, with median values between 1 and 2 x 10^{-3} SI. It is possible that the lower Fe levels reflect minimal input from an exhalative source during their deposition. Base-metal and Au values are not significantly enhanced in these samples.

Eastern Belt

At Scarinish (Locality E) continuous shoreline outcrop of supracrustal rocks stretches for approximately 1 km on the south-western side of Gott Bay to the north of the village of Scarinish (Figure 36). The succession passes northwards from quartz schist into garnet-bearing biotite schist, followed by graphitic quartz schist at the northern end of the wave-cut platform. The graphitic schists locally contain >20% pyrite as streaks, 'splashes' and fine disseminations. The two samples of this lithology are slightly enriched in Cu (322 and 260 ppm) and Au (8 and 3 ppb) but contain background levels of Pb and Zn. Samples of the other two lithologies show no significant enrichment in base metals or Au.

Rubha Hanais (Locality F)

The dominant lithology at this locality is psammitic paragneiss [093 745], which contains slightly elevated Cu (c. 260 ppm). To the north and west the succession passes into amphibolites, containing <5 to >40% plagioclase, with the more feldspathic rocks characteristically containing slightly higher Ca. These amphibolites have an unusually high magnetic signature (median 65 x 10^{-3} SI) and may be part of the basement succession.

Carnan Mor (Locality G)

The majority of the Carnon Mor hill comprises mafic granulite, with median susceptibility of 129 x 10^{-3} . SI [096660 740645]. This lithology contains exceptionally low Cr (7 ppm), and Ni (10 ppm), similar to KLR 4842 on Ceann a Mhara. A narrow belt of plagioclase-hornblende-biotite gneiss is exposed nearby [0906 7406], and contains 3.6% Ca and 4.8% Fe. These data, together with trace element values, suggest that this rock may be dioritic, although the low values of Cr (29 ppm) and Ni (20 ppm) indicate a possible sedimentary origin.

Mineralogy

Twelve samples were selected from Colville's drill-cores from boreholes 1, 1A and 3 (Moss, Figure 37), borehole 7 (Loch a'Phuill, Figure 37) These samples comprised banded, pyroxenous granulites (BH's 1, 1A and 7) and hornblendic gneisses (BH3). Stocks (1994) recorded a PGE grain in hornblendic gneisses from the latter borehole. Detailed mineralogy is given by Fortey (1995). Magnetite is a major constituent of the pyroxenous granulites ranging from orthopyroxenite to clinopyroxenite. Quartz and apatite are common minor constituents. Ilmenite is present in certain samples, but not in others. Rhythmic alternation of magnetite- and pyroxene-rich bands suggests that these rocks originated as banded ironstones. According to Stocks (1994), such rocks occur at a boundary between paragneiss (garnet-biotite granulite) and orthogneiss (hornblende and garnet-hornblende gneiss and schist), and, in part, enclosed wholly within the latter. Petrological descriptions given by Stocks (op. cit.) confirm the presence of garnet as a major mineral in the rocks associated with the magnetite-rich rocks, but as only a relatively minor mineral in the magnetite-rich rocks themselves. The present work confirms this and garnet was not reported from any of the thin sections.

The samples contain variable amounts of sulphide minerals. For the most part, these are of minor significance, involving only accessory quantities of pyrite and chalcopyrite. The sulphide minerals occur in a range of textural settings, some spatially associated with hornblende and biotite, others intergrown with traces of carbonate. In one sample, these sulphides seal members of a set of parallel brittle shear fractures. It is concluded that the sulphides were formed during a late-metamorphic (or post-metamorphic) hydrothermal event. Sulphide minerals were most abundant in the BH3 samples, such as KLR 7059 which includes probable pentlandite and digenite. Stocks (1994) observed a granule of a Pd, Pt, Ni, Te mineral in this sample.

Assays for Au, Pt and Pd indicated that none of these elements is present at high concentrations in the small samples. Highest values recorded are 17 ppb for Au, 6 ppb for Pt and 32 ppb for Pd, with most results for Pt and Pd below the 3 ppb detection limit. There is some evidence to suggest that Pd occurs preferentially in the sulphide-mineralised hornblendic gneiss. Thus Pt was detected in three hornblendic samples from BH3 but was below detection in all but one of the magnetite-rock samples. Pd shows a similar pattern, being undetected in magnetite-rock, but the hornblendic gneiss samples range from 4 to 32 ppb. This pattern is not apparent for Au, although the highest concentration (17 ppb) was recorded in one of the hornblendic gniess samples. The presence of pentlandite, chalcopyrite and a Pd, Pt, Ni, Te mineral in these rocks suggests that the traces of PGE may have been introduced by hydrothermal processes.

Discussion

Exhalative rocks on Tiree are confined to the western supracrustal belt and, as discussed by Whitehouse and Robertson (1995), the supracrustal belt could represent either a different crustal level to the gneisses or a distinct terrane.

The occurrence of iron oxide exhalites within a sediment-dominated succession is similar to the Gairloch and Loch Maree successions. However, the association between magnetite and pyroxene gneiss is unusual and is not comparable with the aforementioned areas, and the chemistry is more similar to the magnetite- and garnet-rich eulysites associated with eclogites at Glenelg (Coats et al., 1996). Textural evidence suggests that the pyroxene-magnetite assemblage formed during a stage of high-grade regional metamorphism. Contacts between magnetite and pyroxene gneisses are poorly exposed at surface and will have been modified by later deformation.

PGE assays failed to confirm concentrations greater than 32 ppb Pd in the small suite of pyroxene-magnetite or hornblendic gneisses examined as part of this project. However, the association between sulphide mineralisation in the form of pentlandite and chalcopyrite and a Pd-Pt-Ni-Te mineral is typical of PGE concentrations in igneous pyroxenites.

COLL

Introduction

A brief reconnaissance of the supracrustal rocks of Coll was carried out. The metasediments are dominantly quartz and feldspar-biotite granulites and appear to be unlikely hosts for mineralisation and the occurrence of meta-igneous rocks is very limited. The supracrustal rocks form three principal belts towards the western end of the island, where they are superimposed on a basement of dominantly acid (granitic) gneiss. The supracrustals, together with their basement, are distinctive for the presence of granulitic textures (Drury, 1972). The western belt extends from Crossapol Bay to Feall Bay, but its central part is concealed by dunes for approximately 2 km^2. It is probable that the same lithologies outcrop again to the east, to form the Loch Breachacha - Hogh Bay belt. Two kilometres to the east of this the eastern belt is exposed, which includes the conspicuous, pure Acha quartzite, which may be traced nearly continuously from just south of Acha [1182 7544], to Clabhach on the north coast. Granitic gneisses are well exposed on Ben Hogh [118 758].

The sediments have been subjected to granulite facies metamorphism, with the dominant lithologies quartz granulites and feldspar-biotite granulites. The quartz granulites are best exposed in the Crossapol Bay - Feall Bay paragneiss zone where they form units generally 5–10 m in width, commonly intercalated with feldspar-biotite granulite. The feldspar-biotite granulite is fine to medium-grained, with a weak fabric and contains sub-centimetric foliation-parallel ribs and clots of plagioclase or, in some cases, more persistent sub-cm bands of quartz.

Lithogeochemistry

Crossapol

A succession of interbedded feldspar-biotite and quartz granulites, with subordinate calc-silicates, is exposed as shallow coastal promontories [112 752]. Individual units are 2–10 m across. Three samples of feldspar-biotite granulite were collected from separate units and showed similar chemical compositions. Median levels for Ca and Fe are 18367 ppm and 45158 ppm respectively. Samples of quartz granulite are, characteristically, low in all the major and transition elements analysed, although one sample contained slightly elevated Pb (70 ppm). No significant enrichment in base metals or Au was encountered, and the succession probably represents a sandstone-shale sequence. A sample of biotite-hornblende schist (KLR 4884) [113005 752930], contains unusually high Ti (13129 ppm), with elevated Ni (222 ppm), Cr (608 ppm) and V (316 ppm) but relatively low Fe. Its chemistry indicates a basic igneous origin. A median susceptibility value (9.5 x 10^{-3} SI)for this sample is unusually high.

Feall Bay

At the eastern end of Feall Bay at Beinn Beag [114 754], a succession of interbedded calc-silicates and impure marbles are exposed. Base-metal levels are low, with Cu, Pb and Zn all <10 ppm. To the north of the marbles on Leac Chogaidh promontory [114280 754960], a 2 m thick unit of hornblende-biotite schist, similar to KLR 4884 outcrops. This sample (KLR 4891) also contains elevated Ti (10899 ppm), Ni (847 ppm) and Cr (1152 ppm), suggesting it was originally an ultramafic rock. Interstitial plagioclase appears to be absent, and the higher Cr and Ni values suggests that this lithology is less evolved than its counterpart.

Hogh Bay

Exposures at the west end of Hogh Bay represent a zone of interbanding of paragneiss and orthogneiss. The orthogneiss sampled (KLR 4892) is a generally massive hornblende-plagioclase-biotite granulite, with localised weak alignment of the hornblende. Minor enrichment in Cu (192 ppm) Ti (9046 ppm) and V (389 ppm) is consistent with a basic origin. The sample was also slightly enriched in Au (5 ppb). This lithology displays a very variable magnetic character - between <1 and >25 x 10^{-3} SI. At the west end of the bay coarse-grained hornblende-plagioclase-biotite and quartz granulites are exposed, interbanded on a 2–15 cm scale. The banding is locally disturbed by feldspathic veining but no sulphides were observed within these bands.

Loch Gortan

Quartz, quartz-biotite and calc-silicate granulites are exposed along the eastern side of this narrow inlet [117 753]. No enrichment in base metals or Au was found in either of the two samples that were collected.

Discussion and conclusions

The paragneisses of Coll comprise dominantly semi-pelitic and psammitic lithologies, with subordinate calc-silicates and marbles and minor meta-igneous rocks. There is no evidence of exhalative horizons within the succession, and sulphides were not observed at the localities visited. It is therefore considered that the Coll succession cannot be correlated with the western belt of Tiree, or with any of the iron or sulphide-facies bearing successions on the mainland.

OUTER HEBRIDES

Introduction

A limited programme of sampling was carried out on these islands. Throughout the Outer Hebrides the dominant rocks are quartzo-feldspathic gneisses of acid to intermediate composition (Fettes et al., 1992). The basement rocks in the areas sampled are dominantly banded or streaky gneiss, commonly with dark lenses composed of coarse aggregates of hornblende. Coarse dappled amphibolitic textures are also a common feature of these rocks. In recent years road improvements have led to the excavation of numerous small roadstone quarries and road cuttings within which these lithologies may be observed.

The supracrustals of these islands have been described in detail by Coward (1969), Jehu and Craig (1927 and 1934) and, more recently, by Fettes et al. (1992). Metasedimentary rocks including calcareous and graphitic gneisses, quartzites and rare marbles, together with biotite-rich garnetiferous gneisses, are exposed as a north-trending belt, c. 1 km wide on average, through the central parts of South Uist and Benbecula. Rocks of similar type also form two supracrustal belts, flanking the South Harris Igneous Complex (Figure 38). This was the subject of an earlier MRP Open File release (Shaw et al., 1993).

Associated with the metasedimentary sequences of both North and South Uist and South Harris are suites of characteristically banded orthogneisses ranging from basic to ultramafic pyroxenites. The basic units are generally more laterally extensive and display an iron-enriched trend similar to modern tholeiites. The ultramafic lithologies generally occur as pods which pass laterally from black amphibolitised clinopyroxenite into plagioclase amphibolite. These were interpreted by Horsley (1978) as being derived by clinopyroxene fractionation of tholeiitic magma. Slight PGE enrichment of the ultramafics, and in remobilised sulphides in metasediments on South Harris (maxima 210 ppb Pd and 36 ppb Pt, Shaw et al., 1993) indicated the potential for similar enrichment in North and South Uist.

Benbecula

At the Market Stance quarry (Figure 38) migmatitic gneisses of highly variable texture are exposed. These range from mafic (hornblende gneiss) to quartz ± biotite ± garnet gneiss and, as such, are typical of many other roadside exposures of supracrustals on North and South Uist. There are no obvious indications of exhalative lithologies. The western face of the quarry comprises dominantly quartz gneiss, exposed over c. 60 m, with modal variations in biotite and hornblende. At the southern end hornblendic and biotitic variants dominate. The biotitic variants show elevated levels of Ba, Cr, Mn and Ni, but similar levels of Ca and Fe to the quartz-rich gneisses.

The hornblendic gneisses are generally fine-grained, with up to 90% hornblende. The composition is 2500 ppm Ti, 8% Ca, 6% Fe, 1100 ppm Ni but low Cr (<60 ppm). Within the limitations of this investigation it was not possible to establish the protoliths of such a variable migmatitic succession.

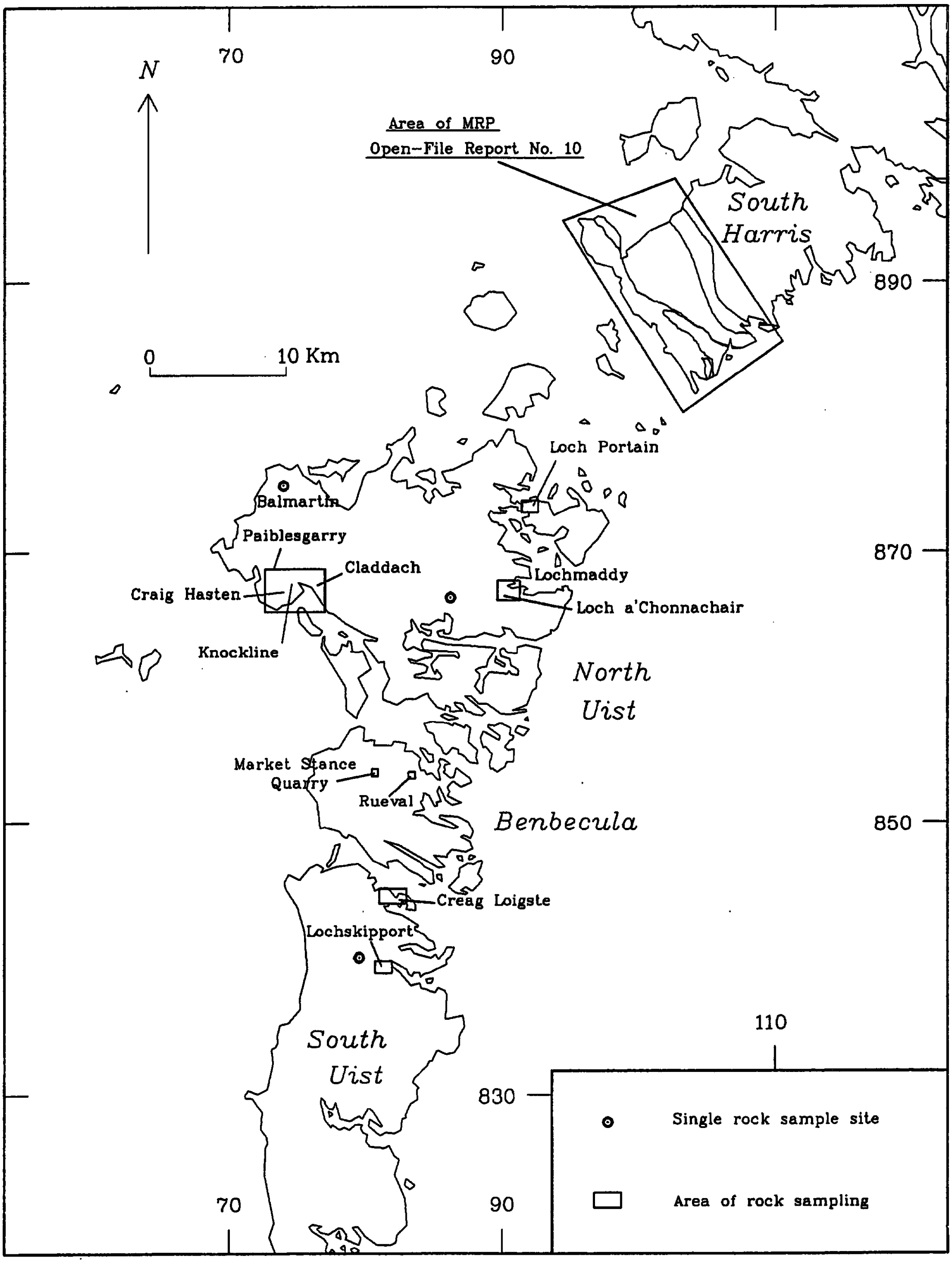

Figure 38 Location map of the Outer Hebrides showing detailed project areas.

Sulphide, dominantly pyrite with subordinate chalcopyrite in one sample [080700 853700], is common across the outcrop. It occurs as fine disseminations, clots, 'splashes' and small streaks, and varies in abundance from 2 to 5%. Slight Au enrichment occurs in all samples, varying from 4 to 17 ppb, with a median of 9 ppb. It is likely that these low levels of Au are associated with the pyrite. Base metal values, with the exception of the sample containing chalcopyrite (314 ppm Cu), are low, with maximum values of 4 ppm Pb and 78 ppm Zn.

North Uist

Ultramafic rocks were sampled at Lochmaddy, Claddach and Craig Hasten (Figure 38), with olivine pyroxenite being the main lithology. Three samples were collected from Claddach [076660 867000], two samples from Craig Hasten [074010 867120] and one from Lochmaddy [090330 867340]. Olivine-rich variants at these localities are readily characterised by higher Cr levels (up to 3363 ppm) and Ni (up to 1805 ppm), whereas subordinate lithologies of amphibolitised pyroxenite contain lower levels of these elements and low levels of the PGE (maximum 7 ppb combined).

A single sample of hornblende gneiss, containing c. 0.5% fine pyrite was collected from Balmartin at [074 875]. The sample contains 11% Fe, 151 ppm Cu and 121 ppm Zn and but Au values are below the detection limit.

At Loch Portain [092 873] on the north-east coast, the main lithology is olivine pyroxenite, and samples are slightly enriched in Pt and Pd up to 18 Pt and 12 ppb Pd. However, in most of these samples Au values are at or close to detection limit. Interstitial sulphide is fine grained and rarely seen, except at two sites where fine-grained interstitial pyrite is present.

South Uist

A sampling transect was carried out from the rocky cove at Creag Loigste [0822 8448] (Figure 38) in a south-westerly direction along the roadside. Three samples of medium-grained clinopyroxenite were collected (KLR 4927, 4928 and 4936), containing up to c. 0.5% interstitial pyrite. Median levels are 7.7% Ca and 6.3% Fe, with 738 ppm Cr and 1289 ppm Ti. At [081380 844265] metasediments (biotite and garnet-hornblende gneiss) are exposed in a road cutting. A sample of garnet-hornblende gneiss, from a 3.5 m wide pod, with a median magnetic susceptibility of 90 x 10^{-3} SI is enriched in Fe (17%), Mn (0.5%) and Ti (14700 ppm) indicating an igneous parentage. The sample is also weakly enriched in Zn (228 ppm).

Discussion

Limited field investigations on North and South Uist and Benbecula revealed supracrustal rocks of similar type to those of South Harris. Mafic and ultramafic lithologies, which in places display modal variations in mafic minerals characteristic of igneous fractionation, are similar to those of South Harris. At one locality near Creag Loisgte, rocks of potentially exhalative origin were exposed, but time limitations prevented a detailed appraisal. Further evaluation of this locality is recommended, using detailed ground geophysics, together with coastal section mapping to the south-west in the vicinity of Loch Carnan. In addition, detailed mineralogical and geochemical comparison between the the pyroxenites of this locality and those of Tiree might be used to model the probable tectonic settings of these rocks and their associated supracrustals.

BASIC AND ULTRABASIC ROCKS IN THE CENTRAL BELT

Introduction

Two brief phases of reconnaissance investigation were carried out over Lewisian basic and ultrabasic rocks in north-west Scotland.In the first phase, lithogeochemical sampling was conducted at localities between Loch Laxford in the north and Gruinard Bay in the south where remnants of formerly extensive layered intrusions have been described in the literature. The platinum-group elements (PGE) were the main focus of interest during this phase of work. In the second programme, carried out in 1994, attention turned to Cu, Ni and Au, in addition to the PGE. During this period sampling was carried out principally in the Scourie, Lochinver and Drumbeg areas (Figure 1).

Sampling and analysis

A total of 55 samples were analysed in the first phase of work. Pt and Pd were determined by lead fire assay of 30 g samples followed by graphite furnace AAS analysis (GFAAS). These analyses were conducted by Alfred H. Knight International of St. Helens, Merseyside. The lower reporting limits were 5 ppb Pd and 10 ppb Pt. In the second period of investigations a further 58 samples were collected. These were analysed for Pt, Pd, Rh and Au, down to levels of 1-2 ppb, by Acme Analytical of Vancouver employing a lead fire assay on 30 g samples followed by either a GFAAS or ICP-MS finish.

In addition to Au and the PGE a wide range of elements was determined by XRF analysis of pressed powder pellets. The samples collected in the first phase were analysed by MESA, formerly of Long Eaton, Nottingham, while those collected in 1994 were analysed by the Analytical Chemistry Group of the BGS.

Lithogeochemistry

The geochemical data obtained in the two periods of investigation have been unified for the purpose of presentation and discussion of results. It is stressed, however, that the elements determined differ between the two phases. In particular, Au was not determined in the first period of work.

The results have been sub-divided on a geographical basis starting in the north of the region. To avoid frequent repetition the prefix 'meta' has been omitted from rock names in the descriptions of the sample localities.

Rhiconich area

At the locality of Poll Iornail cliff, 3 km south-south-east of Rhiconich [226 949], five samples were collected from a series of shallow-dipping sheets, lenses and pods of mafic and ultramafic rocks in extensive cliff exposures. These bodies are locally concordant with the foliation in the enclosing gneisses but, elsewhere, are highly discordant and disrupted. They do not exceed 4 m in thickness and can rarely be traced for more than 10 m. Small-scale impersistent modal layering is locally well developed, but no primary sulphide enrichment was noted. Sporadic late pyrite, up to 1%, was observed in a foliated biotite-hornblendite. This sample (KLR 5030) contained 911 ppm Cu, 617 ppm Ni and 1877 ppm Cr. The highest precious metal level reported from this locality, 15 ppb Pd, was in an orthoamphibolite carrying minor metallic sulphide.

Laxford Shear Belt

During the 1994 programme particular attention was focused on the Laxford Shear Zone, a major north-west-oriented structure which separates the Central or Scourian region of essentially unmodified granulite gneisses of Archaean age from the Laxfordian region to the north, which was affected by later deformation and metamorphism (Beach et al.; 1974, Davies, 1978).

Foindle

In the early 1970s Consolidated Gold Fields Ltd carried out exploration for Cu-Ni in the Scourie area with financial support provided under the terms of the Mineral Exploration and Incentives Grant Act (MEIGA). At Foindle, 5 km north-east of Scourie [218 948], a single inclined borehole was drilled to a depth of 35 m to investigate the cause of high amplitude IP and EM anomalies and the sub-surface extent of mineralisation exposed in a surface gossan. Chemical analysis of this gossan had yielded 980 ppm Cu. Sporadic minor sulphide mineralisation was intersected within a sequence of ultrabasic and basic rocks in the borehole. A single thin layer of sub-massive pyrrhotite, with subordinate pyrite and chalcopyrite, yielded the maximum Cu and Ni values of 1360 ppm and 1030 ppm respectively. In the present programme a single sample of exposed gossan close to the borehole site yielded 1.6% S with attendant levels of 284 ppm Cu and 100 ppm Ni.

Along strike approximately 1 km to the north-west of the borehole site layered mafic and ultramafic rocks are exposed on the south-west side of Loch na h-Airigh Glaise. Late sulphide enrichment comprising about 3% pyrite, associated with irregular quartz stringers, is accompanied by minor enhancements of PGE and Au together with 216 ppm Cu. A thicker ultramafic body about 10 m wide was also located 200 m to the south-west and has an exposed strike length greater than 200 m. No sulphide mineralisation was observed in this body.

Clar Loch

Extensive exposure, 1 km south of Foindle [218 947], of predominantly orthoamphibolite with subordinate ultramafic rocks was located on the east side of Clar Loch. Two sections, each several tens of metres wide and traced for 100 m along strike, were examined and seven samples were collected. Maximum precious metal values, 18 ppb Pt and 16 ppb Pd, are derived from a serpentinised pyroxenite band without visible sulphide. Other samples from these bodies have uniformly low precious and base-metal concentrations.

Loch na Claise Fearna

A road-cut, 1.5 km south-east of Foindle [220 946 and 220 947] provides near continuous exposure over a 750 m section across the Laxford Shear Zone along the south-east side of Loch na Claise Fearna. During 1976 Consolidated Gold Fields Ltd drilled four inclined boreholes, aggregate depth 205 m, in this section to investigate the cause of extensive coincident IP and EM anomalies. Little sulphide mineralisation was intersected, except for sporadic thin bands carrying 10–20% pyrrhotite. Cu and Ni levels were low throughout. Au and Ag concentrations determined in selected sulphide-rich intervals did not exceed the analytical detection limits. It was concluded that the low metal values and narrow widths of the mineralised intervals precluded any favourable economic potential in this zone.

Five rock samples were collected during the 1986 programme, supplemented by a more detailed examination and collection of 13 additional samples during the second phase of work. The south-western third of the road-cut comprises banded amphibolitic gabbro with thin ultramafic units and subordinate quartz-feldspar-biotite gneiss. The remainder of the section is dominated by leucocratic, locally basic, gneiss with sporadic ultramafic bands and associated layered orthoamphibolite. Minor sulphide mineralisation is widespread, principally in association with felsic bands and veins, and is clearly late in origin. The highest PGE concentrations were derived from a gneissose orthamphibolite with locally abundant late pyrrhotite. This sample (KLR 5012) contains 17 ppb Pt, 16 ppb Pd, 1198 ppm Ni, 2837 ppm Cr and 87 ppm Cu. The highest Au concentration (15 ppb) reported from this section was derived from an irregular hornblendite zone with sheared biotite-rich margins against the enclosing gneiss. Cr is enriched to 5481 ppm in this sample, although PGE and Ni levels showed only minor enrichment. Sporadic enhancement of Cu is noted in a few samples, up to a maximum of 442 ppm (KLR 5013). This sample of biotite-rich melagabbro contains local concentrations of late pyrite associated with poddy quartz veinlets. It also contains elevated levels of Zn (761 ppm), Pb (123 ppm), Ba (858 ppm) and Mo (25 ppm).

Gorm Loch - Gorm Chnoc

At this locality, in the vicinity of Gorm Chnoc, north shore of Gorm Loch, 6 km east of Scourie [221 944] Davies (1974) describes a lens of basic-ultrabasic rocks outcropping over a strike length of about 1 km and attaining a maximum width of 400 m. A sequence of ultramafic rock, mafic rock and anorthosite is recognised in the field at least six times within this lens. Remnants of small-scale modal and phase layering are well preserved in rocks which were originally dunites, peridotites and pyroxenites. Davies interpreted this body as part of an original single sheet of Early Scourian age extending along strike to the north-west for at least 12 km.

Ten samples were collected from the Gorm Chnoc body representing the main lithological and textural variants. Metallic sulphide mineralisation was restricted to rare traces of pyrite. PGE contents are not enriched above levels normally found in these rock types. The highest Cu (566 ppm) and Au (12 ppb) concentrations were reported in a heterogeneous plagioclase-rich zone within a strongly foliated orthoamphibolite. Minor streaks and irregular patches of fine pyrite were noted marginal to this feldspathic zone. Lower tenor Cu enrichment, without attendant Au, was also found in two samples of gabbroic rock from this body containing minor pyrite.

Gorm Loch - Clar Loch Mor

In this area, 6 km east-south-east of Scourie between [220 943] and [221 943], basic and ultrabasic rocks similar to those at Gorm Chnoc are exposed over a 2 km strike length in a zone up to about 300 m wide (Beach, 1978). The quality of the exposure is such that continuity of banding, interpreted as original magmatic layering, is clearly demonstrated. The ultramafic bands are thicker and more continuous than those at Gorm Chnoc. However, as at Gorm Chnoc, the content of metallic sulphides is uniformly low. Minor pyrite is widespread in the gabbroic rocks while only sporadic traces are observed in the ultramafic units.

The geochemical results for six representative samples are generally disappointing, with precious metal levels showing no enrichment above concentrations normally expected in these rock types. However, a garnet melagabbro (KLR 5043) containing sporadic enrichment in pyrite, with subordinate chalcopyrite, concentrated in foliated marginal zones and on fracture planes yielded 3351 ppm Cu, the highest value recorded in this survey of the Central Belt. Attendant levels of other metals in this sample are 14 ppb Au, 897 ppm Ni and 273 ppm Zn.

Scourie area

This area extends to the north and north-west of Scourie House. Between [214 945] and [215 945]. O'Hara (1961) and Bowes et al. (1964) described several sheet-like masses of ultrabasic and basic gneisses generally concordant with the enclosing Scourian granulite gneisses. These are cut by younger dolerite dykes (Scourie dykes) oriented north-west - south-east. A total of 14 samples was collected from this area during the present investigations. The majority of the samples were derived from the basic and ultrabasic gneisses, although the Scourie dykes and gneisses were also sampled for comparative purposes.

The highest sulphide contents were noted in gneisses forming rusty-weathering prominent knolls which have been interpreted as relics of metasediment (Beach, 1978). Elevated S contents, up to 3.4%, are accompanied by low tenor enrichment in Cu (310 ppm) and Ni (1311 ppm). In the meta-igneous rocks conspicuous sulphide concentrations were sporadically observed in garnetiferous melagabbros. Minor Cu and Ni enrichments are reported in these rocks but PGE contents are uniformly low. No significant base or precious-metal values are reported from the ultrabasic gneisses. 15 ppb Pt and 30 ppb Pd were present in a sample of coarse hornblendite, but associated levels of Cu and Ni are low.

Loch an Daimh Mor

Five samples were collected from the extensive exposures 2 km south of Scourie [215 942] of ultrabasic rocks situated close to the southern end of Loch an Daimh Mor, which have been described by Peach et al. (1907, p.130) and O'Hara (1961). Samples of serpentinite and anthophyllite-magnesite rock were found to contain low PGE and Cu concentrations. Elevated Ni levels, up to 3136 ppm, are commensurate with values typical of ultramafic lithologies, and Ni/MgO values are consistent with Ni in olivine rather than in a separate sulphide phase. Slightly enhanced PGE (15 ppb Pt, 20 ppb Pd), Ni, Cu and S values were reported in a single sample of 'contact gneiss' (O'Hara, 1961) collected at this location. This comprised a coarse-grained heterogeneous garnet-amphibole-pyroxene rock containing common pyrrhotite, together with minor pyrite and chalcopyrite.

Glac Mhor

Two samples were analysed from the banded mafic-ultramafic body which outcrops in crags on the north-west side of the road at this locality 2.5 km east of Scourie [217 944] (Bowes et al., 1964). No enrichments in metallic elements were reported in these samples.

Drumbeg

At this locality [211 932] 10 km north-north-east of Lochinver, banded peridotite and garnet amphibolite underlie an area of approximately 1 km^2 in a broadly synclinal structure (Bowes et al., 1964). Eight representative samples were collected from this mass, mostly from the southern limb exposed on the north shore of Loch Drumbeg. The two highest Pt values in this survey were derived from this body. A serpentinised peridotite sample (PGR 8041) with no visible sulphide was found to contain 30 ppb Pt and 40 ppb Pd, with associated levels of 115 ppm Cu and 1280 ppm Ni. The second PGE-enriched sample (PGR 8039) was from a small discordant lens of melagabbroic rock containing common pyrrhotite and minor chalcopyrite. Analytical data for this sample are 25 ppb Pt, 20 ppb Pd, 2.2% S, 496 ppm Cu, 556 ppm Ni and 245 ppm Zn.

Loch Poll - Lochan Fada

Seven rock samples were collected from an east-west trending ultramafic and melagabbroic body 8 km north-north-east of Lochinver [210 930 and 211930], which can be traced between the two lochs over a distance of approximately 750 m. This body is between 100 and 150 m wide and comprises principally ultramafic rocks, peridotites with subordinate pyroxenites, which display good modal and grain-size layering. Minor sulphide mineralisation is widespread, mainly in the gabbroic components of the body. Pyrite is the predominant phase and was apparently introduced at a late stage in the evolution of these rocks. Sparse sulphide mineralisation is also locally present in the ultramafic lithologies.

Geochemical data for these samples show generally low precious and base metal contents, comparable with levels normally found in basic and ultrabasic rocks. Pt, Pd and Au are weakly enriched in ultramafic lithologies. The highest Cu value, 100 ppm, was derived from a quartz-veined melagabbro (KLR 5037) carrying about 0.5% pyrite, located close to the southern boundary of the body.

Gorm Loch Mor

Four samples were collected from a north-east - trending gabbroic body which is fairly well exposed over a strike length of a few hundred metres adjacent the north arm of Gorm Loch Mor, 9 km north-north-east of Lochinver [213 930], and attains a maximum width of about 100 m. Weakly banded and disrupted amphibolitised melagabbroic rocks predominate, with local ultramafic bands which may attain thicknesses of 20 m. Minor pyrite is a widespread constituent of the gabbroic rocks, but precious and base metal contents are uniformly low in all samples collected.

North Kylesku - Duartmore

Several extensive sections of amphibolitic gneiss of possible magmatic origin are exposed in road cuttings along the A894 between Duartmore Forest and Loch a Chreagain Daraich, 4–6 km north-west of Kylesku. A sample of thinly banded gneiss with minor late pyrite was found to contain 13 ppb Au and 97 ppm Cu, but no other metals were enriched in this sample. A sample of biotite-bearing hornblendite with minor late sulphide concentrated on foliation and fracture planes was found to contain 3229 ppm Cr and 1254 ppm Ni, but only 20 ppm Cu.

Ben Strome - Maldie Burn

The most extensive area of basic - ultrabasic rocks examined during this survey is located on the east and south-east flanks of Ben Strome on the north side Loch Glendhu [225 935]. In this area multiple sheets of garnet-bearing melagabbros, peridotites and pyroxenites are found over a strike length of at least 1 km with a maximum width of several hundred metres. Sulphide mineralisation within these bodies is sparsely developed and the precious and base-metal levels reported in the six samples analysed are uniformly low. The highest Au and Cu concentrations, 18 ppb and 180 ppm respectively, were derived from a melanocratic band within predominantly gabbroic rocks containing about 0.3% late pyrite on fractures. High Cr abundances were reported from ultramafic lithologies, up to a maximum of 4005 ppm, but no discrete bands of chromite were observed in the field.

Achmelvich Bay

Fairly large sheets, up to 500 m in length, of predominantly ultramafic character are found near Cnoc Beag [204 926] on the north side of Achmelvich Bay and at An Fharaid Mhor on the south side of the bay (Beach, 1978). Five samples from these localities were analysed but yielded uniformly low precious and base-metal values. Cr concentrations are generally high, reaching a maximum of 4281 ppm, but no discrete chromite bands were observed.

Achiltibuie

Immediately east of Achiltibuie banded mafic and ultramafic rocks underlie an area about 1 km in length and several hundred metres wide [203 907]. The rock types present include peridotite, pyroxenite, garnet-amphibolite and anorthosite, but sulphide contents are generally very low. Analysis of six representative samples yielded detectable PGE concentrations in only two. The maximum reported Cu value (270 ppm) was found in a garnet melagabbro containing traces of pyrite and chalcopyrite.

Gruinard Bay

Limited outcrop examination and sampling were carried out in the vicinity of Gruinard Bay. Three localities were examined. Two samples of hornblendite from the ultramafic body at Meall Buidhe [193 889] were found to contain elevated S contents (about 0.5%) and attendant Cu enrichment up to 263 ppm, but PGE levels were below the analytical detection limits. Two samples were also collected from small bodies of banded mafic and ultramafic rocks located on the south and west sides of Lochan an Daimh [198 892]. Minor Pt and Cu enrichment, up to 20 ppb and 262 ppm respectively, were reported in these samples. A single sample was also analysed from a small body of gabbroic rocks located on the east side of the Inverianvie River near the south-east corner of Lochan Dubh [196 889]. Minor Pt and Cu enrichment was also reported in this sample.

Discussion and conclusions

The concentrations of precious and base-metals in the Central Belt mafic-ultramafic lithologies are generally low. The highest PGE contents reported (30 ppb Pt and 40 ppb Pd) exceed levels typical of ultrabasic rocks, but in 90% of the samples there is no such enrichment. Au contents are also low, with a median value of 4 ppb. Low tenor Au enrichment exceeding 10 ppb is present in only 9 samples, normally associated with late, post-magmatic quartz veining and minor hydrothermal sulphide mineralisation. Ni concentrations are generally low with a median value of 402 ppm. These levels in meta-igneous rocks are consistent with the presence of Ni in olivine rather than in a sulphide phase. Two samples with elevated Ni/MgO values are of metasedimentary origin. The highest Cu value reported was 3351 ppm, with no other samples exceeding 1000 ppm Cu. Minor enrichment in metallic sulphides observed in the field is consistent with the analytical data for S (determined on 55 samples only). 25% of the samples analysed contained more than 5000 ppm S.

Overall, on account of the lithogeochemical results and the small physical size of the basic-ultrabasic bodies, it is concluded that no potential exists for significant metallic mineralisation in this region. The reason for the lack of any metal enrichment in these rocks is unclear. No evidence for the presence of any primary magmatic sulphide concentrations has been observed. It may be that no PGE- or Au-enriched sulphide phase was formed or, alternatively, that subsequent metamorphism and deformation resulted in the destruction of any such horizon.

CONCLUSIONS AND RECOMMENDATIONS

Supracrustal rocks in the Lewisian of north-west Scotland have several of the characteristics of 'greenstone belts' in basement gneiss terrane, which host many of the world's gold deposits. Often these deposits are closely associated with banded iron formations (BIFs) and iron-rich exhalites are present in the Gairloch and Loch Maree belts, associated with a mixed volcano-sedimentary succession. Basic tholeiitic volcanics are dominant over flysch-like sediments and host stratiform, Besshi-style, Cu-Zn-Au mineralisation at the Kerry Road locality. Indications of stratiform mineralisation were found at both Flowerdale Forest and Loch Maree, and, in the former area, there are good indications that the mineralisation described by Jones et al. (1987) at the Kerry Road locality is present a further 10 km to the south east. A similar package of chemical exhalative sediments is present in all three areas. Samples of quartz-magnetite schists from two localities, Loch na Beinne (Flowerdale Forest) and Loch Garbhaig (Loch Maree), have levels of Au (up to 4 ppm) of potential economic interest.

The tectono-stratigraphy of the Loch Maree and Flowerdale Forest areas has been clarified and can now be compared with the better known Gairloch area. In particular, the successions at Loch Maree and Gairloch has been correlated, and the chlorite schist described at Abhainn na Fuirneis is thought to be similar to the footwall to the Kerry Road deposit. This provides a better framework to guide more detailed exploration of the supracrustal succession and its contained stratiform mineralisation. The succession at Loch na Beinne is comparable with that at Kerry Road and the presence of sulphide-bearing and banded iron formations with significant gold values is very promising. It is recommended that detailed exploration should concentrate on the Lewisian concealed beneath a shallow cover of Torridonian rocks near Loch na Beinne and north-west along strike. Reconnaissance traverses using ground-based magnetic and VLF-M techniques have identified high amplitude anomalies of limited strike extent at several localities. At Gorm Loch na Beinne these anomalies are coincident with limited exposure of banded oxide and sulphide facies exhalites. The application of these methods to identify mineralisation beneath the sedimentary cover remains to be tested.

Studies of supracrustal rocks in other parts of the Lewisian in the Inner and Outer Hebrides were not promising and there is little indication of economic mineralisation. On Tiree and the Outer Hebrides the supracrustals include basic to ultramafic igneous types which appear to indicate a possible oceanic affinity. The iron-rich rocks on Tiree may be more similar to the BIFs found associated with the eclogites at Glenelg (Coats et al., 1996) rather than to the Loch Maree Group.

The recognition of Au in association with sulphide and banded oxide/silicate facies at Loch na Beinne provides a focus for reconsideration of Au mineralisation processes in the Lewisian. The presence of three micron-sized Cu_3Au grains inside quartz at the Loch na Beinne locality, within a late graphitic shear/fracture zone, may support an epigenetic redistribution model for the mineralisation. Locally pervasive hematitic alteration in magnetite-rich rocks indicates oxidation, possibly during Torridonian weathering.

The importance of exhalative successions as hosts to many of the world's gold deposits needs to be emphasised, even though the genesis of these deposits is a matter of debate. In many cases the Au appears to be stratabound and is associated with sulphide facies exhalites, suggesting that the Au is syngenetic and precipitated from exhalative solutions along with the chemical sediments. Analogues for this type of deposit are those occurring at modern hydrothermal vents, for example Scott and Binns (1995) describe a sulphide deposit in the Pacific with a mean Au content of 15 ppm. A similar case occurs at Kerry Road where the gold is present in the stratiform Cu-Zn sulphide orebody (Jones et al., 1987). However, the association between Au mineralisation (frequently associated with arsenopyrite) and alteration assemblages characteristic of metamorphic retrogression may point to the importance of epigenetic redistribution processes in these types of settings. A recent discussion of the these processses in the Lupin deposit is given by Bullis et al. (1994). Whilst this debate is largely of academic interest, it is important for exploration in the Lewisian as one model would suggest targetting the mineralised horizon in the stratabound Besshi model, and the other would target the reactive iron-rich sediments as suitable hosts for deposition of gold carried by metamorphic fluids.

Exploration for Au, PGE and Ni deposits in the basic-ultrabasic bodies of the Lewisian has not been very successful. The reason for the lack of any metal enrichment in these rocks is unclear and no evidence for the presence of any primary magmatic sulphide concentrations has been observed. It may be that no PGE- or Au-enriched sulphide phase was formed or, alternatively, that subsequent metamorphism and deformation resulted in the destruction of any such horizon. However the present work has been of a very limited nature and further work is needed to test these somewhat negative conclusions.

The following detailed recommendations are made:

1. Detailed geophysical surveys should be carried out along strike from the Loch na Beinne locality to locate mineralisation under shallow cover of Torridonian sediments. Detailed geological mapping should be completed over the inlier.

2. Further work should be carried out in the Loch Maree area, concentrating on the gold-bearing quartz-magnetite schist and the chlorite schist which may correlate with the footwall chlorite schist at Gairloch.

3. Whilst studies of supracrustal rocks in other parts of the Lewisian in the Inner and Outer Hebrides were not promising, the sampling was of a limited reconnaissance nature and there is still some potential for economic mineralisation. In glaciated areas such the Outer Hebrides, dispersion is very limited and only intensive lithogeochemical sampling would reveal the presence of an economic orebody. Alternatively a detailed airborne geophysical survey would be the most effective exploration method for the detection of sulphide mineralisation.

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