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Minerals information GIS for regional development and inward investment in the Northern Highlands of Scotland

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Commissioned Report CR/03/034N

BRITISH GEOLOGICAL SURVEY

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T Colman, K Rollin, F McEvoy, R Smith, A Benham, A Gunn, M Shaw

Front cover

View looking west of Inverpolly Forest with the peaks of Torridonian sandstone, Cul Mor on the right, Cul Beag on the left taken from 1.5 km north-east of Elphin, Sutherland.

Bibliographical reference

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Executive summary

The principal aim of this project, funded by the Department of Trade and Industry (DTI), is to stimulate exploration for metalliferous minerals in the Northern Highlands of Scotland, thereby promoting inward investment, job creation and the development of infrastructure in the region. The Northern Highlands study area occupies about 27,000 km^2 located to the north and west of the Great Glen, including the Hebrides, Orkney and Shetland. The regional geology is highly varied, comprising mainly Archaean and Proterozoic metamorphic rocks and Palaeozoic sedimentary rocks. Intrusive igneous rocks are also widely developed. This geological diversity enhances the potential of the region for the occurrence of a wide range of mineral deposit types. The Northern Highlands are under-explored, relative to other parts of Scotland; nevertheless, this study has documented more than 350 recorded mineral occurrences.

A minerals-related Geographic Information System (GIS) was created to hold all available geological, geochemical, geophysical and mineral occurrence data for the region. Areas covered by designated environmental constraints were also incorporated in the GIS. New digital datasets utilised in the study include regional multi-element stream-sediment geochemistry and geophysical and Landsat TM lineaments.

The region is prospective for a wide range of mineral deposit types including: volcanogenic massive sulphide (VMS) copper-lead-zinc mineralisation in supracrustal rocks of the Archaean Lewisian terrane in the Gairloch area and platinum-group elements (PGE) in the Unst ophiolite, Shetland and in the Loch Borralan and Loch Ailsh igneous complexes of the Assynt district. These targets are relatively well known and are limited to small areas by their geological settings. In contrast, gold deposits of mesothermal and epithermal styles may occur more widely. Epithermal gold mineralisation associated with Lower Devonian rocks has been documented in east Sutherland and may be present elsewhere. Mesothermal gold deposits developed at deeper levels in the crust, possibly associated with acid-intermediate intrusions and regional fault systems, are another attractive target. Deposits of these types may be relatively small, high-grade deposits, which are well suited to exploration and exploitation by smaller (SME or junior) mining companies.

Mineral prospectivity analysis to identify areas favourable for epithermal and mesothermal gold deposits was carried out using the ArcSDM™ program. Weights of evidence and fuzzy logic techniques were used to produce prospectivity maps that show areas with potential for the occurrence of these deposit types. This analysis identified eight new targets where follow-up exploration is recommended. Five targets are located in the north-east of the region between Loch Fleet and Strathy Forest. The other three targets occur in the west of the region, between Loch Linnhe and Loch Maree. Five of the target areas are relatively free of environmental constraints, which can simplify obtaining permission for any development.

Prospectivity analysis of a region can increase inward investment by mineral exploration companies. Exploration is a global industry and companies require timely and rapid access to information to make decisions on the relative attractiveness of different areas, commodities and deposit types. The project is designed to make a wide range of information available to the industry and to enhance the profile of the region as a potential area for investment. The text of this report and a GIS-viewing program are available on CD.

1 Introduction

1.1 RATIONALE

The Northern Highlands of Scotland are one of the most sparsely populated parts of the EU. The area of this study includes all of mainland Scotland north of the Great Glen, the Inner and Outer Hebrides, Orkney and Shetland (Figure 1.1). The total land area is about 27 000 km^2. Unemployment is high and primary industries are few, but it is also a region of outstanding environmental interest and scenic beauty. One method of stimulating inward regional investment is through developing indigenous mineral resources. It is therefore important to have systematic and comprehensive scientific information concerning the mineral resources of the region in order to inform the debate on the balance between minerals extraction, wealth creation and protection of the environment.

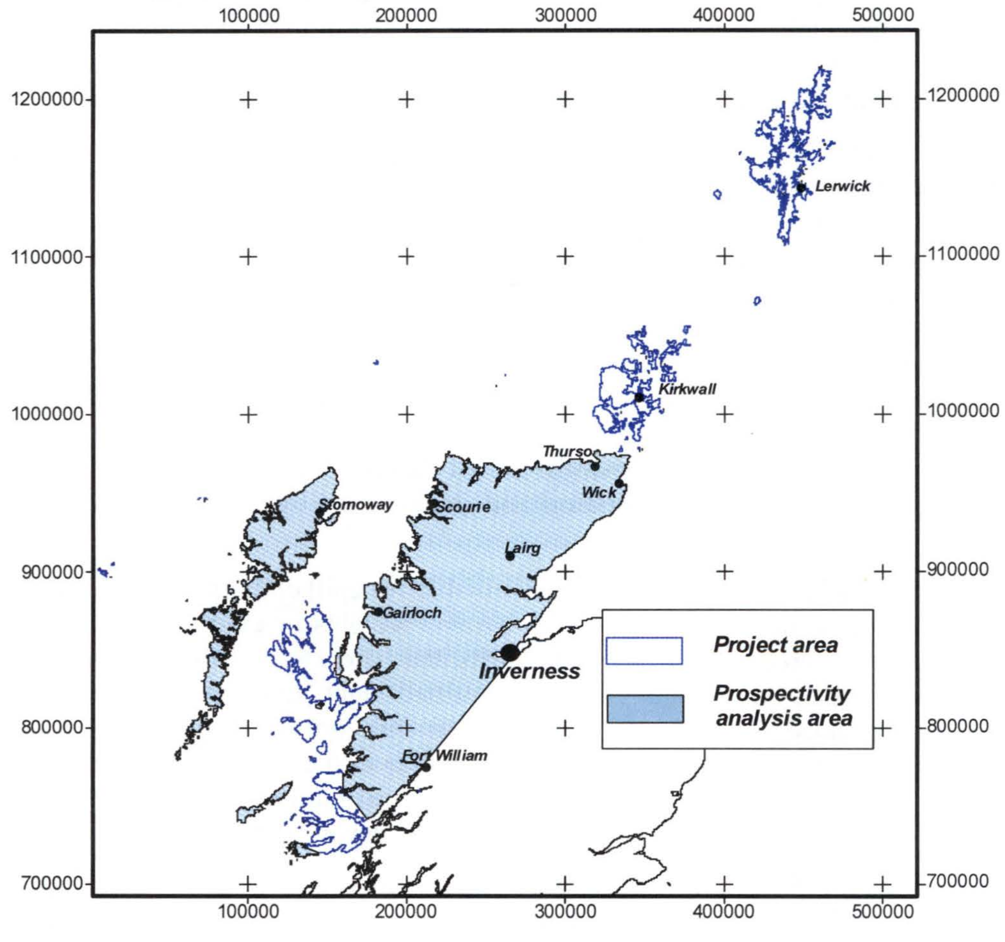

Figure 1.1 Study area

The Northern Highlands of Scotland have not had a significant metal mining history, though a number of small deposits have been worked sporadically over the past 200 years. The region has been very isolated and, until the last century, communications were very difficult; most transport routes were by sea and overland transport was very slow. The Highland Clearances of the 18th and early 19th centuries largely emptied the formerly populated land and replaced subsistence agriculture with sporting estates for shooting, stalking and fishing. The owners generally also owned the mineral rights, with the exception of gold and silver, which are mainly owned by the Crown. All these factors combined to discourage the individual prospector and to lower the possibilities of chance discoveries of metalliferous minerals. The only significant mineral deposits discovered and worked prior to the 1960s were the Strontian lead vein in Morvern, the Raasay iron ore deposit, the Clothister Hill magnetite skarn, the Kildonan alluvial gold deposit in Sutherland and the Sandlodge copper vein in Shetland.

The Northern Highlands of Scotland is an area of diverse geology with potential for a wide range of metalliferous mineral commodities [including gold, platinum-group elements (PGE), base-metals (copper, lead, zinc), uranium, rare metals (tantalum, niobium) and the rare-earth elements]. For many of these commodities new industrial applications are under development and their potential markets are increasing. This increases their attractiveness for exploration investment in the global market place. Hitherto exploration activity in the region has been cursory and sporadic and the area is under-explored relative to the Scottish Grampian Highlands and Southern Uplands where companies, such as Consolidated Goldfields, RTZ, BP and Amax, have conducted major exploration programmes. It is also important to note that overseas new mines are being planned to work some of the commodities mentioned above in terrain previously considered unprospective or where previously known targets have become economic as a result of changing market conditions e.g. Voisey's Bay nickel deposit, Labrador; PGE in northern Finland.

Over the past forty years the worldwide upsurge in mineral exploration has resulted in some reconnaissance studies of the Northern Highlands. The Highlands and Islands Development Board commissioned Robertson Research Ltd to investigate the metalliferous and industrial mineral potential of the area in the late 1960s (Anon., 1969; Mathews, 1972). The publication of a number of reports resulted in several small mining companies carrying out exploration in the Oykell and Rosehall areas. The Institute of Geological Sciences (now the British Geological Survey) published a summary of the mineral resource of the 'crofter counties' of Scotland which roughly coincide with the boundaries of the current project (Berridge, 1969). Consolidated Goldfields and Phelps Dodge investigated most of the granites in the area during the early 1970s for the possibility of porphyry style copper mineralisation using reconnaissance stream-sediment geochemistry. The mineralisation section includes reference to some of the commercial mineral exploration projects which have been completed in the Northern Highlands area.

The most significant mineral deposit in the area is the Gairloch copper-zinc deposit near the eponymous settlement in Wester Ross. It was found by Consolidated Gold Fields in 1979, following up a reference to a 'copper-bearing limestone' in a 1907 BGS memoir (Peach *et al.*, 1907). The deposit is estimated to contain around 0.6 million tons at a grade of about 1% copper and 0.5% zinc. The metal in the ground is thus worth about £10 to £15 million at current prices. However, the small size and low grade make it currently uneconomic to develop. Other significant metalliferous mineralisation discovered in the last 40 years includes platinum-group element (PGE) mineralisation on Unst in Shetland and uranium mineralisation near Helmsdale.

The Loch Aline glass sand operation is the most important non-metalliferous mineral deposit in production in the area. Other, smaller non-metalliferous deposits include the Ledmore marble deposit and the Cunningsburgh talc deposit.

This study is intended to provide a summary of available information on the area, review models for potential mineral deposit types which may be present and identify areas which are considered prospective for those styles of mineralisation.

1.2 PREVIOUS WORK RELEVANT TO MINERAL EXPLORATION

The British Geological Survey has been active in the Northern Highlands since the first geological maps of the area were published towards the end of the 19th century. The memoirs by Peach and Horne (Peach *et al.,* 1907) on the north-west Highlands and by Bailey (1924) on Mull have become classics. Follow-up of a reference to copper-stained limestone in the 1907 memoir led directly to the discovery of the Gairloch Cu-Zn-Au deposit in 1979. A summary report on the mineral potential of the area was completed by Berridge (1969). An evaluation of the mineral potential of north-western Sutherland was carried out by Robertson Research for the Highlands and Islands Development Board (Anon., 1969). This concentrated on the available and potential resources of constructional and industrial minerals as metalliferous minerals were excluded from the remit of the evaluation. However, recommendations were made for metal exploration in several areas, some of which were followed up (Newman, 1971). The Scottish Office and the Department of the Environment also commissioned Wardell Armstrong to investigate the environmental consequences of non-ferrous mineral extraction in Scotland (Anon., 1993). This contains summary information on the main metalliferous deposits known at the time. More recently Dames and Moore completed a review of the mineral development potential of the Highlands and Islands (Green, 1998) and the Shetlands Islands Council commissioned a report on precious metal distribution in the Shetlands (Buchanan and Dunton, 1996). Both of these reports suggest areas for additional work. A major ten-year BGS research project started in 2001, covering the entire Moine Thrust region in the north-west of the area. The aim of the project is to produce modern maps and digital datasets, including imagery, within a GIS framework of the entire Moine Thrust area.

Three national programmes, designed to provide incentives for commercial mineral exploration, started in the early 1970s and operated in the Northern Highlands. They were a) a grant scheme for commercial mineral exploration, b) baseline geochemical surveys and c) baseline BGS mineral exploration.

1.2.1 Commercial mineral exploration

The Mineral Exploration and Investment Grants Act 1972 (MEIGA), funded by Department of Trade and Industry, gave grants for mineral exploration throughout Great Britain for the ores of non-ferrous and precious metals, fluorspar, barium minerals and potash, provided the results were deposited with the BGS. The programme was intended to stimulate private sector exploration and development. It was very successful in attracting a wide variety of large and small companies in the early to mid 1970s, but was suspended in 1984.

Nineteen MEIGA projects were completed in the Northern Highlands area between 1971 and 1984 and are listed in Table 1.1 and shown in Figure 1.2. Eight of these were taken to the drilling stage. All the resulting data, together with selected drillcore, are available for inspection at the BGS. The projects are referred to in the text of this report in the form of (MEIGA) followed by the report number, as in (MEIGA 63). There are also other mineral exploration projects which were carried out prior to, or after, the operation of the MEIGA scheme and others which did not qualify for assistance or were withdrawn after application. These are not listed in Table 1.1.

Table 1.1 MEIGA projects in the Northern Highlands

MEIGA number	Project name	Company name	Commodities
2	Scotland copper/nickel	Consolidated Goldfields Ltd	Cu Ni
3	Molybdenum	Consolidated Goldfields Ltd	Mo Cu Ni
6	Ghrudie	Atlantic and Oceanic Resources Ltd	Mo
58	Clebrig	Acmin Explorations (Uk) Ltd	All
63	Rosehall	Oykel Minerals Ltd	Cu Pb Zn Mo
82	Ousdale	Riofinex	U
85	Coulin	Noranda Kerr Ltd	Cu Pb Zn
89	South Kyle	Oykel Minerals Ltd	Cu Pb Zn Mo

113	Assynt	Noranda Kerr Ltd	Cu Pb Zn
114	Glen Calvie	Noranda Kerr Ltd	Sn Cu Pb Zn
120	Cunningsburgh	Riofinex	Cu Ni
125	Mill of Cairston	Riofinex	U
136	Fetlar-Unst	Noranda Kerr Ltd	Cu Ni
150	Vidlin	Grenmore Holdings	Cu Pb Zn
158	Strontian Barite	Baroid (UK) Ltd	Ba
173	Gairloch	Consolidated Goldfields Ltd	Cu Zn Au
249	Garths Ness	Grenmore Holdings	Cu Zn
250	Cunningsburgh	Grenmore Holdings	Cr Ni PGE
254	Sandlodge	Grenmore Holdings	Cu

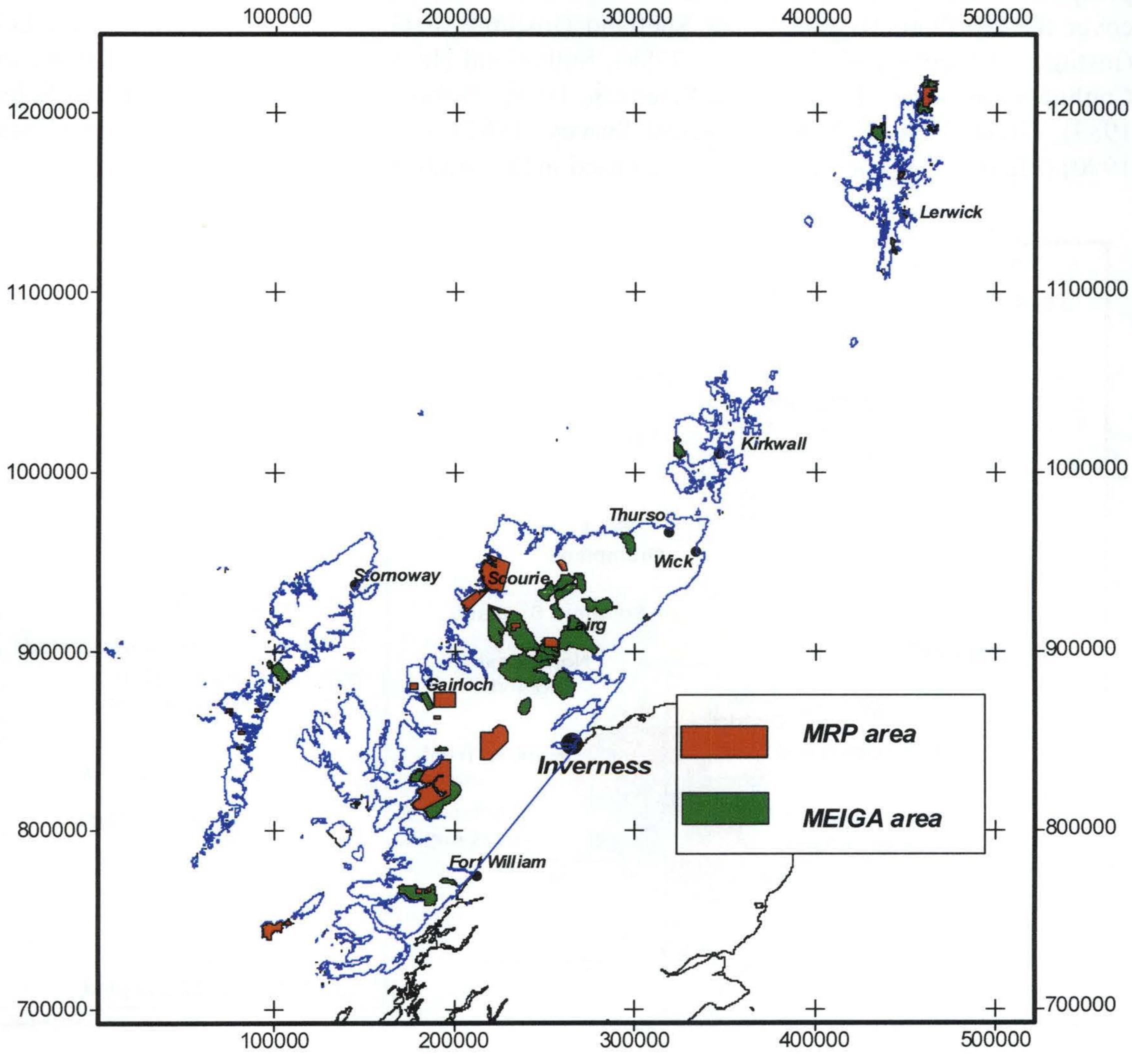

Figure 1.2 MRP and MEIGA areas

1.2.2 Geochemical surveys

The BGS Geochemical Baseline Survey of the Enviroment (G-BASE) programme, formerly the Geochemical Survey Programme (GSP), is funded by the Office of Science and Technology to undertake the systematic geochemical mapping of Great Britain. The work started in northern Scotland in the early 1970s and has progressed southwards as far as East Anglia. The programme employs stream-sediment sampling at a density of one sample per km^2 with analysis currently for up to 40 elements, though only 16 elements were routinely analysed in the Northern Highlands. Water, soil and panned stream-sediment samples are also collected. Data accompanied by an explanatory text are presented in geochemical atlases and are also available for sale in digital format. Interactive, multicomponent digital image processing of the datasets enables the geochemical characteristics of specific formations to be quickly established and searches carried out for geochemical patterns associated with various styles of mineralisation.

The Northern Highlands of Scotland have been covered by approximately 57,480 samples that were originally analysed in the 1970s for 16 elements: Ba, Be, Bo, Cr, Co, Cu, Fe, Pb, Mn, Mo, Ni, U, U in water, V, Zn, and Zr. Samples collected from northern Scotland were recently reanalysed for a number of elements previously not determined: Sb, As, Bi, Cd, Ca, Ga, La, Li, Mg, P, K, Rb, Ag, Sr, Sn, Ti, and Y. These include the gold 'pathfinders' arsenic (As), bismuth (Bi) and antimony (Sb) which have been used in this study to assist in the identification of prospective areas within the Northern Highlands. The published geochemical atlases which cover the Northern Highlands are Shetland (Institute of Geological Sciences, 1978a), Orkney (Institute of Geological Sciences, 1978b), Sutherland (Institute of Geological Sciences, 1982), Caithness (Institute of Geological Sciences, 1979), Hebrides (Institute of Geological Sciences, 1983), Great Glen (British Geological Survey, 1987) and Argyll (British Geological Survey, 1990) (Figure 1.3). The sample locations used in this study are shown in Figure 6.5.

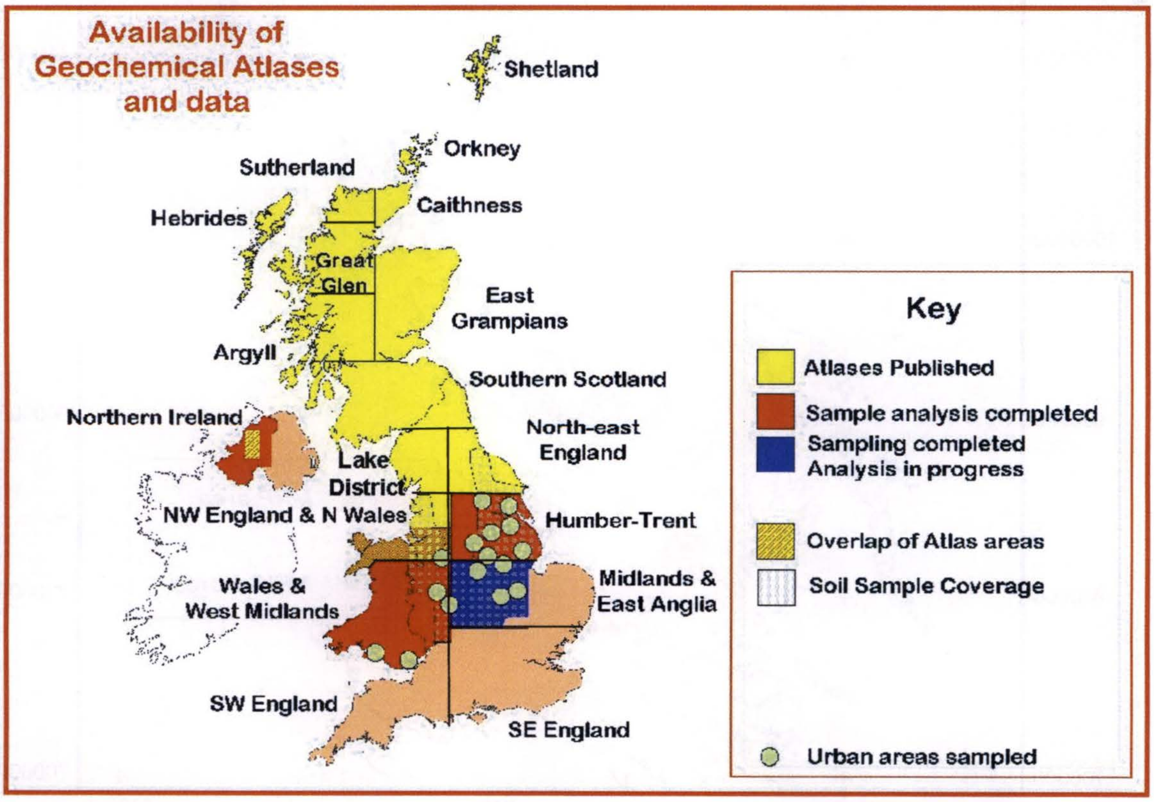

Figure 1.3 G-BASE published atlases and data

1.2.3 Mineral Reconnaissance Programme (MRP) data and reports

The BGS MRP was funded by the Department of Trade and Industry between 1973 and 1997 to provide baseline geological, geochemical, geophysical and metallogenic information on potentially prospective areas in Great Britain that would encourage private-sector investment. The work was at various levels, from initial reconnaissance to diamond drilling, but did not go beyond the discovery stage of a mineral deposit. Although work was generally aimed at specific styles of mineralisation, a wide range of elements was determined and a variety of techniques used. The results are published in a series of over 150 reports and data releases. Nine MRP projects were completed in the Northern Highlands. The results of three additional smaller investigations were published as Data Releases. The reports and data releases are listed in Table 1.2 and the areas investigated are shown in Figure 1.2. In 1998 the MRP was replaced by the Minerals Programme with the emphasis on re-assessment of old datasets, prospectivity modelling and data provision.

Table 1.2 MRP reports and data releases for the Northern Highlands

Number	MRP Reports
3	Molybdenite mineralisation in Precambrian rocks near Lairg
4	Investigation of copper mineralisation at Vidlin
6	Report on geophysical surveys at Struy
35	Geophysical investigation of chromite-bearing ultrabasic rocks in the Baltasound - Hagdale area
73	Platinum-group element mineralisation in the Unst ophiolite
106	Marine deposits of chromite and olivine
131	Platinum-group element mineralisation in the Loch Ailsh alkaline igneous complex
140	Mineral exploration for gold and base metals in the Lewisian and associated rocks of the Glenelg area
146	Mineral exploration in Lewisian supracrustal and basic rocks of the Scottish Highlands and Islands
MRP Data Releases	
Number	**Title**
1008	Data arising from drilling investigations in the Loch Borralan intrusion
1011	Rare earth elements in alkaline intrusions
1012	Mineral investigations in the Scardroy area

1.3 MINERAL LICENSING IN BRITAIN

1.3.1 Mineral rights

The following section is taken from the BGS guide to mineral exploration in Britain (Colman and Cooper, 2001).

The rights to non-fuel minerals in Great Britain, with the exception of gold and silver, are mainly in private ownership although a significant proportion is owned by the Crown and by Government departments and agencies. Uranium and other prescribed minerals relating to the production of atomic energy belong to the mineral rights owner, but may be compulsorily purchased by the Secretary of State for Trade and Industry with compensation under powers granted in the Atomic Energy Act 1946. Although mineral rights are generally held by the surface landowner, they may have been retained by a previous landowner when the surface freehold was sold, particularly in areas with a long history of mining such as south-west England. There is no national register of mineral rights, but the Land Registry may have details of surface ownership and current ownership of mineral rights. The registers are open for public inspection.

The right to exploit minerals in the foreshore (beach) and on the sea bed within the limits of national jurisdiction is vested in the Crown under the Continental Shelf Act 1964 and, apart from coal, oil and natural gas, these resources are managed by the Crown Estate Commissioners. The only exceptions are the counties of Cornwall and Lancaster, where the foreshore is owned by the respective Duchies, and where grants of the foreshore have been made by the Crown to other parties.

The mineral rights to the noble metals, gold and silver, in most of Britain are owned by the Crown, and a licence for the exploration and development of these metals must be obtained from the Crown Estate Commissioners through the Crown Mineral Agent. There is no standard application form or licence. Applications to explore an area should be made to the Crown Estate Commissioners accompanied by a proposed work programme and details of the applicant's financial resources and technical ability. The Crown Mineral Agent then decides on the area allowed, the fee and royalty payable and the suitability of the work programme. A provisional exploration licence is usually issued for one year and can be extended. Such extention being dependent on the applicant's progress. The exploration licence can be converted into a mining lease, subject to the applicant's progress and prospects. Annual reports to the Crown Estate Commissioners are required; the data normally only remains confidential for the duration of the licence and/or lease. The exploration licence confers no rights of entry and the applicant has to negotiate access with surface rights owners and obtain planning permission from the local authority if necessary. The areas currently under licence are shown on a map (updated annually) in the BGS United Kingdom Minerals Yearbook. Since 1987 the results of prospecting for gold and silver have been passed to the BGS by the Crown Estate Commissioners and some are now available for public inspection along with other information from the BGS archives.

The rights to gold and silver in the former county of Sutherland in northern Scotland are held by the Duchy of Sutherland. In the Isle of Man title to all minerals, including gold and silver, is vested in the Manx Department of Industry through the Minerals Act 1986. The Department issues exploration and development licences.

The Mines (Working Facilities and Support) Act 1966, as amended, provides a means by which an operator who is either unable to trace the mineral rights owner, or cannot reach an agreement on reasonable terms with him, can obtain the necessary authority to explore for and work minerals. The Act can also be used to acquire any ancillary rights needed to facilitate the working of minerals. Although the legislation rarely has to be used, its existence is of value to prospective mineral operators as a means of persuading landowners to reach agreement. The Royal Institution of Chartered Surveyors has produced an informative guide to this Act (Anon, 1983a) and has also published a useful, if now somewhat dated, discussion paper on access to mineral resources in Britain (Anon, 1986).

1.3.2 Access to land

Most land is owned by the occupier or farmer who holds the surface rights. Permission must generally be obtained from the surface landowner to gain access to land for prospecting, geological mapping and geochemical and geophysical surveying. The permission of the mineral rights owner, where he is not the surface owner, is not necessary. Such an arrangement confers no rights to exploit minerals if found. Informal, even oral, arrangements may be acceptable where reconnaissance work is being undertaken, but where more costly exploration work is contemplated the company should seek a written agreement with the surface landowner.

The approach of companies varies, but many prefer to have a flexible legal agreement allowing surface access for prospecting, including overburden drilling and geophysics, with the right of a first refusal to an option over the mineral rights after a specified time.

The property agreement usually involves a small payment to the relevant surface and/or mineral rights owners. The establishment of local contacts or a local office is a useful step in developing an exploration programme in an area, as tracing, and negotiating with, land and mineral rights owners may sometimes be time consuming. It can be an advantage to seek out owners of major tracts such as the Crown Estate Commissioners, the Duchy of Cornwall, the Forestry Commission, sporting estates, water authorities and, increasingly, pension funds and other financial institutions. Access to quite large areas can be obtained in this way, and negotiations may be held with estate officers used to legal agreements. In Scotland the most comprehensive and publicly available source of information on estate boundaries is that compiled by Wightman (1996).

The services of a land agent experienced in mineral agreements may be advisable if large-scale exploration is envisaged. The Country Landowners Association has published a booklet entitled 'Minerals' (2nd Edition 1983) which provides guidelines for negotiating prospecting and mining leases from the landowner's point of view. The Institution of Mining and Metallurgy has published the proceedings of a meeting on 'The legal aspects of prospecting in the United Kingdom' (Anon, 1983b). The proceedings include a description of obtaining mineral exploration permission in south-west England and the planning application system.

The British Geological Survey has experience of working in every part of Britain. Mineral exploration companies should make early contact with the BGS to obtain background information on the geology, mineralisation and previous exploration of any area. The BGS must be informed in writing, under the Mining Industry Act 1926, of the sinking of boreholes or shafts exceeding 30 m in depth; records of the operation, including drill logs, must be kept, and the BGS must be permitted to inspect the operation and remove representative samples if it so wishes.

1.3.3 Planning controls on mineral operations

As in other developed countries, Britain is subject to planning controls governing most forms of 'development' of land, including mining activities, under the guidance of the Office of the Deputy Prime Minister (ODPM).

In Scotland, the relevant Act is the Town and Country Planning Act (Scotland) 1972, as amended by the Town and Country Planning (Minerals) Act 1981. There is no separate regime for mineral planning. Proposals for mining activities are dealt with by the authority responsible for all forms of development control. In Highland, Borders, Dumfries and Galloway Regions and Orkney, Shetland and Western Isles, planning control is exercised by the Regional Council or Island Authority. Elsewhere it is the responsibility of the District Council, although Regional Councils have reserved powers related to structure planning responsibilities.

The key feature of the planning system is that most forms of development in Britain require planning permission before development can take place. Each application is considered on its merits. Prospective developers should make their planning applications on forms provided by the planning authority. The application will be considered by a planning committee which comprises elected councillors advised by the County Planning Officer and assisted, in minerals cases, by the Minerals Officer. Developers are strongly advised to discuss their proposals with the Minerals Officer first before making any formal application. The Minerals Officer will be able to advise developers on their applications and on what supporting information will be required to help the planning committee reach a decision. The addresses of the County, Region and District planning departments, and their Minerals Officers, are listed in Harrison and Machin (1999).

In considering applications for planning permission, planning authorities will take into account the provisions of the development plan. In Great Britain, the broad framework for the use of land is provided by Structure Plans. Local mineral plans will build on this framework with more site-specific proposals. All parts of Great Britain are covered by Structure Plans; a number of

Mineral Local Plans are published. Prospective mineral developers should acquaint themselves with the appropriate development plans. They set out policies for future mineral development and often contain useful information about past and current mineral working in the area. They also contain criteria against which mineral development applications will be assessed and describe policies for the restoration and after-use of mineral sites.

Although all mineral working activities come under the control of the Town and Country Planning Acts, certain operations, including most mineral prospecting activities that have little effect on the environment, do not require specific planning permission. These include drilling exploration boreholes, sinking small test pits and carrying out geophysical and geochemical surveys provided that i) the operations do not last longer than twenty eight consecutive days, ii) the work is not in environmentally sensitive areas, such as National Parks, and iii) the sites are restored soon after operations cease. The operations in this case are defined under the Town and Country Planning General Development Order 1988 (GDO) and planning permission is assumed to have been granted.

If the developer has notified the planning authority in advance then the twenty eight day period is extended to four months. Mineral developers should discuss their intended exploration activities with the relevant Minerals Officer to determine if their proposals fall within the scope of the GDO.

After the planning committee has considered the planning application they may decide to approve it, refuse it, or approve it subject to certain conditions. In practice most permissions for mineral development have conditions attached which are designed to control their impact on the environment. For example, conditions may be imposed which control the hours of working and access arrangements, set noise limits and limit the depth of working. Other conditions may govern the restoration of the site.

If the application is refused, or the conditions are unacceptable, the applicant has the right of appeal to the Secretary of State for the Environment, Transport and the Regions. An appeal following refusal of a minerals application usually results in a public inquiry, conducted by a planning inspector, in order that all individuals or organisations with a genuine interest may be given the opportunity of presenting their case. The inspector has delegated powers to determine the appeal. However, in certain circumstances, the Secretary of State will make the decision, taking account of the inspector's recommendations.

The Secretary of State also has the right to 'call in' planning applications. In practice, it is established policy that minerals cases will be called in only if they raise issues of regional or national importance. Before determining a called-in case, the Secretary of State will hold a public inquiry in a manner similar to an appeal case. One recent called-in application was that for the Hemerdon tungsten-tin open pit deposit on the border of the Dartmoor National Park. The application was approved, subject to certain conditions. Others, which have been granted full planning permission, include the Cononish and Cavanacaw gold mines. The major Duntanlich underground baryte mine, near Aberfeldy, was refused permission in 1997 and again on appeal in 1998.

Applications for mineral working in some environmentally sensitive areas such as National Parks (NP), Areas of Outstanding Natural Beauty (AONB) and Sites of Special Scientific Interest (SSSI) will be subject to the most rigorous examination. However, large-scale mineral operations for china clay, fluorspar, limestone, potash, roadstone and slate are carried out within National Parks from open-pit and underground mines on a basis of national need, indigenous industry and local employment.

A considerable amount of mineral exploration has been carried out in Britain in recent years by numerous British-based and overseas companies. The domestic minerals industry and the planning authorities have generally enjoyed a cooperative and constructive relationship in recent years. However, companies without any experience of operations in Britain would be well advised to seek professional advice before attempting to carry out work likely to require planning permission.

Further useful information on minerals planning can be found in the Minerals Planning Guidance Notes (MPGs) issued by the Department of the Environment and its successors, from 1988 onwards. These set out Government policy and provide updated information on the 1981 Minerals Act. They can be found from the link http://www.bgs.ac.uk/mineralsuk/planning/legislation/.

1.4 CONSTRAINTS ON MINERAL EXPLORATION

A number of environmentally important or sensitive areas in Scotland are protected by a variety of designations. These may be local, regional, national or international. They are administered by Scottish Natural Heritage [http://www.snh.org.uk/] which is a publicly funded body. The designated areas are shown below in Figure 1.4. Contact with SNH is advisable if any exploration work is contemplated within, or close to, any of these designated areas.

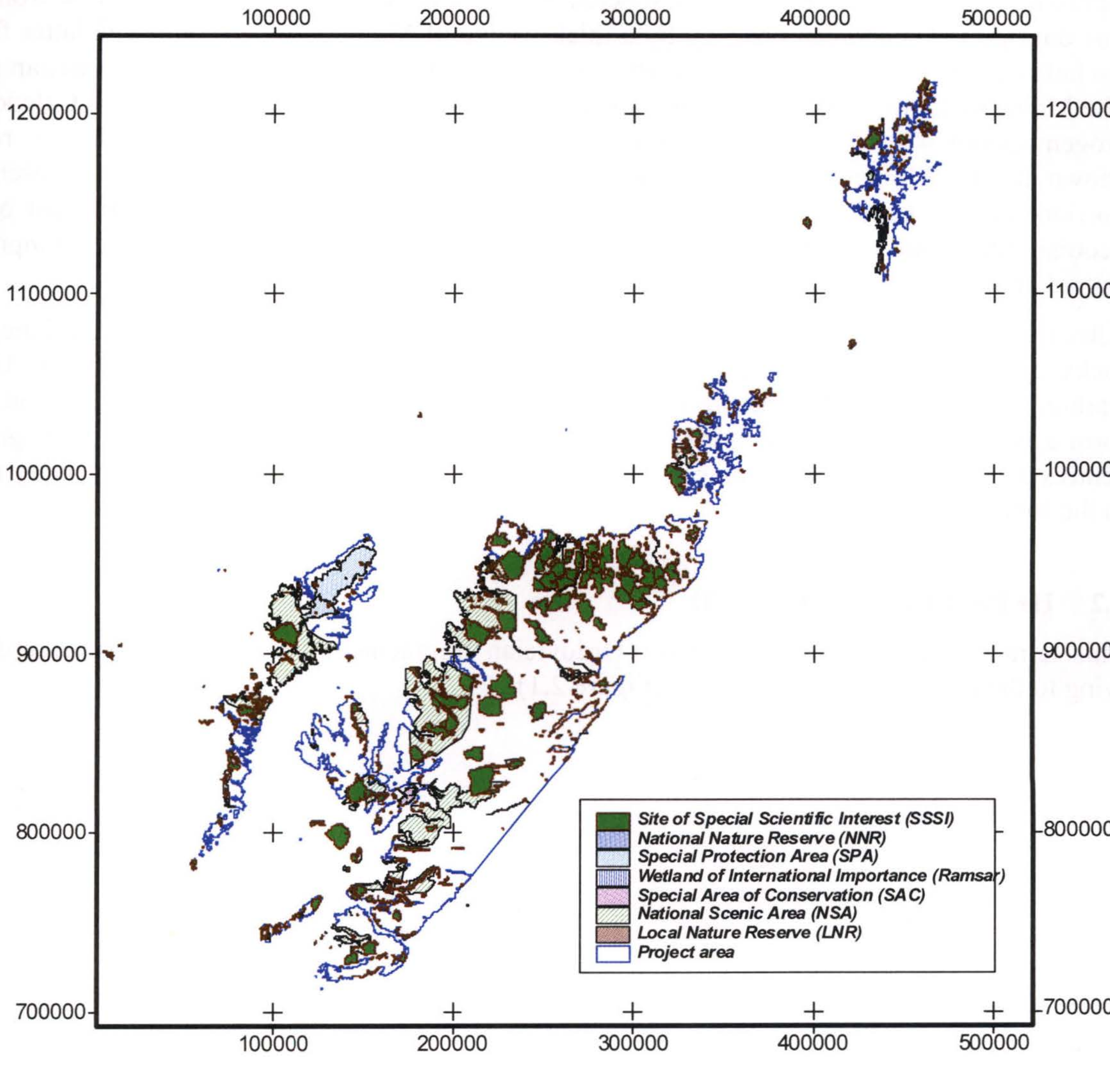

Figure 1.4 Major environmental designations

2 The geology of the Northern Highlands

2.1 INTRODUCTION

The Northern Highlands of Scotland cover a large, relatively remote area. The region has the broadest age range of rocks in the British Isles and includes a wide variety of lithologies and structures. Many of these have become 'classic' localities for the study of structural, petrological and mineralogical problems during the early part of Britain's geological evolution. The North-West Highlands memoir (Peach and others, 1907) was the forerunner of many publications on the Archean and Proterozoic rocks of the area. However, much of the area is concealed under extensive glacial and peat deposits. This, coupled with its remoteness and lack of development, has meant that its mineral potential is not as well known as other areas of Britain.

Ancient Archean to Cambro-Ordovician rocks are preserved in the Hebridean Foreland (Figure 2.1). The Archean rocks are highly metamorphosed gneisses of the Lewisian Complex, which represents a fragment of the ancient supercontinent, Laurentia, which was overthrust from the east during the Caledonian orogeny by a thick wedge of Moinian Supergroup. The latter forms the bulk of the Northern Highlands Terrane together with minor intercalations of Lewisian rock. The Moine rocks were metamorphosed about 800-700 Ma and again during the main Caledonian orogeny about 470 Ma. The tectonised junction between the foreland and the Moine rocks, known as the Moine Thrust Zone (430-420 Ma), includes wedges of Lewisian basement, Torridonian and Cambro-Ordovician strata. Shetland, which lies well to the north-east of the Scottish mainland (Figure 2.1), also includes a wedge of Grampian Terrane comprising Dalradian Supergroup and ophiolitic rocks.

After the Caledonian orogeny and its associated igneous intrusive activity, red-bed sedimentary rocks of the Old Red Sandstone Supergroup were deposited. A thin succession of Upper Carboniferous rocks is known from Morvern and igneous rocks of Permo-Carboniferous age form a widespread but minor intrusive suite. The Palaeocene volcanic eruptions from igneous centres associated with the opening of the Atlantic Ocean preserved Mesozoic sedimentary rocks in the Inner Hebrides.

2.2 HEBRIDEAN FORELAND

This terrane is an Archean to Cambro-Ordovician fragment of the Laurentian supercontinent lying to the west of the Moine Thrust (Figure 2.1).

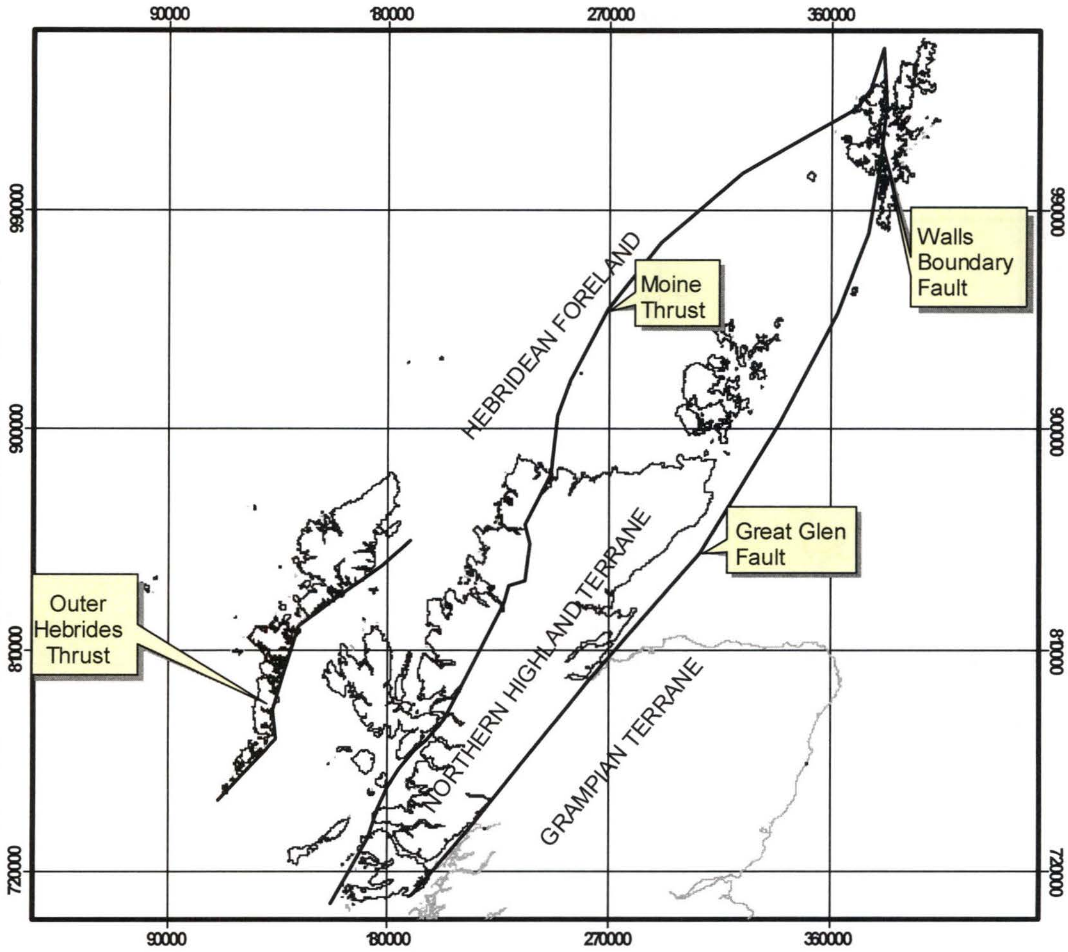

Figure 2.1 Major terranes in the Northern Highlands

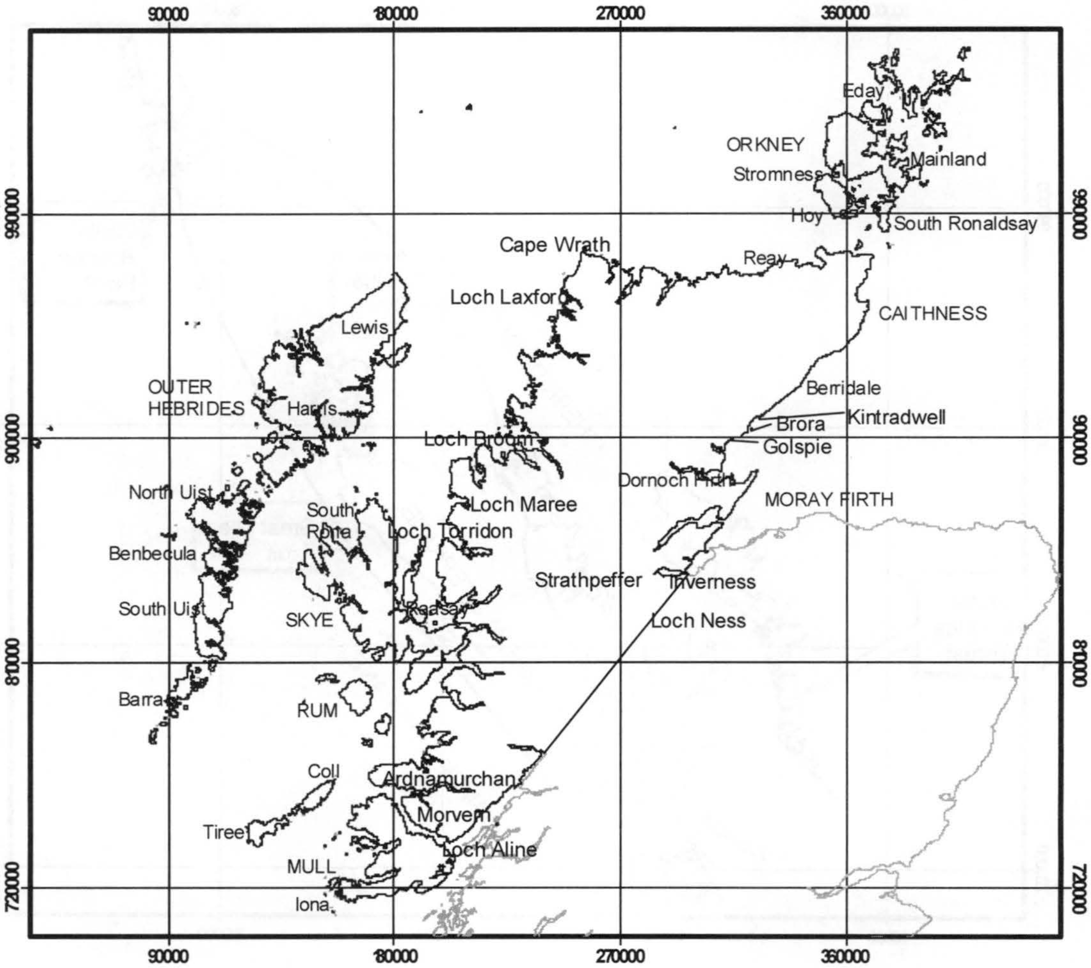

Figure 2.2 Northern Highlands showing main localities mentioned in the text

2.2.1 Lewisian Complex

The Lewisian Complex that underpins the foreland developed as continental crust between 2900 and 1100 Ma. Since it is cut by the easterly-dipping Outer Hebrides Thrust (Fettes *et al.,* 1992) and at depth on seismic lines, by the Flannan Thrust (Fyfe *et al.,* 1993), the Lewisian Complex may have been thrust towards a true foreland farther west on Laurentia. The Lewisian presently forms a narrow tract on the north-westernmost Scottish mainland and crops out on the Outer Hebridean islands of Lewis and Harris, North and South Uist, Benbecula and Barra, and the Inner Hebridean isles of Coll, Tiree, and parts of Iona and Raasay (Figure 2.3).

The Archean and early Proterozoic rocks of the Lewisian Complex (Figure 2.3) include mainly quartzo-feldspathic gneisses, basic and ultrabasic gneisses and intrusive rocks, metasedimentary rocks and granites. The Archean protolith can be dated back to about 2900 Ma, but parts were reworked in later tectono-metamorphic episodes. The earliest known episode is the early Scourian (Badcallian) deformation, which occurred deep in the crust at high metamorphic grades from 2800 to 2600 Ma. This culminated in the intrusion of late Scourian intermediate and granitic bodies. In the late Scourian (Inverian), about 2500 Ma, steep north-west trending linear deformation belts developed at mid-crustal levels.

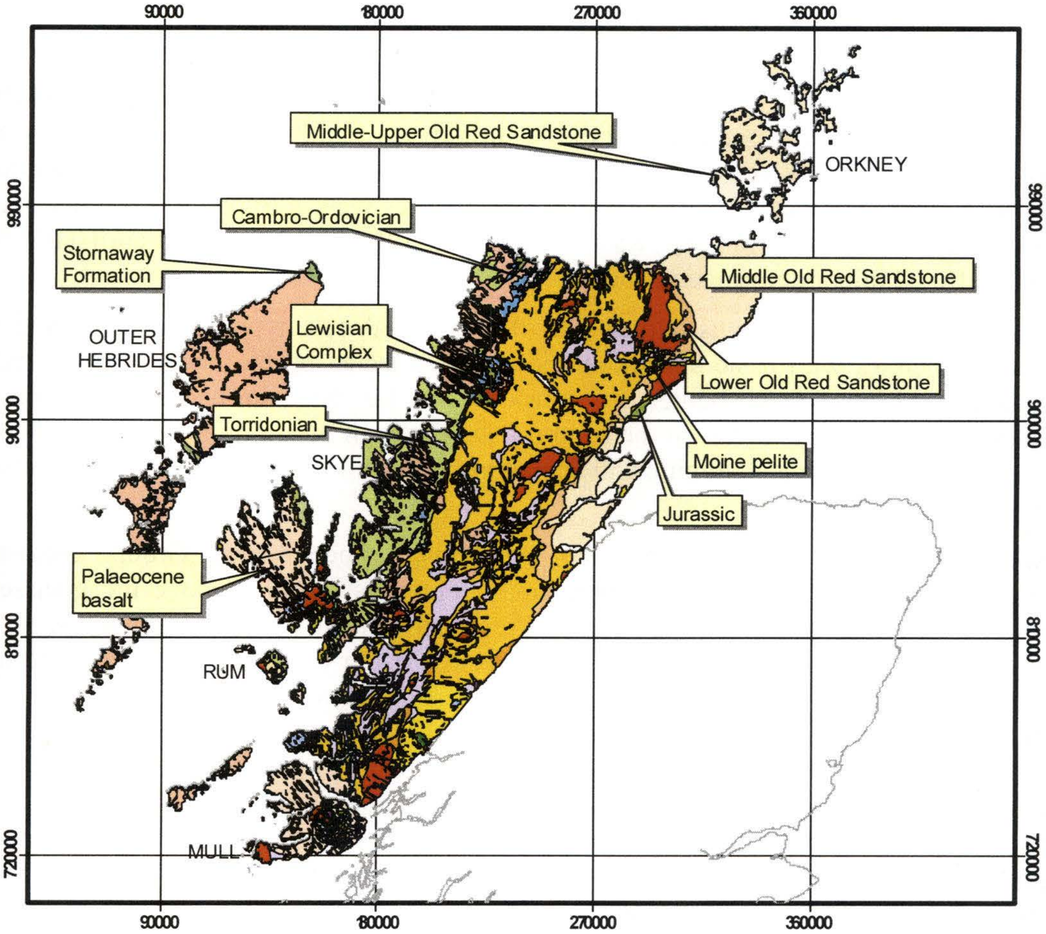

Figure 2.3 Solid Geology of the Northern Highlands from 1: 625 000 Geological Map

On the mainland the complex extends from Cape Wrath (Figure 2.2) southwards to Loch Torridon. It can be divided structurally into three belts: (i) central, (ii) northern and (iii) southern

The central belt from Loch Laxford to Loch Broom (Figure 2.2) consists of Scourian banded gneiss including a variety of basic and ultrabasic intrusions. They are metamorphosed up to granulite facies in which mafic gneiss layers include clinopyroxene and orthopyroxene, hornblende and plagioclase. The early Scourian ductile deformation affected all these gneisses and the later Scourian deformation was concentrated into north-west–south-east deformation zones bounded by shears causing some retrogression of pyroxene to hornblende and biotite. Later (2400-2200 Ma) undeformed north-west-trending, steep-sided tholeiitic Scourie dykes cut the Scourian gneisses. Slightly younger ultramafic dykes trend nearly east-west.

Granulite-grade basic and ultramafic bodies are particularly common in the Scourie and Assynt areas where they compose up to 20% of the complex. Ultrabasic lenses occur up to several tens of metres in length. The larger bodies are locally layered and commonly composed of olivine, pyroxene, hornblende, garnet and spinel. Basic rocks generally contain pyroxene, hornblende and plagioclase, commonly with banding which varies from ultramafic to anorthositic in composition. The basic bodies vary in size from a few centimetres to kilometres in length, but tend to be concentrated in north-west trending zones such as that south of Loch Laxford, which is 2 km wide. The compositional banding may represent original igneous layering, but alternatively may relate to later deformation and chemical segregation. Both processes may contribute to the layering as, over a wide area south of Loch Laxford, banding has been interpreted as representing disrupted layered mafic complexes (Davies, 1974). On the basis of geochemical studies of the ultramafic bodies commonly associated with metasedimentary rocks it was concluded that the ultramafic rocks are part of an oceanic crust accreted to continental crust at a subduction zone (Tarney and Weaver, 1987). The mafic material at depth probably melted to produce the large volumes of tonalitic magma.

Later, Laxfordian deformation and metamorphism to amphibolite grade (c. 1800-1700 Ma) extensively overprinted the gneisses and the Scourie dykes in the northern and southern belts of the mainland. The overall tectonic regime resulted in a pattern of tight synforms with attenuated fold limbs. Late Laxfordian granite sheets and pegmatites were intruded c. 1700 Ma and a late Laxfordian minor microdiorite suite was intruded at c. 1400 Ma. From then until 1100 Ma, the complex suffered minor deformation and brittle faulting

The northern and southern belts, either side of the central belt, typically contain acid biotite-hornblende gneisses with basic and ultrabasic bodies affected by the Scourian and Laxfordian deformations. Most of these bodies are considered to be the deformed and metamorphosed equivalents of the Scourie dykes in the central belt. The high metamorphic grade of these rocks has produced migmatites and granitic and pegmatitic veins, all with a foliation locally folded into major upright structures.

In the centre of the southern belt, the supercrustal Loch Maree Group, consisting of metasedimentary schists and metavolcanic amphibolites, is infolded above the gneisses. This pre-Laxfordian group is estimated to be early Proterozoic in age (c. 2000 Ma, Park *et al.,* 1994). It may have been deposited as a result of crustal extension occurring above a low-angle late Scourian shear zone or formed in an intracratonic rift system that stretched from Canada to Finland (Floyd *et al.,* 1989). The Loch Maree Fault splits the group into two areas, the Gairloch-Flowerdale Forest and the Loch Maree schist belts, which are successions of hornblende schist, semipelite, quartzose and garnet-mica schist, and carbonates, associated with calc-silicates. The metamorphic assemblages are typical of middle to upper amphibolite-grade. The rocks are interpreted to have been tholeiitic metavolcanics, clastic and chemical sediments such as wacke, mudstone and limestone, which occurred together with relatively thin banded- iron formation and exhalative lenses dominated by silicate and oxide facies.

In South Harris (Fettes *et al.,* 1992) a metasedimentary supracrustal assemblage includes quartzites, graphitic schists, marbles and finely banded amphibolites. The associated (originally layered?) basic rocks are mainly found in the south and range in composition from ultramafic to felsic. Chemically they are similar to modern tholeiites. However, most of the Lewisian Complex on Harris consists of granodioritic and tonalitic gneisses of slightly later igneous origin. These are thought to have formed an extensive intrusive suite into the supracrustal rocks. In South Harris a pre-Laxfordian igneous complex ranging from gabbro to diorite intruded the metasedimentary belts at c. 2250–2000 Ma. Locally abundant sulphide phases, such as pyrrhotite, pyrite, chalcopyrite and chalcocite occur in websterite dykes (Witty, 1975).

On Tiree (Figure 2.2), Lewisian gneisses include metacarbonates and metapelites, as well as magnetite-bearing rocks considered to have been banded ironstones originally. A 6-8 m thick band of white marble with a greenish serpentinite mottle has been quarried on Iona.

2.2.2 Torridonian Supergroup

The Upper Proterozoic Torridonian Supergroup (Figure 2.3) on the Hebridean Foreland comprises mainly continental arkosic red sandstones, lying with marked unconformity on Lewisian basement. It consists of three groups, the Stoer, Sleat and Torridon (the youngest and most widespread), with a composite thickness of about 7000 m, deposited in rifts on the foreland.

On the mainland the basal Stoer Group, dated at c. 950 Ma, outcrops along the eastern side of the Coigach Fault (Stewart, 1993). The Group comprises three formations, the Clachtoll (oldest), Bay of Stoer and Meall Dearg Formations. The basal Clachtoll Formation includes locally derived breccio-conglomerates and red sandstones. Thin Torridonian sandy mudstones on the

Stoer Peninsula are reported to contain a small stratiform copper deposit (Fermor, 1951). The basal Torridonian includes locally derived conglomerate and some exotic quartzite pebbles.

At the base of the Torridonian on Skye, the Sleat Group is up to 3500 m thick, and consists of coarse-grained grey fluvio-deltaic sandstones with subordinate lacustrine or shallow marine mudstones derived from the west (Nicholson, 1991).

The Torridon Group lies with apparent conformity on the Sleat Group on Skye but rests unconformably on the Stoer Group to the north where extensional faulting occurred prior to the unconformable deposition of the overlying 6000 m thick Torridon Group. The latter group contains the Diabaig (oldest), Applecross, Aultbea and Cailleach Head Formations (Stewart, 1993). The Diabaig Formation comprises lacustrine sediments with local coarse-grained fanglomerates. The overlying Applecross Formation is mainly fluvial sandstone, locally in fining-up sequences. The Aultbea Formation is a generally finer sandstone deposited in alluvial fans (Williams, 1969). In the Cailleach Head Formation, cyclic grey shales pass up into tabular red sandstones, representing delta advance into fresh water lakes (Stewart, 1991).

2.2.3 Cambro-Ordovician rocks

Cambro-Ordovician rocks are preserved in a narrow belt to the west of the Moine Thrust (Figure 2.3). Cambrian sediments were deposited in a shallow sea transgressing on to the eroded Torridonian surface.

The basal Eriboll Sandstone Formation, up to 100 m thick, is a cross-bedded quartz-arenite containing pebble-rich beds near its base. The overlying An t' Sron Formation (c. 50 m thick) includes coarse-grained feldspathic arenites, thin quartzites and dolomitic sandstones and mudstones. The Fucoid Beds Member contains rare pisolitic ironstones and the mudstones generally have a high potash content, which is contained in finely divided K feldspar. The mudstones were once considered to have economic potential as a fertiliser (Berridge, 1969), since they are also dolomitic and locally contain a small percentage of phosphate. This was considered (Swett, 1966) to be the result of authigenic growth caused by migrating K_2O derived from the overlying Durness Group carbonates. The mid-Cambrian to Llanvirn (Wright and Knight, 1995) Durness Group (c. 1250 m thick) contains grey dolostones, some of which are stromatolitic but the dolomite is mainly secondary. Local intraformational breccias and chert beds are present. Oolite beds and palaeokarst features indicate short-lived shallow to emergent facies. Towards the top of the group, white limestone and siliciclastic layers occur, but generally the clastic content decreases upwards.

2.3 NORTHERN HIGHLANDS TERRANE

The Moine Supergroup (psammite and pelite on Figure 2.3) effectively constitutes the Northern Highlands Terrane together with Lewisian inliers. On Shetland the Northern Highlands Terrane is faulted against Moine and Dalradian rocks of the Grampian Terrane (Figure 2.1). Igneous activity within the terrane is pre-, syn- and post-Caledonian deformation. The younger successions lie unconformably on the rocks affected by the Caledonian event.

2.3.1 Lewisian inliers

Deformed hornblende and biotite gneisses within the Moine Supergroup are considered part of the Lewisian Complex occurring either as attenuated isoclinal fold cores or thrust slices (or both). Lewisian and Moinian metabasites have been distinguished geochemically (Moorhouse and Moorhouse, 1979).

The largest of the inliers, the Glenelg-Attadale Inlier, is the only one where a basal Moinian conglomerate indicates an unconformity with the Lewisian rocks. The Glenelg Inlier (Figure 2.6) contains relicts of high-grade eclogite rocks and at its margin a zone of talc occurs, which was once mined.

2.3.2 Moine Supergroup

The Moine Supergroup, which lies between the Moine Thrust and the Great Glen Fault, comprises a thick sequence of metamorphosed shallow marine quartzo-feldspathic sandstones with subordinate mudstones and a basal conglomerate. The present mineral composition of the rocks also depends upon their metamorphic grade and the extent to which they have been migmatised. The mudstones generally form pelites with a high contents of mica, mainly muscovite, but also including biotite and chlorite. Garnet and kyanite are present locally. The sandstones were metamorphosed into quartzo-feldspathic psammites. Rare metalimestones are exposed, for example, in Glen Dessary and Ardgour; at the latter outcrop and Glen Urquhart (Figure 2.6) they are associated with pelites of Dalradian aspect. There are also rare amphibolites, metabasites and serpentinites which are considered pre-Caledonian minor intrusions.

The Moine Supergroup contains several migmatite zones, including the major Loch Shiel Migmatite Complex, which extends from the Ross of Mull northwards to Dornoch Firth. On the south-east side of the Loch Shiel Complex and extending into the Loch Eil Group is the West Highland Granite Gneiss (Figure 2.6). This coarse granitic gneiss generally has a foliation defined by biotite micas. The origin of the granite gneiss has been much debated: it may be an anatectic melt, a thrust slice or a true intrusion (Johnstone and Mykura, 1989).

The Loch Coire and Strath Halladale complexes (Figure 2.5) occur farther north in Sutherland and not only contain lit-par-lit migmatites but also various granitic bodies. Geochemical study of the Loch Coire gneisses has shown that their formation requires the metasomatic introduction of sodium (Brown, 1967).

Where possible, the Moine Supergroup is divided into three groups; the Morar (oldest), Glenfinnan and Loch Eil Groups (Soper *et al.,* 1998). The youngest radiometric age dates on detrital zircons from the Moine provide a maximum age of 1005 Ma for the supergroup (Kinny *et al.,* 1999). The West Highland Granite Gneiss (Figure 2.6) was intruded during a tectonometamorphic event at c. 873 Ma (Friend *et al.,* 1997). Recent dating indicates a thermal metamorphic event at c. 740 Ma within the Moine Supergroup. The event(s) around 800 Ma are referred to as Knoydartian (Morarian). However, Soper and England (1995) argued that these are extensional events related to rifting on the passive margin of Laurentia. The main deformation and metamorphism occurred during the Caledonian Orogeny (c. 470 Ma). Late thrusting occurred during the Scandian Orogeny (430-420 Ma).

The oldest group, the Morar Group, contains a lower psammite (pebbly in the west) with subordinate semipelites which become thicker towards the top. Heavy mineral bands are common near the base and the rare calc-silicate ribs become more common towards the top. The overlying Morar Pelite is dominantly pelitic, locally rhythmically striped and includes calc-silicates. The Upper Morar Psammite is pebbly in the west, with common semipelite bands and calc-silicate ribs throughout. It forms a major regressive sequence within a dominantly shallow marine Morar rift-basin.

The Sgurr Beag thrust generally separates the Morar Group from the younger groups and several slices of Lewisian rock lie within the slide zone.

The Glenfinnan Group contains interbanded psammites and pelitic gneisses. A lower pelitic gneiss, the Lochailort Pelite, contains subordinate psammitic or semipelitic stripes, amphibolite and calc-silicate lenses. The upper, Glenfinnan Striped Schist is predominantly siliceous psammite with some quartzite and pelitic gneiss as well as amphibolite and calc-silicate lenses. The group is interpreted as partly a distal equivalent of the Morar Group and partly as a later transgressive thermal re-equilibration sequence (Soper *et al.,* 1998).

The Loch Eil Group is the youngest within the Moine Supergroup and is a variably quartzose psammite with very subordinate pelite and semipelite. Calc-silicate lenticles are common. The group was deposited as shallow marine sands in a rift-basin to the east of the Morar rift-basin (Soper *et al.,* 1998).

On Skye, the Tarskavaig Nappe contains Moinian strata intermediate in character between Torridonian sandstones and the Moine Supergroup. Near Stromness on Orkney, Moinian gneisses form enclaves in Caledonian granites.

On Shetland dissimilar Moinian rocks lie in parts of the Northern Highlands and Grampian terranes separated by the Walls Boundary Fault, which Flinn (1992) took to be a northerly continuation of the Great Glen Fault (Figure 2.4). West of the fault they form part of the Sand Voe schuppen zone (Flinn, 1988), which he compared to the Moine Thrust Zone.

2.3.3 Dalradian Supergroup

Just west of the Walls Boundary Fault on Shetland, Dalradian rocks comprise a succession of quartzose, calcareous, and muscovitic schists and a hornblendic gneiss.

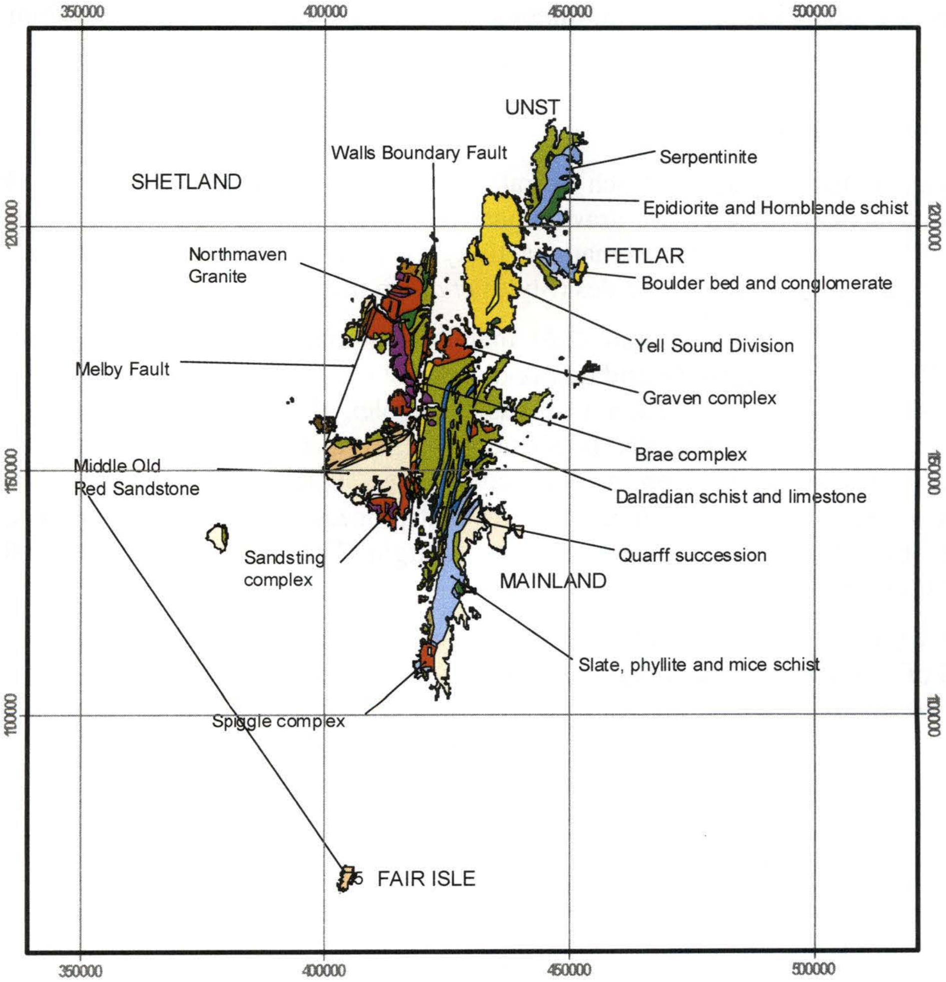

Figure 2.4 Solid Geology of Shetland adapted from the 1: 625 000 Geological Map

East of the Walls Boundary Fault on Shetland the metamorphic rocks have been divided into three major tectonic units (Mykura, 1976). The first consists of one thick series of metasedimentary rocks which young eastwards. In the west the variably migmatised feldspathic psammites (Yell Sound Division, Figure 2.4) have been tentatively correlated with the Moine rocks on the Scottish mainland and if they are continuous with the Dalradian Supergroup, they may include the Grampian Group. The overlying quartzites, pelites and gneisses are in turn overlain by flaggy psammite with four thick limestone intervals tentatively equated with the Lochaber and Appin Groups of the Dalradian. The top of this succession is largely phyllitic with quartzose grits and some metamorphosed spilitic lavas, tentatively equated with the Argyll and Southern Highland Groups. The second tectonic unit, the Quarff succession (Figure 3), lies to the east and consists of permeation gneisses, semipelites and gritty limestones. The third unit lies in eastern Unst and Fetlar where a nappe pile includes serpentinite, metagabbro and conglomerate. This nappe pile (Flinn *et al.,* 1979) is the result of ophiolite obduction at c. 450 Ma. The steeply stacked thrust zones include phyllite, graphitic schist and greenschist.

2.4 IGNEOUS ACTIVITY

Extensive igneous activity occurred as a result of the Caledonian Orogeny. It includes early and later suites of Caledonian plutons and minor intrusions, varying in composition from ultramafic to granitic.

2.4.1 Basic to syenitic rocks

Near Assynt, the late Caledonian Loch Borralan and Loch Ailsh complexes include ultramafic to syenitic suites, some of which are gravitationally differentiated in situ. A late magmatic origin coupled with hydrothermal/metasomatic activity is probably responsible for the associated platinum-groups minerals and tellurides (Styles *et al.,* in prep).

The Glen Scaddle complex (Figure 2.6) mainly comprises two-pyroxene gabbroic diorites (Bailey, 1960), although appinite and quartz-diorite are minor constituents and hornblende schist occurs in sheared zones. The Glen Loy basic complex (Figure 2.6) comprising hornblende gabbro, appinite and mica-diorite, is about 4 km in diameter. The hornblende gabbro is rhythmically banded locally on a decimetre scale, which is interpreted as an original gravitational crystal settling. Grading indicates that progessively younger layers occur towards the centre of the body from a steep to vertical margin. The Clunes tonalite lies 10 km to the north-east (Figure 2.6).

The Glen Urquhart complex (Figure 2.6) is an ultrabasic body about 3.5 km^2 in area, now composed of serpentinite. The complex includes amphibolite bands comparable to the early basic suite and the complex resembles that at Glen Scaddle, which also appears to lie in a synformal position. The outcrop is characterised by calc-silicates and skarns that are thought to be the products of contact metamorphism related to the serpentinite intrusion.

The Glen Dessarry syenitic complex (Figure 2.6) has an elliptical outcrop elongated with a north-north-easterly trend.

The three post-tectonic syenitic intrusions around Loch Loyal (Figure 2.5) are zoned (Robertson and Parsons, 1974) and have sodic to ultrasodic rocks in their aureoles due to metasomatism.

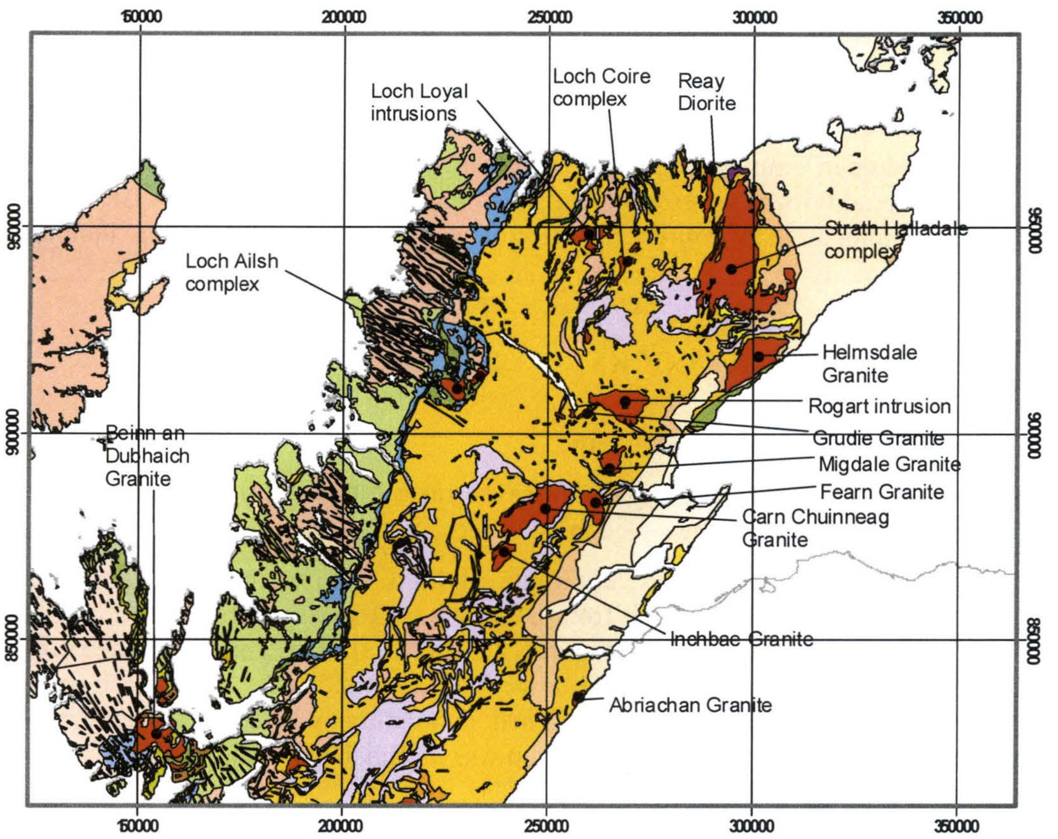

Figure 2.5 Main Caledonian igneous intrusions in the northern part of the Northern Highlands

2.4.2 Granites

The syn-tectonic granite masses of Carn Chuinneag and Inchbae (Figure 2.5) are magmatically linked but were intruded at slightly different stratigraphic levels. The earliest intrusions in the Carn Chuinneag complex were probably the pyroxene gabbro and diorite, which were amphibolitised by the intrusion of the main porphyritic granite. The latter is now a foliated coarse biotite-granite gneiss. A later, finer grained more acid augen gneiss intrudes the granite gneiss. Within the Carn Chuinneag intrusion there are small zones of riebeckite-bearing gneissic granite and a more restricted garnetiferous albite gneiss with magnetite and cassiterite-bearing bands on the north-west flank of the mass. The age of emplacement of the granite is c. 560 Ma (U-Pb zircon; Pidgeon and Johnson, 1974).

The post-tectonic 'Newer Granites' are a widespread group of plutons and smaller bodies intruded during late Ordovician to Silurian times (440-400 Ma). Nearly all can be classed as 'forceful granites' (Read, 1961) as they pushed aside the surrounding rock, although in some cases, magmatic stoping was also involved. Many of the intrusions are granodiorites or even diorites, forming a calc-alkaline suite ranging from appinite to granite. The intrusive complexes commonly have an older, more basic marginal zone which deformed as more magma intruded the core.

Of the granites indicated on Figures 2.4, 2.5 and 2.6 the Strontian complex is the largest, with an area of about 225 km^2, and is truncated to the south-east by the Great Glen Fault. Few are known to be associated directly with mineralisation but hydrothermal fluids have caused some alteration zones. The large Helmsdale Granite (Figure 2.5) is overlain by Lower Old Red Sandstone which is enriched in uranium (Gallagher *et al.,* 1971). The small Grudie Granite (Figure 2.4) appears to have been the locus of base-metal sulphide mineralisation and molybdenite is unusually common here. (Gallagher *et al.,* 1974). Fenite-type metasomatism affected the small Abriachan Granite which lies north-west of Loch Ness (Figure 2.5).

2.4.3 Minor Intrusions

Suites of Caledonian granite, pegmatite and aplite veins are common throughout the Northern Highlands. Two additional suites have been distinguished (Smith, 1979): a late- to post-tectonic Microdiorite Suite and an entirely post-tectonic Minette Suite including lamprophyres and felsites.

2.5 POST-CALEDONIAN ROCKS

2.5.1 Old Red Sandstone Supergroup

The Old Red Sandstone Supergroup comprises terrestrial late Silurian to Devonian clastic strata laid down unconformably on the Caledonian orogen.

The Lower Old Red Sandstone Sarclet Group (Mykura, 1991) crops out on the coast in eastern Caithness but mainly lies in one belt from Berridale to Reay (Figures 2.2 and 2.3), with another from Dornoch Firth to Loch Ness (Figures 2.2 and 2.3). The group includes conglomerates, pebbly sandstones and sandstones in the lower part and mudstones and sandstones in the upper part. The feldspathic sandstones are enriched in uranium where they overlie the Helmsdale Granite. A Lower Devonian age for this group was established based on miospores palynological age determinations (Collins and Donovan, 1977).

On Orkney near Stromness, probable Lower Old Red Sandstone (Yesnaby Sandstone Group ?Emsian) rocks include a basal conglomerate with shales bearing phosphatic nodules, followed by sandstones.

The Middle Old Red Sandstone (Figure 2.3) rocks of Orkney and Caithness (i.e. the Stromness and Caithness Flagstone groups respectively), continue south-westwards through east Sutherland to the Black Isle. In the north the sedimentary facies is mainly lacustrine but towards the south, fluvial facies prevail.

The flagstone succession reaches up to 4 km thick in Caithness but the base is irregular and unconformable and associated with conglomerate beds. Most of the succession consists of well-defined rhythmic units generally 5 to 10 m thick, which reflect deposition in a broad shallow lake. In both Caithness and Orkney, the flagstone groups were widely quarried in the past as paving slabs and building material.

Many of the thin phosphatic argillites contain 0.01–0.2 % U (Michie and Cooper, 1979). Uranium and lead are enriched in dolomitic shales and conglomerates near the underlying Moine Supergroup. The origin of the metals is probably syngenetic or diagenetic, with later igneous and tectonic activity enhancing ground water redeposition.

The overlying Eday Group (over 1 km thick) on Orkney includes massive red and yellow sandstones with intervals of flagstones, marls and local volcanic lavas and tuffaceous sandstones. On Hoy, Orkney (Figure 2.3) thick red and yellow sandstones together with a basal volcanic member are classified as the Hoy Sandstone Formation (Givetian-Frasnian) and they lie unconformably on the Middle Devonian sequence.

On Shetland Mainland (Figure 2.4) the Middle Old Red Sandstone includes sandstones, conglomerates, breccias and volcanic rocks deposited in separate basins.

2.5.2 Permo-carboniferous rocks

At Inninmore Bay on the Morvern peninsula (Figure 2.2) sandstones are interbedded with dark mudstones, fireclays and thin coals. The fossil flora content suggests that the beds are early Westphalian (Johnstone and Mykura, 1989).

A suite of minor Permo-Carboniferous intrusions in the West Highlands runs roughly east-west in the Loch Eil - Loch Arkaig area. They are associated with vent breccias usually with a matrix of monchiquite. Lamprophyric dykes and sills on south and west Orkney and northern Caithness cut the Old Red Sandstone strata and K-Ar dating (Mykura, 1976) indicates that they are late Carboniferous in age. Because lamprophyric rocks are considered to originate within the mantle, they are able to bring up diamonds and sapphires from great depths although this is dependent on lithospheric thickness and geothermal gradient, amongst other parameters (Leake and others, 1995). A monchiquite dyke of this suite at Loch Roag on Lewis contains gem-quality sapphire.

2.5.3 Triassic rocks

Small outcrops of mainly fluvial Triassic sandstone and conglomerate occur in Wester Ross and southwards to Morvern. A thin basal conglomerate is common and local, pedogenic carbonate developed in overbank deposits.

In the Outer Hebrides (Figure 2.3), the Permo-Triassic Stornoway Formation (Storetvedt and Steel, 1977) is a thick red-brown conglomerate with subsidiary sandstones and minor cornstones and mudstones. It was probably deposited as alluvial fans in a half-graben.

Near Golspie (Figure 2.2), pale calcareous sandstones overlain by red and green mudstones with pedogenic carbonate and chert can be correlated with the Stotfield Cherty Rock Formation to the south of the Moray Firth.

2.5.4 Jurassic rocks

The Jurassic successions crop out on Skye and Raasay where Lower Jurassic limestones, sandstones and mudstones include the Raasay Ironstone, a chamositic oolite 2-3 m thick, which was formerly mined on the island. The Middle and Upper Jurassic consists of interbedded limestones, sandstones, mudstones and minor oil-shale interbedded with thin limestones.

On the east coast, Jurassic strata lie in a condensed succession near Golspie (Figure 2.3) where the deltaic sequence includes one formerly mined coal bed, the Brora Coal, which is about 1 m thick.

Near Kintradwell (Figure 2.2), Upper Jurassic boulder beds and sandstones, thought to be submarine mass flows and fans formed in gullies on the syn-sedimentary Helmsdale Fault, interfinger with marine mudstones (Pickering, 1984).

2.5.5 Cretaceous rocks

Cretaceous beds are preserved below Palaeocene lavas in the Morvern area, mainly around Loch Aline (Figure 2.2). The beds comprise Greensand overlain by about 12 m of white sandstone, which is mined for glass sand.

2.5.6 Palaeocene (Tertiary) rocks

During the Palaeocene, the start of rifting to form the North Atlantic caused igneous activity from several centres in north-west of Scotland. On Skye (Figure 2.3) and Mull outpourings of basaltic lava built up to at least 1800 m thick. The lavas, including pitchstone, are also exposed on Canna, Eigg, Muck and Morvern. Thin clastic beds, and local seams of lignite, lie below, and interstratified with, the lavas. Associated intrusive centres mainly consist of gabbro, ultrabasic rock, granophyre or granite and involved ring-dyke and cone-sheet intrusive mechanisms as well as underground cauldron subsidence

On Rum (Figure 2.2), a layered intrusion contains chromite and a few small occurrences of sulphide mainly associated with peridotite and locally containing gold and platinum-group elements. Similar ultramafic to granitic suites occur on Skye and locally contact metamorphism has produced marbles. Related metasomatism has introduced fluorine and boron giving rise to assemblages of skarn minerals. Magnetite is concentrated near to the contact of the Beinn an Dubhaich Granite (Figure 2.6) on Skye. Some of the skarns associated with these intrusions contain metamorphic minerals such as sapphire found on Mull and Ardnamuchan.

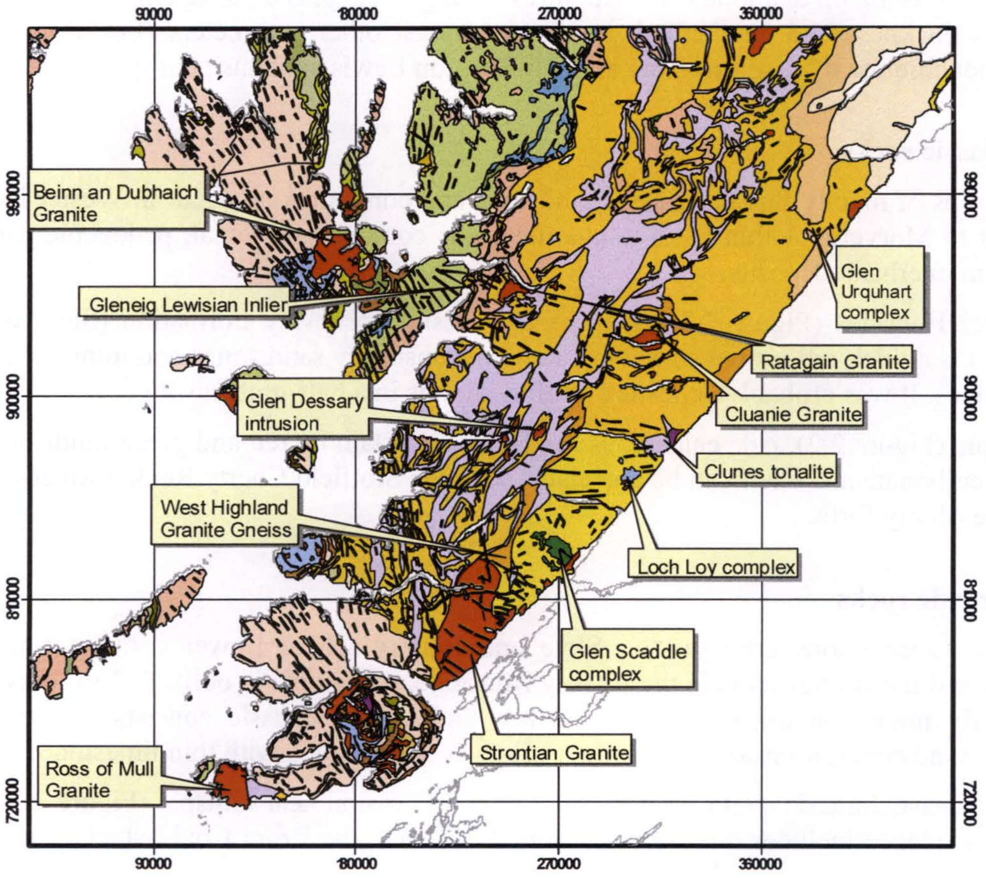

Figure 2.6 Main igneous intrusions and Lewisian inliers in the southern part of the Northern Highlands

2.5.7 Quaternary

Quaternary ice caps developed over the higher exposed uplands sweeping seawards radially depending on the strength of flow of the various ice sheets. Deposition of glacial deposits is generally thin, but locally masks the solid geology.

Deeply decomposed rock lies below glacial till in the Helmsdale, Ratagain and Glenelg areas and on Lewis. It may be the result of tropical weathering during late Tertiary times, but could also be the effect of hydrothermal activity, faulting and Quaternary weathering. Such weathering could account for the rusty brown weathering of the schists near Gairloch due to the oxidation of their sulphide content.

Glacial till can blanket mineral deposits but most tills are locally derived, even though some erratics have come from as far afield as Scandinavia. Glacial morainic and alluvial deposits on Rum contain chromite grains and these have been swept onto the adjacent beaches and immediate offshore area (Emeleus, 1997). Heavy minerals are also present off Unst and the Outer Hebrides. Fluvioglacial mounds were locally deposited and provide potential sources of sand and gravel.

Late to post-glacial gravelly raised beaches occur mainly on the eastern coast, blown sand is common on west-facing coasts. The alluvium that accumulated in the larger straths is mainly sand and gravel with silt, mud and peat layers.

Diatomite occurs in lake deposits on Northern Skye and was once worked at Loch Cuithir. Similar but smaller diatomite deposits are known on Lewis, Mull and Eigg.

Blanket and basin peat is common in the Northern Highlands. The hill slopes are rarely blanketed by more than 1 m thickness of peat, but in intervening basins, 2–6 m of peat is common. Extraction of peat for local use as fuel was formerly common and large potential resources remain.

3 Mineralisation in the Northern Highlands of Scotland

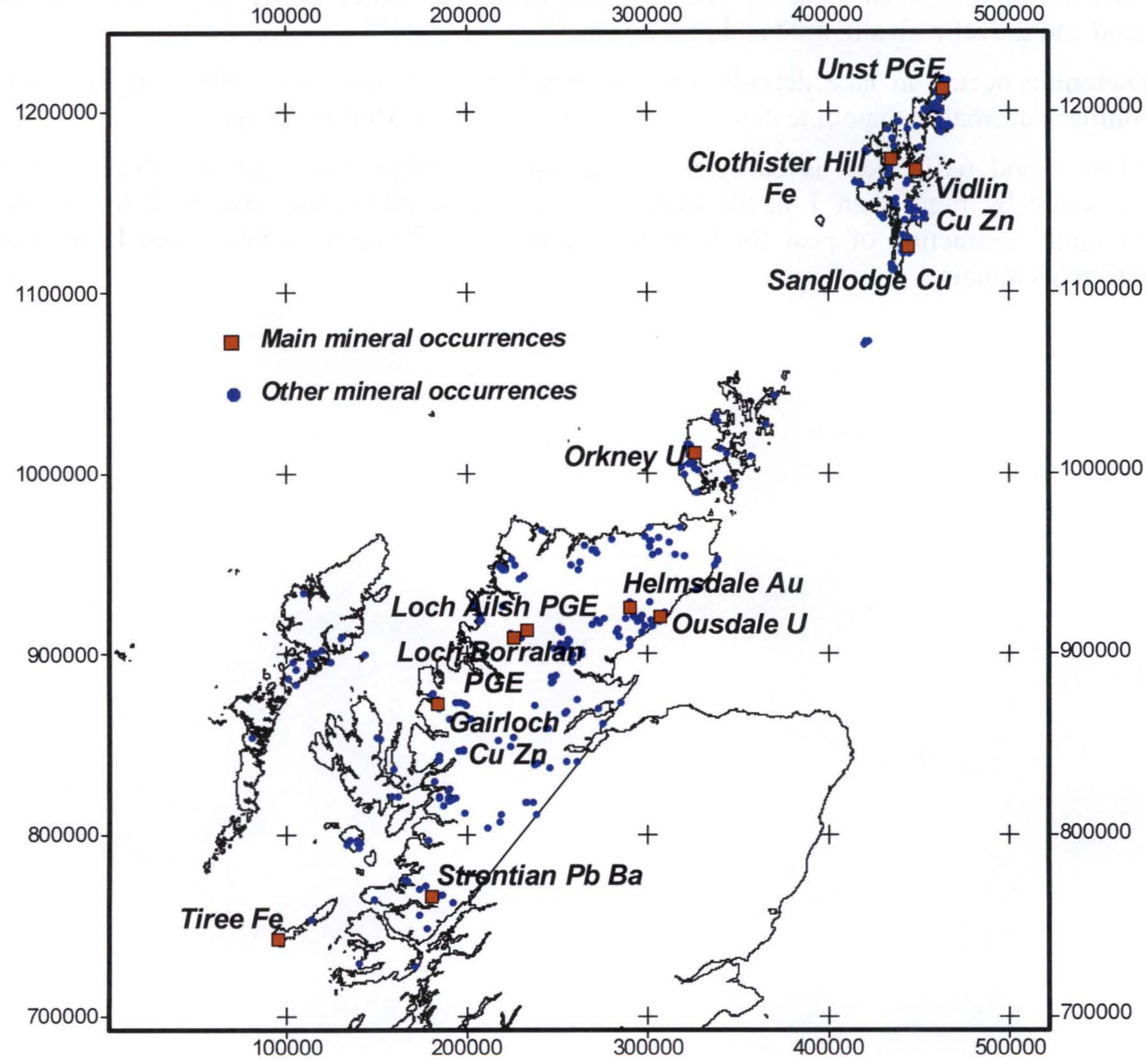

Figure 3.1 The distribution of mineral occurrences in the Northern Highlands

3.1 INTRODUCTION

The most important historic mineral workings in the Northern Highlands are at Strontian, Sandlodge and Unst, where barium and lead and zinc, copper, and chromite were exploited respectively. Since 1970 mining companies and the British Geological Survey (BGS) have discovered a number of new mineral localities including the Gairloch and Vidlin deposits. Commercial exploration was assisted between 1971 and 1984 by the Mineral Exploration Investment Grants Act 1972 (MEIGA), and all reports of work undertaken under this programme are held by the BGS. A list of all relevant MEIGA activities is given in Table 1.1. The BGS has published a number of reports on work carried out in the Northern Highlands as part of the MRP during the 1980s and 90s (Table 1.2).

3.2 KNOWN MINERAL OCCURRENCES

The known mineral occurrences in the Northern Highlands can be grouped into the following categories:

1. Occurrences associated with acid and intermediate intrusions
2. Occurrences associated with mafic and ultramafic complexes
3. Volcanogenic massive sulphide (VMS) occurrences
4. Skarn-type occurrences
5. Occurrences associated with Devonian sedimentary and volcanic rocks
6. Alluvial occurrences
7. Vein occurrences
8. Other occurrences

A complete listing for the Northern Highlands region is given in Appendix 1 which was taken from the BGS Mineral Occurrence Database. Further details of mineralisation within the Northern Highlands are provided in the geochemical atlases published by the BGS as part of the G-BASE sampling programme of Great Britain.

3.2.1 Occurrences associated with acid and intermediate intrusions

CARN CHUINNEAG

The Carn Chuninneag-Inchbae complex is located in Easter Ross, approximately 20 km east-south-east of the Dornoch Firth (Figure 2.5). The complex was intruded between structural episodes of the Moinian and represents two separate, but magmatically linked, bodies emplaced at slightly different stratigraphic levels (Johnstone and Mykura, 1989). The masses have had a complex evolution involving basic rocks, amphibolites and feldspathic granitic rocks and they have been affected by several phases of deformation and faulting.

Metalliferous minerals have long been known to occur within and around the complex: galena occurs in a sheared lamprophyre dyke to the north of the complex and cassiterite in magnetite-rich bands within the garnetiferous albite gneiss on the northwest shoulder of Carn Chuinneag (Peach *et al.,* 1912). Hand specimens of the magnetite-cassiterite bands within these rocks contain up to 900 ppm Sn and 1350 ppm Zn. Molybdenite with chalcopyrite occurs in a north-trending 50 cm thick quartz-breccia vein in the pelitic hornfels at the northern edge of the Carn Chuinneag complex. A small outcrop of weakly uraniferous gneiss in the vicinity of the magnetite-cassiterite bands contains up to 1000 ppm Nb and 400 ppm Zr (Gallagher *et al.,* 1971).

BEN LOYAL COMPLEX

The Ben Loyal syenite complex (Figure 2.5) consists of three masses: Ben Loyal, Beinn Stumanadh and Cnoc nan Cullean. Heddle (1901) recorded thorite, galena, sphene and topaz from pegmatite boulders in the north-west of the Ben Loyal mass, and more recent discoveries have included a monazite-like mineral, baryte and celestite in the Loch Loyal area. Gallagher *et al.* (1971) found anomalous concentrations of thorite and allanite in the Cnoc nan Cullean mass especially where pyroxene has been transformed to amphibole. Uranium minerals have also been noted at the western side of the Ben Loyal mass in minor shears adjacent to a northerly-trending fault Gallagher *et al.* (1971).

Limited rock and stream-sediment sampling was carried out by the MRP over the Ben Loyal area in 1990 to investigate occurrences of rare earth elements as well as PGE (Shaw and Gunn, 1993).

Enrichment in REE occurred in two rock samples and in both stream-sediment and panned-concentrate samples taken from the Allt Liath catchment in the Cnoc nan Cullean intrusion. These samples recorded values of 5667 ppm La and 19785 ppm Ce, however no significant PGE values were noted. Minor enhancements in REE were also noted in the Ben Loyal intrusion.

GRUDIE (OR GHRUDIE) GRANITE

The Devonian Grudie granite (adamellite) is located at the southern end of Loch Shin in the central part of the Northern Highlands and intrudes siliceous granulites and schists of the Moine series (Figure 2.5). Read *et al.* (1926) and Gallagher (1970) identified galena-fluorite veining cross-cutting the granite and schist country rocks on the eastern side of the granite. A soil survey suggested the possibility of further mineralisation towards the north-east corner of the granite (Gallagher and Smith, 1976).

In 1971 Atlantic and Oceanic Resources carried out magnetic and Induced Polarisation surveys over the eastern half of the Grudie Granite to investigate additional mineralisation related to veining that was thought to represent a possible fault system 30 to 60 m wide at the contact of the granite and the schist country rocks. The survey identified only minor anomalies that were not followed up (MEIGA 6).

Oykel Minerals Ltd. undertook a reconnaissance mineral survey of the Strath Oykel area in 1972 (MEIGA 63). This work identified veins containing up to 10% galena and baryte in the Rosehall area during stream sediment sampling. These were thought to represent a low-temperature hydrothermal vein system. No further work was done in the area despite recommendations that additional geophysical and geochemical work be undertaken in the area (Matthews *et al.,* 1972).

RATAGAIN COMPLEX

The Ratagain Igneous complex is situated on the shores of Loch Duich close to the Isle of Skye (Figure 3.2). The complex comprises a suite of Caledonian igneous rocks intruded into metamorphosed Lewisian and Moinian rocks and bounded to the south by the north-east-trending Strathconan Fault. The complex has a distinctive alkaline chemistry with marked enrichments in barium, strontium and rare-earth elements. Quartz-fluorite-calcite vein mineralisation is restricted to the quartz-monzonite, particularly in the vicinity of the Strathconan fault system (Alderton, 1988). These veins are narrow and discontinuous with complex mineralogy including sporadic galena, molybdenite, sphalerite, chalcopyrite and pyrite, together with minor amounts of rare minerals including electrum. Alderton (1988) reported Au and Ag values (up to 5.46 ppm Au) occurring in hessite, electrum and argentiferous galena. He suggested that the Ag-Au-Te mineralisation was introduced after the pyrite and molybdenite by a separate unrelated mineralising event.

The complex was sampled for gold and PGE by the MRP in 1996 but few anomalous results were recorded (Coats *et al.,* 1996). It appears that the mineralisation in the complex is never very localised or intense and has caused extensive, low-grade gold enrichment rather than being focused by a late-stage intrusion or an active fault zone (Coats *et al.,* 1996). However, the Strathconan fault zone itself is a potentially more attractive exploration target as it extends for 100 km. In the Scardroy area gold anomalies were reported in this zone by the MRP (Coats *et al.,* 1993). Coats and others (1996) also suggested the area around the Ratagain complex could be prospective for a Besshi style of base-metal mineralisation similar to that present at Gairloch, since some calc-silicate rocks in the area contain relatively high levels of copper and also some gold. There is some potential for the occurrence of PGE, but limited unpublished MRP work did not identify any anomalous areas.

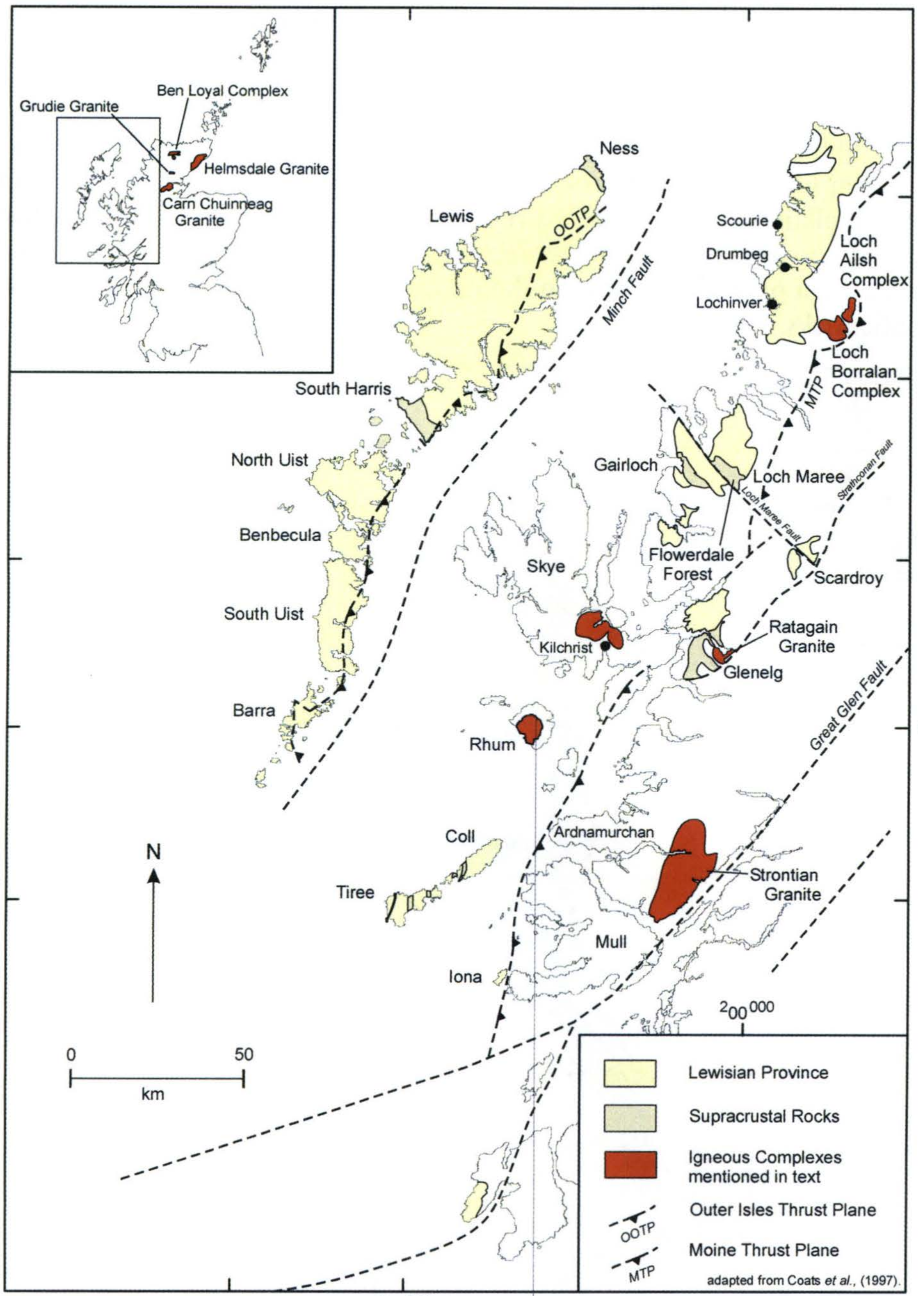

Figure 3.2 Distribution of igneous complexes and important localities mentioned in text

3.2.2 Occurrences associated with mafic, ultramafic and ophiolite complexes

UNST

Significant chromite and PGE mineralisation occur in the ultramafic rocks of the Unst ophiolite in Shetland, a group of islands approximately 150 km north-east of the Scottish mainland. The Unst ophiolite comprises 60 km^2 of basic and ultrabasic rocks thrust over a migmatite basement (Figure 3.3). There are four major units; a basal harzburgite overlain in turn by dunite, clinopyroxene-rich cumulates and gabbro.

Between 1820 and 1945 some 50,000 tonnes of chromite were produced from many small pits near Balta Sound during intermittent mining operations (Mykura, 1976). Mining ceased after the Second World War due to the exhaustion of near surface deposits. The chromite mineralisation occurs in the northern part of the island around Balta Sound (Figure 3.3) within the lower ultramafic sections of the Unst ophiolite complex (Flinn, 1970; Flinn, 2001). The mineralisation comprises discontinuous near-vertical lenses, generally less than 20 m in maximum dimensions.

Since cessation of production, various commercial and scientific investigations have been carried out to identify additional chromite deposits (MRP 35) (Johnson *et al.*, 1980). Since 1982 most attention has been focused on PGE associated with the chromite. Initial work by Prichard *et al.* (1981) identified platinum-group minerals (PGM) at two localities on Unst. Subsequent research by Prichard and co-workers (Prichard *et al.*, 1986) identified a wide range of PGM at many localities in the Unst ophiolite, mainly in the ultramafic sections of the complex but also in the overlying mafic rocks.

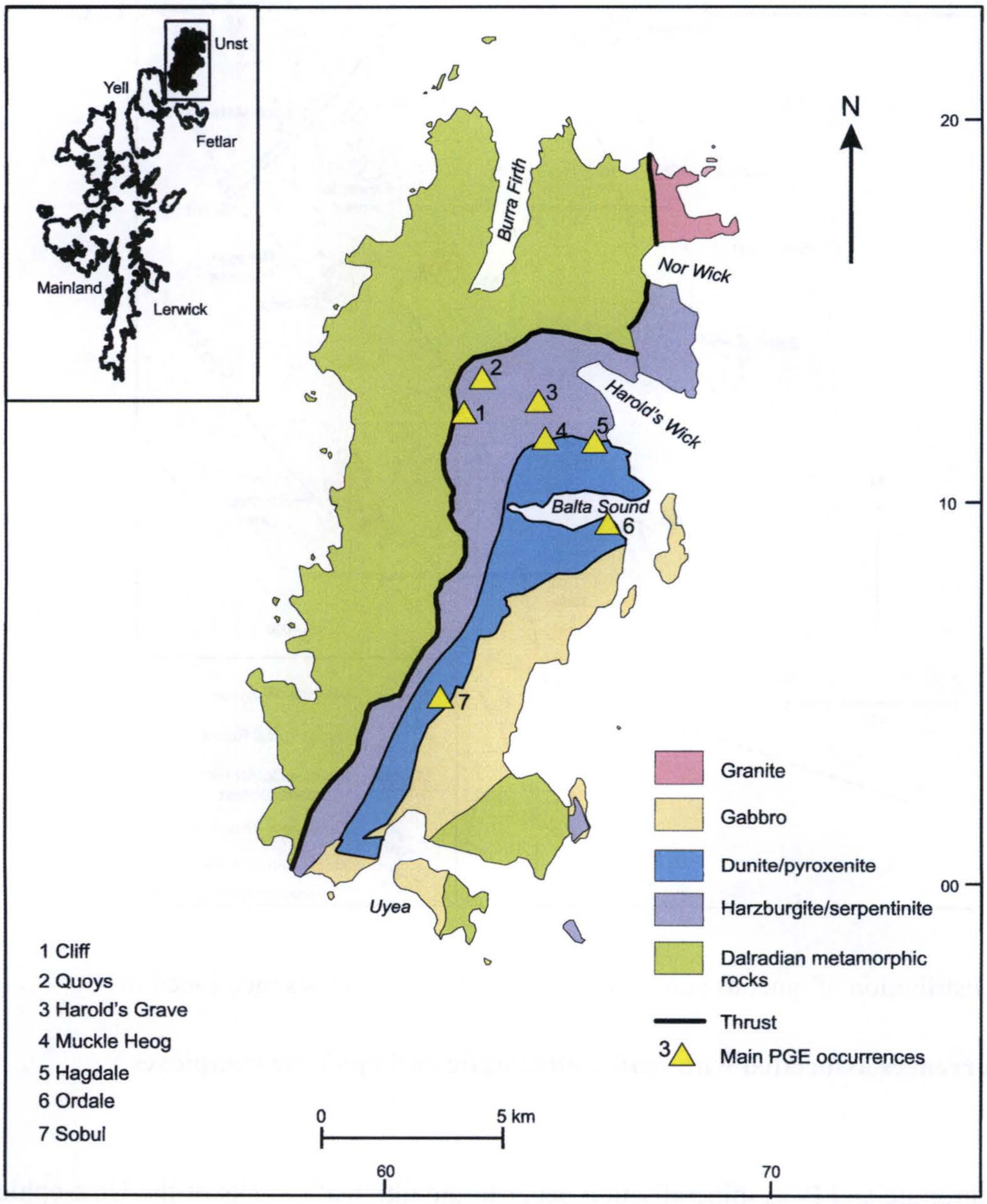

Figure 3.3 Simplified geology of Unst with the main PGE occurrences

In 1984 the MRP carried out PGE exploration over the Unst ophiolite (Gunn *et al.*, 1985). A combination of drainage, overburden and rock sampling indicated widespread enrichment in the basic-ultrabasic rocks. High concentrations of all PGE occur in chromitite, chromite-rich dunite and dunite from a zone of talc-carbonate alteration in the Cliff area (Leake and Gunn, 1986). Gunn *et al.* (1985) reported maximum values of 25 ppm Pt and 46 ppm Pd from the Cliff area. This mineralisation is dominated by Pt- and Pd-bearing species such as sperrylite and stibiopalladinite. Similar Pt-Pd enrichment, although at lower grades, was reported from several other localities. Elsewhere Ru-Ir-dominant mineralisation was identified e.g. at Harold's Grave (Figure 3.3) (Gunn, 1989).

In 1984-85 Esso Minerals Ltd conducted further exploration for PGE involving shallow drilling over the basal harzburgite, but with limited success. In 1999 Leicester Diamond Mines Ltd of Vancouver, Canada carried out further investigations, including diamond drilling, in the most prospective areas, focused mainly on the Cliff occurrence in the north-west of the complex. The only significant intersection reported by the company was 5.82 ppm Pt and 16.99 ppm Pd over 1.83 m core length.

It is important to note that the Cliff-type Pt-Pd dominant mineralisation is most unusual. PGE mineralisation in ophiolites is generally dominated by Ru, Ir and Os that are much less valuable and have fewer commercial applications than Pt and Pd. For this reason, the values reported by Gunn (1989) in several largely untested areas indicate potential for the occurrence of economic mineralisation. In particular, structurally-controlled targets identified by drainage geochemical data and high values in the pyroxenite cumulate sections merit further investigation. The area would require further boreholes or trench sections through the mineralised zones to assess the economic significance of the PGE mineralisation.

Talc occurs in the ultramafic rocks on Unst where it has been worked in the past at Quoys and at Cross Geo, near Clibberswick. A talc-magnesite deposit has also been mined at Cunningsburgh on Mainland Shetland. The mineralogy of the deposit has been described by Bain *et al.* (1971).

RUM, SKYE AND MULL

The Tertiary igneous complexes of Rum, Skye, and Mull (Figure 3.2) include well-known minor occurrences of chromite (Brown, 1956) and more recent discoveries of high PGE values (Butcher *et al.,* 1999; Pirrie *et al.,* 2000). The complexes developed contemporaneously with the Skaergaard Complex of eastern Greenland in which PGE-Au mineralisation has been recently identified (Neilsen and Schønwandt, 1990). The Skaergaard Complex occurs within a 150 m-thick layered succession of leucocratic and melanocratic gabbros in the upper part of the Middle zone of the intrusion. Intersections of up to 3 ppm Pd+Pt over 10 m have been recorded, together with an estimated resource of 40 million tons grading 2.38 ppm Au, and a further >100 million tonnes grading 1.9 ppm Au (Neilsen and Brooks, 1995).

The Rum Complex consists of three main components, the Eastern Layered Series, the Western Layered Series and the Central Series, as well as a number of mafic-ultramafic plugs cut by dykes in the marginal areas. These rocks were formed from the intrusion of picritic and basaltic magma at the boundary between the Lewisian gneiss and the Torridonian Sandstone (Emeleus *et al.,* 1996). Although no drilling or systematic sampling has been undertaken in Rum, Power *et al.* (2000 and 2002) identified PGE values exceeding 2 ppm in some sulphide-rich lithologies. They suggested that the area around Glen Harris in central Rum was the location of the central magma chamber where potentially significant PGE mineralisation could be located.

LOCH AILSH AND LOCH BORRALAN

The Loch Ailsh and Loch Borralan complexes (Shand, 1910) belong to a group of alkaline plutonic intrusions and associated dykes and sills of late Caledonian age located in the Assynt district of the Moine Thrust Belt of north-west Scotland (Figure 3.2). The Loch Ailsh Intrusion (Figure 3.4) was emplaced into Cambro-Ordovician sediments of the Ben More nappe prior to the main movements on the Ben More and Moine thrusts which are major planes of disruption in the Assynt area. U-Pb dating of zircons indicates a minimum age of intrusion at Loch Ailsh of 439 ± 4 Ma (Van Breeman *et al.,* 1979). The earliest intrusive events in the Loch Borralan complex are dated at 430 ± 4 Ma (Van Breeman *et al.,* 1979).

The Loch Borralan body is a complex, multi-stage intrusion, occupying an area of about 26 km^2, emplaced into Cambro-Ordovician sedimentary rocks of the Durness Limestone Group. The complex comprises two intrusive suites: an early one of pyroxenites, nepheline-syenites and pseudoleucite-syenites; and a later one of feldspathic syenites and quartz-syenites. The ultramafic rocks comprise biotite-magnetite pyroxenites, commonly with andradite, and hornblendites. On the basis of geophysical and drilling evidence the largest body underlies an area approximately 1500 m in length and up to about 300 m wide along the south-western margin of the intrusion. It dips towards the north-east at about 70° and plunges beneath syenitic rocks to the south-east. Drilling shows that the ultramafic rocks are intercalated with screens of heterogeneous syenite, varying from leucocratic to andradite-rich. Both intrusive and gradational relationships to the pyroxenites are observed.

The petrological diversity, complex tectonic setting and poor exposure make it difficult to unravel the detailed petrogenesis of the Loch Borralan intrusion. The early ultramafic and feldspathoid-bearing rocks appear to have an overall sheet-like laccolithic form. The later alkali feldspar-syenites and quartz-syenites punch through the early suite and may have a stock-like form.

The Loch Ailsh complex is located less than two kilometres to the north-east of the Loch Borralan Complex (Figure 3.4). It underlies an area of about 10 km^2 and comprises a minor early suite of ultramafic and mafic rocks and three more extensive phases of sodic leucocratic syenites (Parsons, 1965a and 1965b; Parsons *et al.,* 1983). The three-dimensional form of the intrusion is obscure although it is believed to be a sill-like body emplaced between Proterozoic basement rocks and an overlying cover of Lower Palaeozoic sediments.

Ultramafic rocks are exposed over a distance of approximately 4 km in a narrow zone along the south-eastern margin of the Loch Ailsh intrusion in the Allt Cathair Bhan valley. They comprise predominantly medium- to coarse-grained clinopyroxenites containing variable proportions of interstitial magnetite, brown amphibole, phlogopite, sphene and apatite that are interpreted as late magmatic phases. Modelling of geophysical data shows that the pyroxenites in this zone dip steeply to the south-east beneath the Cambro-Ordovician sediments (Parsons, 1965a).

A high amplitude magnetic anomaly reported by Parsons (1965) over the south-western margin of the Loch Borralan complex stimulated commercial interest in the area as a potential source of titaniferous magnetite. Robertson Research International Ltd. conducted a detailed ground magnetic survey over this sector of the intrusion followed by drilling of four diamond drillholes across the main anomaly in 1969-70 (Matthews and Woolley, 1977). A second phase of drilling was carried out in the same area by Consolidated Gold Fields plc in 1975. In view of the high apatite contents recorded in these boreholes, the BGS undertook a programme of research to investigate the phosphate potential of this part of the complex. This work, completed in 1981, involved a detailed gravity survey and drilling 37 shallow boreholes over an area of about 3 km^2. Notholt *et al.* (1985) reported that the pyroxenitic rocks contain variable amounts of apatite (generally 0.3–9 wt%), magnetite (about 10%), biotite, garnet and hornblende. The magnetite is slightly titaniferous and also contains an average of about 0.3% vanadium.

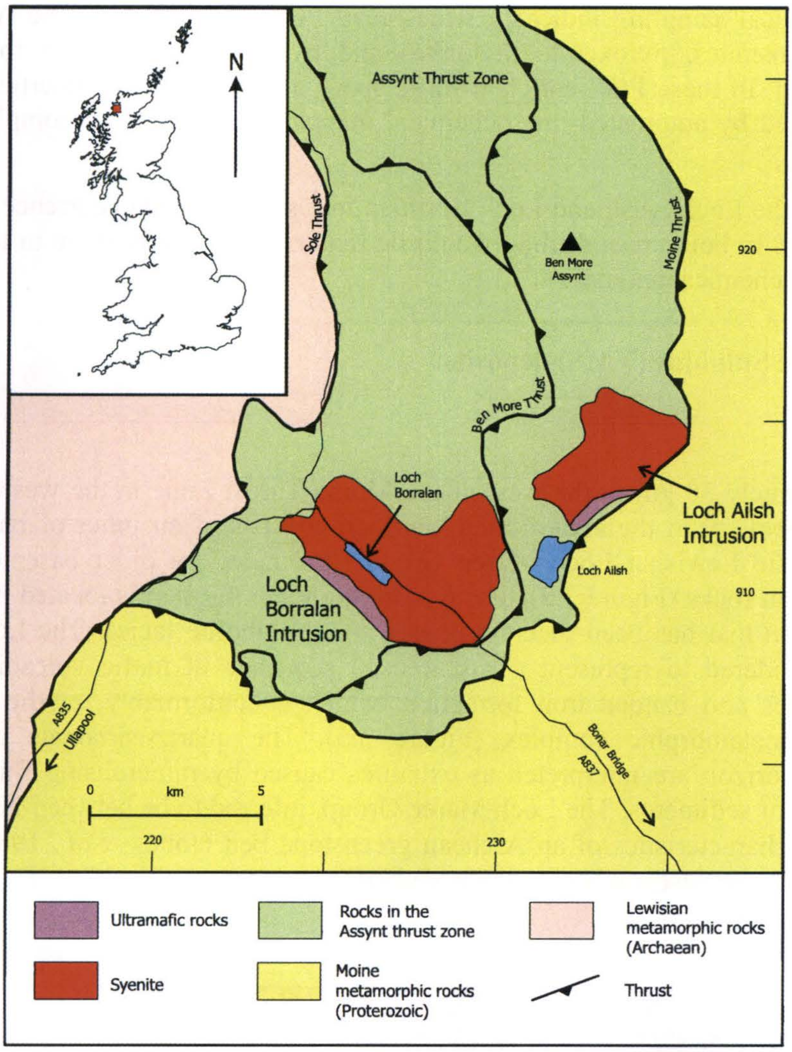

Figure 3.4 The geological setting of the Loch Ailsh and Loch Borralan Complexes

PGE analysis by BGS of the drillcore from the earlier phosphate investigations revealed widespread high values of Pt and Pd in pyroxenites, together with sporadic low tenor enrichment in heterogeneous mafic syenites and skarns. Maximum values were 328 ppb Pt and 550 ppb Pd in a 0.5 m intersection in one borehole, with values averaging 450 ppb combined Pt + Pd over a 2 m interval. The elevated PGE values are commonly associated with calcite veining, chalcopyrite and low tenor enrichments in gold. In the light of these results further drilling was carried out by the MRP at Loch Borralan in 1989. Ground access restrictions precluded further testing of the main area of high PGE values in the central and south-eastern part of the main pyroxenite body. Consequently 4 boreholes were drilled to the north-west of the main body: 3 inclined holes tested the pyroxenite exposed in the Bad na h-Achlaise and a fourth was drilled to investigate a high amplitude magnetic anomaly about 400 m to the east. Low tenor Pt and Pd enrichment was identified in these heterogeneous, veined pyroxenites and garnet pyroxenites, commonly associated with enrichments in Cu and also locally in Au (Shaw *et al.,* 1992).

The only documented commercial exploration in the Loch Ailsh intrusion comprises largely unsuccessful soil geochemical and ground geophysical surveys for base-metals carried out by Noranda-Kerr (U.K.) Ltd in the early 1970s (MEIGA 113). However, as a result of the encouraging PGE data reported from the Loch Borralan complex, the mafic and ultramafic rocks in the Loch Ailsh complex were investigated by the MRP (Shaw *et al.,* 1994). Reconnaissance sampling of drainage sediments and bedrock indicated localised PGE enrichment in mafic and ultramafic rocks in the south-east and northern parts of the complex. Follow-up detailed basal overburden and lithogeochemical sampling indicated widespread PGE enrichment in the Allt Cathair Bhan valley in pyroxenites, pyroxenite mylonites and pyroxenite skarns, up to a maximum of 300 ppb Pt + Pd. In these PGE-enriched rocks sperrylite (PtAs) and isomertieite (Pd + Sb + As) were identified by automated microchemical mapping, together with complex tellurides of Pd, Ag, Bi and Pb.

Good potential exists in both the Loch Ailsh and Loch Borralan intrusions for the occurrence of additional PGE mineralisation. In both areas drilling would be required at an early stage to test known geophysical and/or geochemical anomalies.

3.2.3 Volcanogenic Massive Sulphide (VMS) deposits

GAIRLOCH

Gairloch is situated approximately 30 km to the west of the Moine Thrust Zone in the western part of the study area. The geology in the area around Gairloch consists of an inlier of basic volcanics and sediments of the Lewisian Loch Maree Group surrounded by older basement gneiss and younger Torridonian rocks (Figure 3.5). The Cu-Zn-Au mineralisation is located in a quartz-carbonate-schist horizon that has been metamorphosed to amphibolite facies. The Loch Maree Group rocks are considered to represent a supracrustal sequence of mafic volcanics, greywackes, limestones, shales and banded iron formation, which unconformably overlie an older Lewisian high-grade metamorphic complex (Figure 3.5). The quartz-carbonate and associated quartz-magnetite horizon are interpreted as exhalites caused by mineralising fluids venting onto or into the seafloor sediments. The Loch Maree Group, inferred to be between 2300 and 2400 Ma old, has many characteristics of an Archean greenstone belt (Jones *et al.,* 1987). The mineralisation is believed to represent a Besshi-style VMS deposit.

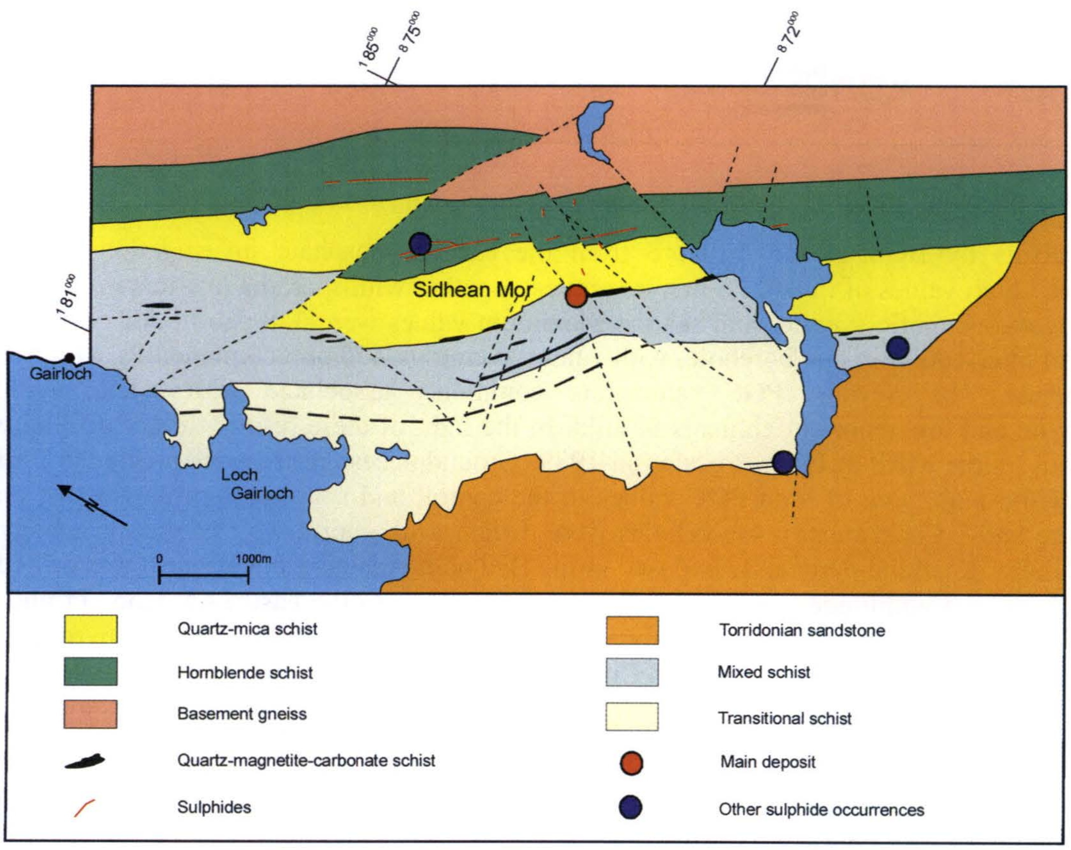

Figure 3.5 Geology of the Gairloch area (adapted from Jones *et al.* 1987)

The first description of mineralisation at Gairloch was given in the North-west Highlands memoir (Peach *et al.,* 1907), which describes a malachite-stained gossan near Kerrysdale. The outcrop was recorded as a "brown-weathered limestone…mixed with talcose streaks and siliceous layers which contain a good deal of pyrite and some chalcopyrite". Consolidated Gold Fields geologists re-discovered this outcrop in 1978 and realised its significance as an indicator of possible additional mineralisation in the area. Samples of the gossan contained up to 9.90% Cu, 0.63% Zn, 8.4 ppm Au and 27 ppm Ag (MEIGA 173). Drilling by Consolidated Gold Fields confirmed the existence of a laterally persistent 4 m thick mineralised quartz-carbonate schist horizon containing pyrite, chalcopyrite, sphalerite and native gold. The mineralisation has a strike length of at least 1 km and contains a resource of about 0.6 Mt at a grade of 1.2% Cu, 0.6% Zn and 1.4 ppm Au. The deposit has undergone intense polyphase ductile deformation and faulting with amphibolite facies metamorphism (Jones *et al.,* 1987). A separate pyrrhotite-rich horizon, up to 4 m thick but with lower Cu and Zn values, was also drilled on Sidhean Mor about 1000 m north of the main deposit. Figure 3.6 shows the location of the main sulphide occurrences in the Gairloch area.

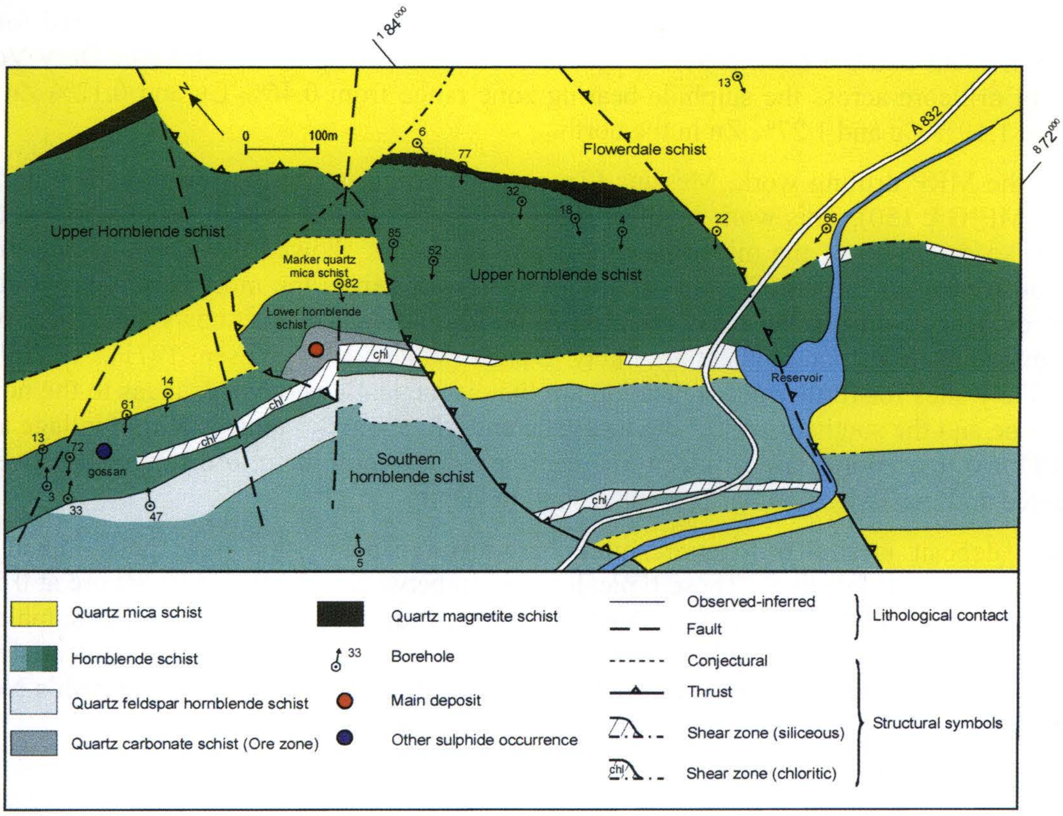

Figure 3.6 A simplified geological map of the main Gairloch deposit (adapted from Jones *et al.* 1987)

A detailed gravity and magnetic survey by Coats *et al.* (1997) identified a high-amplitude positive magnetic anomaly associated with the supracrustal rocks in the Gairloch area. This has raised the possibility of further sulphide mineralisation within the Loch Maree Group up to 10 km along strike from the existing deposit since Besshi-style deposits often occur in clusters (Slack, 1993). Grade-tonnage plots indicate that the largest Besshi-style deposits (e.g. Windy Craggy, Canada; Ducktown, USA) contain more than 1 Mt of copper, comparable to tonnages of the largest volcanogenic massive sulphide deposits in the world. Typically Besshi-type deposits contain 1.3 Mt of massive sulphide with a Cu grade of 1.43% (Slack, 1993).

VIDLIN

The Vidlin area, in the northern part of mainland Shetland was mapped in 1930 by Haldane, who noted sulphide mineralisation at three localities on Vidlin Ness and an additional occurrence east of Skeo Taing on Dury Voe to the south (Figure 3.7). The mineralisation comprises massive sulphides, (dominantly pyrrhotite with lesser amounts of chalcopyrite, sphalerite and galena), hosted by sulphide-bearing quartz-rocks grading into sulphide-bearing tremolite rocks and sulphide-rich amphibolites. Seventeen samples analysed during initial investigations by the MRP recorded values up to 12.2% Cu, 1.7% Zn and 0.23% Pb (Garson and May, 1976). Coordinated geological, geochemical and geophysical investigations in the area between Vidlin Ness and Dury Voe were carried out by the MRP during 1975, followed by a six hole drilling programme in early 1976 (Garson *et al.,* 1976). These holes intersected a stratabound Cu-Zn-Pb VMS deposit striking approximately north-south that was proven to be laterally persistent for at least 500 m and in depth to 100 m (Garson *et al.,* 1976). The sulphide-bearing horizon varied in thickness from about 10 m to less than 2m. Both the thickness and grade of the deposit increase to the north under the sea. Geophysical (I.P., magnetic, and E.M.) and, to a much lesser extent, deep overburden geochemistry investigations suggested that the sulphide zone continued for a further 3 km south under a thick cover of peat and sand to outcrop on the shore of Dury Voe. Analyses of drillcore across the sulphide-bearing zone range from 0.46% Cu and 0.12% Zn in the south to 1.19% Cu and 1.27% Zn in the north.

Following the MRP drilling work, Messina (Transvaal) carried out further diamond drilling in late 1976 (MEIGA 150). This work involved 1850 m of drilling in eleven boreholes to test the dip and strike extension of the mineralised horizon. This work showed that the mineralisation thinned and weakened in both Cu and Zn grades southwards from the most northerly outcrop. However, evidence from similar massive sulphide bodies in Scandanavia shows that where one sulphide mass has been found, others are likely to exist (Vokes, 1969; Nilsen, 1971). At Vidlin, the most likely sites for further mineralisation are the magnetically anomalous areas to the north in Vidlin Voe and the southern part of the magnetic and I.P. anomaly south of Vidlin village and as far as Drury Voe. Wider use of electromagnetic methods could help to distinguish between disseminated and massive sulphides present at shallow depth.

The Vidlin deposit is similar to stratabound base-metal deposits that have been mined in Scandanavia at several localities. These typically contain between 1.5 Mt and 10 Mt ore at 0.5 – 1.3% Cu and 0.5 – 1.7% Zn (Garson *et al.,* 1976). The discovery of stratabound sulphides associated with metabasic rocks at Vidlin is significant because it demonstrates the potential for additional occurrences at this horizon in the Dalradian of Shetland, for example at Garth's Ness (MEIGA 249).

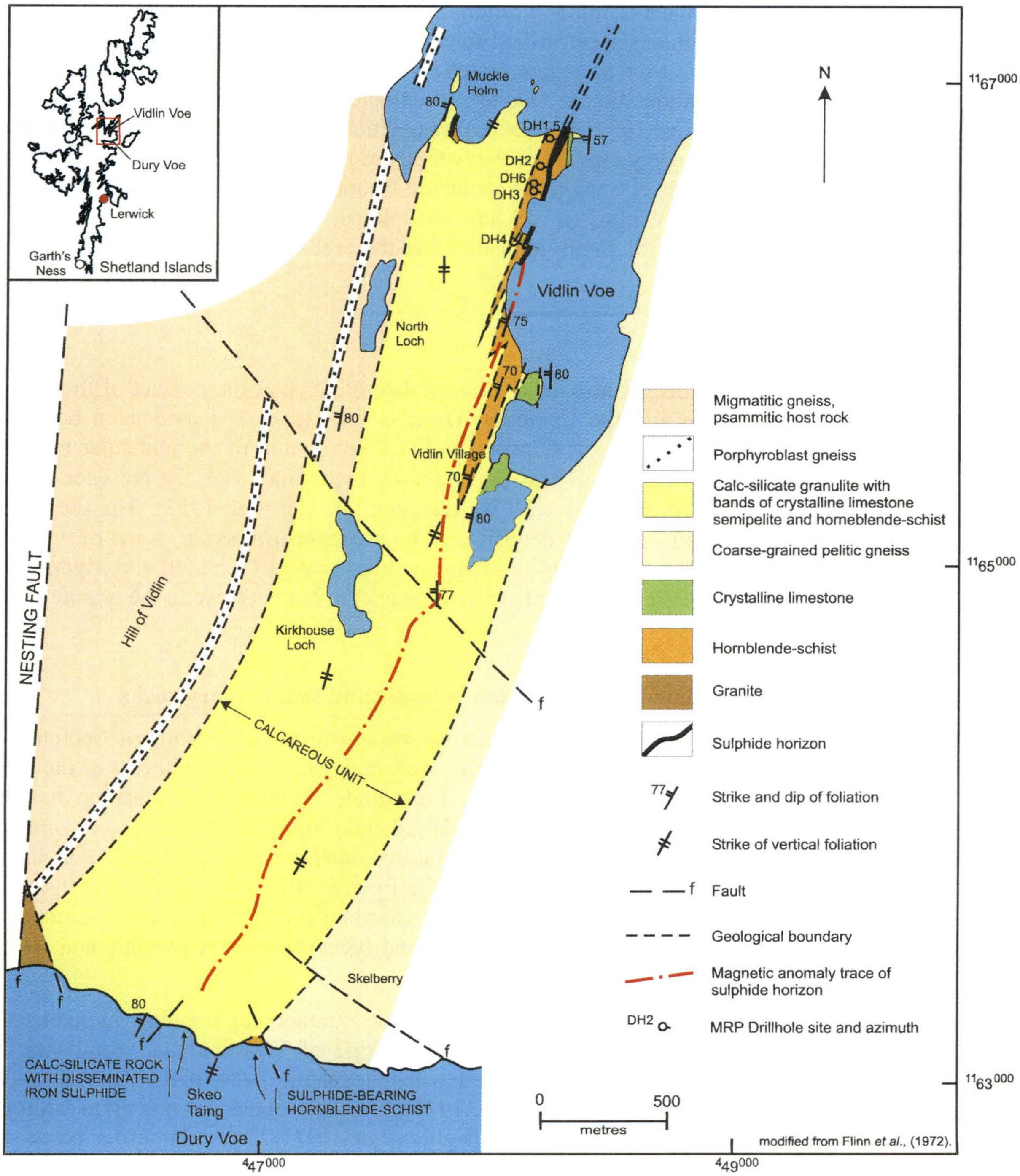

Figure 3.7 Geology of the Vidlin area (modified from Flinn *et al.* 1972)

3.2.4 Skarn-type deposits

SHETLAND

Magnetite was mined at Clothister Hill in Mainland Shetland during World War Two and again between 1954-57 when between 6000 and 10,000 t were extracted (Groves, 1952). The ore is high purity (60-67% Fe) with very low phosphorus content (0.006%). The orebody averages 3 m thick, striking north-south for 53 m and extends to a depth of 22 m (Mykura *et al.,* 1976). A magnetometer survey in 1942 discovered four other anomalies within the same schist belt as the original deposit. However drilling of five holes over the strongest of these anomalies failed to intersect any significant magnetite mineralisation. Following reassessment of the magnetometer survey, a further eight boreholes were drilled over this and the other anomalies. However, no further magnetite mineralisation was intersected despite the presence of various indicator features of skarn mineralisation such as calcite and epidote veining which were identified near the original discovery (Groves, 1952). The lack of magnetite in the boreholes has been attributed to a possible irregular and steeply dipping orebody that was not intersected due to its small cross-sectional area, or to disseminated magnetite occurring throughout the schist country rocks. The original magnetite deposit at Clothister Hill has been almost worked out: drillholes testing the extension of the mineralisation at depth indicated that the orebody rapidly peters out below its deepest worked level.

SKYE

A small magnetite deposit occurs at Kilchrist on the Isle of Skye at the contact of the Tertiary Beinn an Dubhaich granite and the Cambrian Durness limestone. The associated host rocks suggest that it may be a skarn deposit (Groves, 1952). Exploitation of the lenticular magnetite pods for iron ore during World War II was prevented by their small size, the presence of up to 1% Cu (as chalcopyrite) and problems with waterlogged pits (Groves, 1952). The presence of copper suggests the possibility that the deposit may be a copper-iron skarn, some of which are known to host gold (Theodore *et al.,* 1991). Magnetometer surveys (Whetton and Myers, 1949; Merrall, 1994) indicated the presence of other small magnetite bodies close to the granite contact that have not been tested.

3.2.5 Occurrences associated with Devonian volcanic and sedimentary rocks

The Devonian Old Red Sandstone (ORS) outcrops widely in the Highlands of Scotland and occurs intermittently along the east coast of the Scottish mainland along the border of the Moray Firth up to the Great Glen Fault at Inverness. Low-grade uranium mineralisation has been discovered at several localities in the Northern Highlands, together with a lesser number of higher-grade occurrences. The main localities on the mainland occur in the Middle ORS of the Orcadian cuvette, in the Helmsdale granite and in the Lower ORS at the north-east edge of the pluton (Bowie *et al.,* 1970; Gallagher *et al.,* 1971). Uranium mineralisation also occurs in the Orkney Islands were it is associated with the ORS and brecciated zones (Michie and Cooper, 1979).

The Middle ORS contains shale bands with low-grade stratabound uranium mineralisation. These include the Caithness Flags at Murkle Bay, Bridge of Westfield and Broubster. The uranium mineralisation is commonly associated with phosphatic beds, particularly fossil fish beds, as well as black shale horizons (Tweedie, 1979). Thorium concentrations up to 5000 ppm in fish remains have also been discovered (Gallagher *et al.,* 1971). The uraniferous black shale horizons are thin (1-3 cm), but thicker more erratically mineralised dolomitic shales and conglomerates can reach over 30 cm thick. However, it is only the phosphatic horizons that are persistently radioactive over thicknesses of 30 cm. Uranium is also associated with shears within the Helmsdale granite. Weakly radioactive zones occur associated with deeply weathered porphyritic granite.

The Lower ORS in the Ousdale Burn area contains five main occurrences of uranium mineralisation associated with a thick sequence of Ousdale Arkose overlying the Helmsdale granite. In most cases uranium occurs in the form of uraninite that is extremely fine-grained and intimately associated with small specks of hydrocarbon. Where the arkose is exposed in the area, it is heavily jointed with radioactivity levels that do not vary consistently with either structure or bedding (Bowie *et al.,* 1970). Average uranium content over one section was estimated to be 50 –100 ppm U, but individual samples contained up to 500 ppm U. These estimates were based, however, on surface samples, and the presence of radian baryte, together with the relatively short half-life of radium, suggests leaching of uranium and therefore the consequent possibility of the existence of higher values at depth (Bowie *et al.,* 1970). In part to test this hypothesis, 41 shallow percussion boreholes were drilled in 1971-72 by Rio Finex Ltd (MEIGA 82). The results of this drilling suggested that the uranium mineralisation in the lower Ousdale Burn area was tabular in form, dipping eastwards and truncated westwards by reverse faulting which downthrows mudstones beneath arkose (Gallagher *et al.,* 1971). Uranium enrichment of up to 300 ppm between 3 and 8 m depth was recorded in one borehole, together with anomalous values of copper, lead, molybdenum, arsenic and tungsten. This suggests that supergene enrichment of uranium is likely. The occurrence in the Ousdale Arkose has given rise to the speculation that uranium-bearing deposits may lie concealed at the base of the ORS elsewhere in the area (Johnston and Mykura, 1989), though with the exception of the Riofinex work, no further exploration drilling has been carried out in the area.

Low-grade uranium mineralisation within the ORS in the Orkney Isles predominantly occurs in the Rousay Flags and older sediments of the ORS. Uraniferous hydrocarbon is also occasionally found in the Yesnaby Sandstone Formation and ashy silts of the Stromness Flags. The principal lithologies hosting the mineralisation are phosphatic sediments that have been modified by leaching and localised remobilisation and re-precipitation. In places the uranium content of the rock can reach 1000 ppm, and it is usually accompanied by an increase in phosphate in the order of 1% P_2O_5 to every 70-80 ppm uranium. The drilling of a mineralised fault breccia at the Mill of Cairston on Mainland intersected up to 5.5% Pb and 0.1% U over 0.92 m (MEIGA 125) suggesting that additional exploration along strike is warranted (Michie and Cooper, 1979).

In addition to the occurrences mentioned above, two other low-lying drift- and lake-covered anomalies that merit further study are Northern Hoy and the Central Mainland of Orkney (Michie and Cooper, 1979). At Northern Hoy several unexplained uranium-in-stream-sediment anomalies and a set of strong small radioactive anomalies occur along a fault line. In Central Mainland there are numerous uranium anomalies in stream waters and sediments.

3.2.6 Alluvial gold occurrences

The discovery of alluvial gold in the Helmsdale area prompted a gold rush in 1868. More than 3000 oz of gold were recovered from this area between 1868-1870, including a nugget of over two ounces found in 1869 (Adamson, 1988; Rice, 1993). The distribution and abundance of gold in this area has been well documented (e.g. Heddle, 1901; Dawson and Gallagher, 1965), but until recently the original source of the gold was unknown. It was thought that the gold must have been eroded from hydrothermally altered schists and from disseminated grains from within the granite and surrounding rocks since no main lode has ever been located (Gallagher *et al.,* 1971). However, the discovery of auriferous breccia around the headwaters of the River Brora (Crummy *et al.,* 1997) has suggested the possibility of an epithermal gold locality hidden under the Devonian rocks, analogous with the Rhynie gold locality in Aberdeenshire.

Gold deposits associated with hot springs are well documented (e.g. Berger 1985), and they are recognised at forming at depths between 100-200 m below the surface. The chert at Rhynie, north-east Scotland, initially famous for its exceptional preservation of some of the oldest plants in the world, has also been shown to have been a product of hot spring activity (Rice *et al.,* 1995). Rice *et al,* (2002) identified high gold values in the Rhynie Chert associated with extensive and long lived hot spring activity with at least 53 chert horizons identified in a unit about 35 m thick. One of these units has been intensely altered to a quartz-pyrite-adularia assemblage and has significant gold, tungsten and arsenic anomalies.

Work by Crummy *et al.* (1997) identified some of the features found at Rhynie in the Brora area. These include bedrock gold mineralisation in brecciated and vuggy crystalline quartz, chert and chalcedonic rocks, associated with a Lower Devonian oulier, 25 km to the west of the well-known Helmsdale alluvial gold occurrences. Such rocks are characteristic of the upper part of a feeder zone to an exhalative hydrothermal system and fluid inclusion work on these rocks has revealed formation temperatures of 170-240°C. Crummy and co-workers suggest that deep weathering of the remains of such a hydrothermal system may have produced the alluvial deposits around the headwaters of the River Helmsdale and in doing so destroying any evidence of primary bedrock gold mineralisation in the area. They conclude that east and central Sutherland is prospective for exhalative epithermal gold mineralisation and the associated deeper-level feeder zones. Accordingly, as part of this project, limited geochemical sampling has been carried out to test this hypothesis in this area and other Devonian inliers.

3.2.7 Vein-style occurrences

Vein occurrences are the most common style of mineralisation found in the Northern Highlands. Vein workings vary greatly in size: some were clearly small trials, whilst others were worked extensively for many years and have yielded thousands of tons of ore.

An estimated 12,000 t of copper and iron ore were mined between 1789 and the early 1920s at Sandlodge Mine in the Shetland Islands. This deposit occurred in two north–south-trending veins, 3-5 m thick, converging at depth. Ore minerals included limonite, haematite, malachite, chrysocolla, siderite and chalcopyrite (Mykura *et al.,* 1976).

Galena-bearing veins, with associated sphalerite and baryte, were worked between 1722 and 1904 at Strontian in western Scotland. This mineralisation occurs in a number of east–west trending veins, of which the Main Vein was the most important. The area is famous as the type locality of the mineral strontianite ($SrCO_3$). The steeply dipping veins occur in fault zones in Moine psammites adjacent to the Strontian granite (Sabine, 1963). The Main Vein has been exploited by both open-cast and sub-surface workings at three mines: Whitesmith to the west, Clashgorm or Middleshop in the centre, and Bellsgrove to the east. Two kilometres west of the Whitesmith workings lies the Corrantee mine where two veins carrying galena and baryte dip towards the south at 75°. The Scottish Canadian Company carried out a drilling programme at Corrantee in 1968 but the results of this exploration are not known. Drilling by NL Industries Incorporated in 1977 indicated that rather than being a continuous vein, the Main Vein deposit consists of a number of lenticular mineralised bodies within, and parallel to, a well-defined shear zone which is up to 30 m wide and dips steeply towards the south (MEIGA 158). An attempt was made to re-open the mine in 1983 for baryte by Strontian Minerals Limited (Mason and Mason, 1984), but low grades and mineral separation problems caused closure in 1986. Limited geophysical investigations (VLF-EM and magnetics) by the MRP attempted to delineate crush zones and associated Permo-Carboniferous basic dykes that host the mineralisation (Kimbell, 1986). Probable extensions to known orebodies were discovered during these surveys and geophysical, geological and possibly geochemical follow-up was recommended. No further work has been carried out since this study.

A number of small-scale workings on lead and zinc veins occur elsewhere in the Highlands e.g. Loch Shin and Strathcomair, south-east of Glenelg (Wilson and Flett, 1921). Further galena-bearing veins occur at Glen Glass (Wilson and Flett, 1921), and disseminated galena was recorded at Loch Carron in the Fucoid Beds affected by the Kishorn Thrust by Bowie *et al.* (1966). At Struy, west-south-west of Inverness, three lead- and zinc-bearing veins in Moine schists were mined on a small scale during the first half of the 19th century (Russell, 1946; Burley, 1976).

Several minor mineral occurrences are found on Fair Isle, south of Shetland. In 1912 copper was briefly extracted at Copper Geo where the ore contained various copper minerals including digenite, chalcopyrite, bornite and covellite in association with scapolite and calcite (Mykura *et al.,* 1976). Copper is also associated with scapolite at north and south Reevas in western Fair Isle, while chalcopyrite and ankerite occur in veins at Duttfield on eastern Fair Isle (Wilson and Flett, 1921).

Other minor metalliferous vein occurrences include a galena-baryte bearing vein at Hill of Sour, 6 km south of Thurso, in Caithness, and a molybdenite-bearing quartz vein at Badnaybay in

Sutherland that may be related to the Loch na Seilge sill. Molybdenite also occurs in a quartz-albite-oligoclase pegmatite intruded into hornblendic rocks at Achfarry in Sutherland. Chalcopyrite and copper silicate minerals have been reported by Heddle (1901) in veins at Rhiconich near Scourie in Sutherland.

3.2.8 Other occurrences

SHETLAND

Exploration for gold was carried out over the Shetland Islands in 1994 (Buchanan and Dunton, 1996). The purpose of this was to identify the source of anomalous results from a previous survey (Flight *et al.,* 1994) and to delineate areas for detailed exploration. Detailed lithogeochemical sampling identified up to 1.2 ppm Au in a conformable, phyllite-hosted pyritic band in the Muness area of Unst. The pyrite horizon outcrops at the coast, where its width varies from 2 to 12 m and its maximum observed length is approximately 75 m. Channel samples taken across an 11 m section of the pyrite horizon have an average gold content of 275 ppb. Further anomalous arsenic and gold values occur in soils over the unexposed section of the pyritic horizon. The results indicate some potential for Au mineralisation.

SUTHERLAND AND CAITHNESS

Small quantities of haematite were extracted from a north-north-east-trending crush zone over a strike length of 430 m at Achvarasdal in Caithness, and minor disseminated galena has been noted in arkose at Loch nan Clachan Geala also in Caithness (Institute of Geological Sciences, 1979).

A thin (60 cm) bed of interbedded shale and sandstone containing small amounts of chalcocite nodules was reported by Fermor (1951) in Torridonian rocks at Clachtoll, northwest of Lochinver in Sutherland.

Small quantities of Cu, Ni, Ag and Au were recovered from trials near Loch Duich between 1904-1905. The metals were recovered from pyrite and pyrrhotite concentrations in a Lewisian gneissose band about two metres wide. Gold concentrations were reported to be approximately 1.5 ppm (Peach *et al.,* 1910; Wilson and Flett, 1921).

Geochemical and geophysical surveys undertaken by Riofinex North Ltd. between 1989-1990 in the Glen Oykel area revealed a number of gold and lead anomalies. A trenching programme undertaken to determine the extent of these anomalies recorded a maximum value of 4.14 ppm Au over 5.3 m in a unit thought to represent a silicified sediment. No further work was carried out subsequent to this discovery though the trench section that yielded the highest gold value was open to the north-west (Tear and Hazleton, 1991). A limited programme of diamond drilling was also carried out but no details are available.

Between 1975-76, Consolidated Gold Fields Ltd. undertook geophysical work in the Scourie area of Sutherland (MEIGA 3) in response to encouraging results from grab samples that yielded up to 0.9% Pb, 0.5% Zn and 0.08% Cu. The environment was considered to have potential for a Broken Hill-type deposit, and five inclined boreholes were drilled under the MEIGA programme to test two geophysical anomalies. Several minor sulphide zones containing pyrrhotite were recorded from these holes, however these were shown to be deficient in nickel as well as having uniformly low lead and zinc values. Although no mineralisation of economic importance was discovered, the holes revealed more mineralisation than had previously been recorded (locally up to 20% sulphides) and thus accounted for the observed geophysical anomalies.

Outer Hebrides

The Outer Hebrides have few mineral occurrences in relation to their size. In the early stages of World War Two, the Chiapaval pegmatite near Northton and the Sletteval pegmatite east of Roneval were quarried for potash-feldspar on a considerable scale. A suite of rare-earth minerals as well as uranium-bearing minerals were recorded by Knorring and Dearnley (1959). No further work has been done at this site. Limited MRP studies were carried out to determine the potential for the occurrence of metalliferous mineralisation in the Lewisian gneisses and ultramafic units. The ultramafic rocks are slightly enriched in PGE, up to 52 ppb Pt and 210 ppb Pd, especially in rocks marginal to the shear zones on the south-west side of the South Harris Complex (Shaw *et al.,* 1993). Sulphide mineralisation associated with minor Au enrichment was recorded from the Market Stance quarry on Benbecula (Coats *et al.,* 1997), but no further work has been carried out.

In addition to the G-BASE sampling programme, a geochemical survey was undertaken by Stockwell (1989) to investigate the potential for gold in the Outer Hebrides. Although no significant mineralisation was discovered it was suggested that the Laxfordian age north-west trending shear zones may merit further exploration since they occur in proximity to large metasedimentary units that resemble greenstone terranes which elsewhere in the world host important gold and base-metal deposits.

Inner Hebrides

Skye

Iron was extracted from a two metre thick Upper Lias chamositic and sideritic stratabound ironstone at Raasay on the Isle of Skye during World War 1 until 1919. The iron content of the rock is 23-25%. Estimated resources at the time of mining were 10 Mt with an estimated further 6 Mt in the Beinn na Leac inlier further north on the island (Groves, 1952). Greenish oolitic limestone with an average iron content of 11.96% has been recorded from borehole intersections at the mouth of the Bearreraig River in Skye but no further work has been undertaken at this locality (Anderson and Dunham, 1966).

Tiree

The Geological Survey discovered a magnetite-rich pyroxene gneiss outcrop on Tiree in 1922 (Figure 3.8). A re-assessment of its economic potential involving a magnetometer survey over the area in 1942 showed that the strike length of the magnetite gneiss is 7 km. Initial rock sampling showed average values of 68% Fe, 3% SiO_2, and 0.21% P. The silica and phosphorus content were too high for any commercial use and further work was abandoned (Groves, 1952). Colvilles Ltd. drilled ten inclined boreholes between 1958-59 to test the continuity of the magnetite horizon along strike. This showed that the magnetite occurs discontinuously within varying rock types along strike and that the strongest anomalies were localised and caused by magnetite-pyroxene gneisses and granulites. A geochemical and petrological study of this magnetite gneiss by Stocks (1994) suggested that the rocks were Algoma-type Banded Iron Formation (BIF). A Pd-Pt-Te-Ni mineral was identified during this study although its origin is uncertain.

Figure 3.8 The magnetite-gneiss at Tiree

3.3 FUTURE MINERAL POTENTIAL

On the basis of this review, the following areas are considered favourable for the discovery of additional mineral resources:

1. The widespread occurrence of high Pt-Pd values in the Unst ophiolite suggest that economic resources of PGE may exist in the ultramafic rocks of the complex. Further work needs to be carried out to test targets in several areas.
2. The area around the Besshi-style Cu-Zn-Au deposit at Gairloch should be further explored. Additional zones of mineralisation that have greater economic potential may exist along strike from the deposit.
3. Additional low-grade molybdenum and tin localities around the Carn Chuinneag-Inchbae Complex.
4. The alluvial gold in the Helmsdale area may be derived from a concealed epithermal gold deposit. Further work for epithermal gold should be carried out over Devonian rocks in east Sutherland.
5. Low grade disseminated uranium mineralisation has been discovered in the Ousdale area in the Lower Old Red Sandstone and in phosphatic beds in Orkney. Potentially economic higher-grade deposits may occur underneath the ORS.
6. Small iron-copper skarn deposits occur in Skye. The presence of copper at levels of up to 1% suggests they could be copper-iron skarns and therefore may also contain gold. This has not yet been investigated.
7. PGE in Loch Ailsh and Loch Borralan. Drilling is required to check untested geochemical and geophysical anomalies.
8. Besshi-style mineralisation at Vidlin has been tested by drilling close to the exposed mineralisation on the shores of Vidlin Voe, north of Vidlin village. The mineralisation increases in grade and width to the north under the sea, but has not been tested over a 2 km strike length to the south.

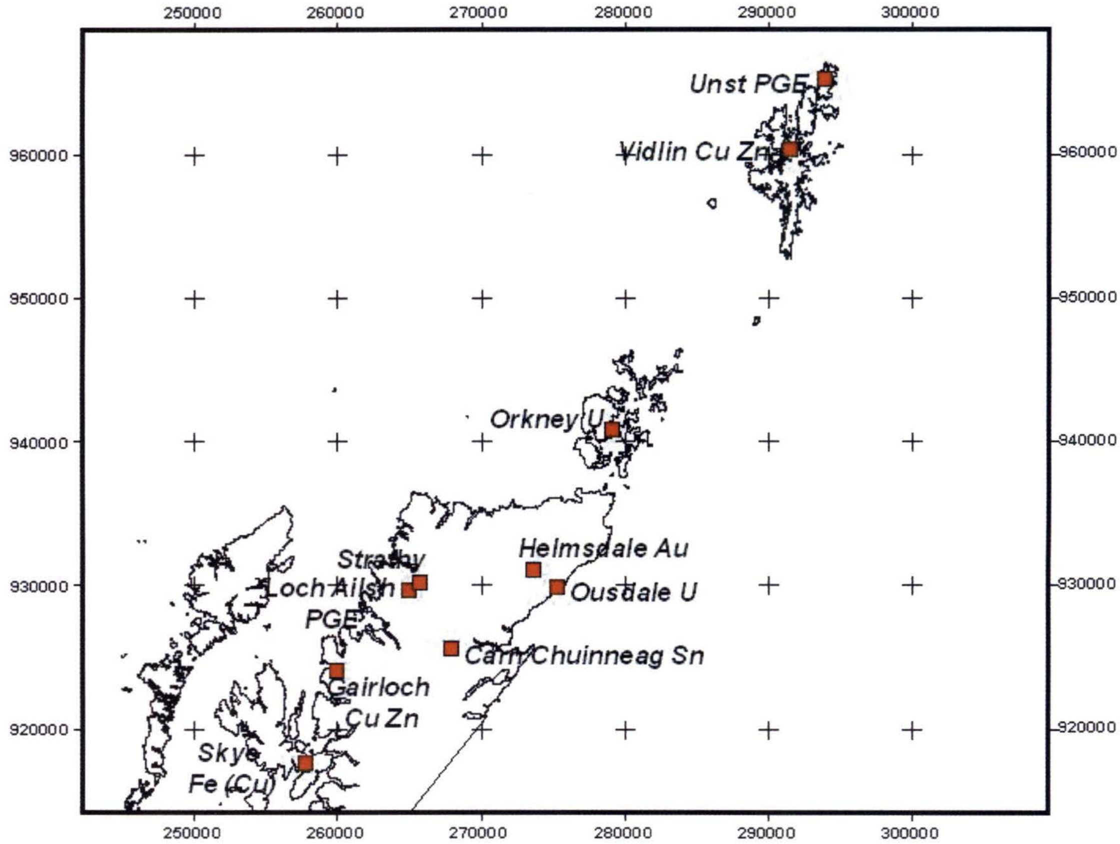

Figure 3.9 Areas with exploration potential

4 Mineral deposit models

Mineral deposit models are now an essential tool in mineral exploration. They provide the knowledge, the constraints and the comparisons necessary for the exploration geologist to make judgements on the potential of any area for selected types of ore deposit. They also enable the classification of existing ore deposits or occurrences which may be useful in further exploration and development.

Mineral deposit models have developed from the empirical knowledge developed during decades of mineral exploration. Common factors were noted, such as proximity to granites in the case of skarns, and these have been codified into sets of geological and mineralogical parameters which are then grouped into various classifications. These can be generalised, such as 'granite-related mineralisation, or more specific, such as 'Epithermal low-sulphidation gold deposits' or Mississippi Valley-Type lead-zinc deposits'. The publications of Cox and Singer (1986) and Kirkham *et al.* (1993) embody the most comprehensive knowledge of mineral deposit models.

There are a large number of deposit models: Cox and Singer list 141 within 14 general lithological associations. Many of them are rare, or have only a few major occurrences. They are all incomplete or imperfect to some extent, but are continually being revised on the basis of new exploration and research. Five deposit models have been identified, apart from minor hydrothermal veins and stratiform uranium, which are considered to have some potential for discovery in the Northern Highlands. These are

- Epithermal gold mineralisation
- Mesothermal gold mineralisation
- Volcanogenic massive sulphide mineralisation
- PGE mineralisation associated with ophiolite intrusions
- PGE mineralisation associated with alkaline intrusions

VMS and PGE types have been considered in Section 3. They are restricted to specific, small, reasonably well known areas and so have not been the subjects of the prospectivity analysis described later. The epithermal and mesothermal gold mineralisation types have a potentially wider occurrence and accordingly the favourability for these deposits has been modelled using a prospectivity mapping system based on ArcSDM™.

4.1 EPITHERMAL GOLD MINERALISATION

4.1.1 Introduction

Epithermal precious metal deposits generally form at depths of less than 1 km, most commonly in volcanic terranes closely associated with arc- and Andean-type calc-alkaline and shoshinitic volcanic rocks above subduction zones. Metals are dissolved from the volcanic rocks by circulating fluids and are deposited as a result of complex chemical reactions at temperatures in the range 100–300°C. They occur in a variety of geological structures and environments in response to the changing conditions as the pressurized metalliferous fluids ascend through the crust and react with the rocks. Cooling, fluid mixing and boiling are among the processes responsible for deposition of the ore minerals. Epithermal deposits represent attractive exploration targets in volcanic terrains with low-grade, large-tonnage disseminated ores and high-grade veins being the two most economically important deposit morphologies. The most important examples of epithermal mineralisation occur in the circum-Pacific area and include the Hishikari deposit in Japan, El Indio in Chile, Emperor in Fiji and Waihi in New Zealand.

4.1.2 Types of epithermal deposits

Two principal classes of epithermal deposits have been established on the basis of the nature and distribution of associated hydrothermal alteration, the deposit morphology and the textures of the ore and gangue minerals. These classes are known as:

i. low-sulphidation or adularia-sericite deposits.

ii. high-sulphidation or alunite-kaolinite deposits.

This division reflects fundamental differences in fluid chemistry that are related to the environments in which the deposits form. High-sulphidation deposits are derived from oxidised, acidic, sulphur-rich fluids generated in the volcanic-hydrothermal environment. In contrast, low-sulphidation deposits are produced by reduced, near neutral, sulphur-poor fluids comparable to those found in modern geothermal settings. The nature and distribution of alteration in these systems can provide important information on the parent hydrothermal system, the distribution of palaeotemperatures and the location of mineralised targets. Where low temperatures are indicated this suggests preservation of all or most of the epithermal system and hence potential exists for the discovery of underlying mineralisation. Where higher palaeotemperatures are suggested by the alteration assemblage, high-level epithermal mineralisation may have been removed by erosion. An overview of the main characteristics of epithermal gold deposits is provided by Hedenquist *et al.* (1996). Known epithermal mineralisation at Rhynie and Brora associated with the ORS in the Highlands is of the low-sulphidisation type: consequently only this type of mineralisation is discussed below.

4.1.3 Features of epithermal precious metal deposits

Epithermal deposits generally occur at convergent plate boundaries, commonly in volcano-plutonic continental margin settings. They are generally hosted by calc-alkaline sub-aerial volcanic sequences of intermediate to acid composition. In several deposits the host rocks are calc-alkaline or shoshonitic in character (i.e. high total alkalies, high K/Na and enriched in Large Ion Lithophile Elements (LILE)). Shoshonitic rocks are commonly formed during the late stages of arc evolution at sites distant from the trench (Müller and Groves, 1993).

In northern Britain, Devonian volcanic rocks were deposited in a continental-margin setting related to the closure of the Iapetus Ocean at about 425 Ma. They are mainly calc-alkaline but become generally increasingly alkaline towards the north-west, such that the lavas of the Lorn Plateau are shoshonitic in character. Given an appropriate tectonic setting, a critical aspect in the assessment of regional favourability is the presence of underlying igneous intrusions that provided heat for the circulation of fluids and also may have acted as a source of various components of the hydrothermal system. Sub-volcanic intrusions emplaced at a high level in the crust above large deep magma chambers provide an appropriate mechanism for the transfer of heat and for the generation of fluid circulation. The locations of these intrusions on a regional scale are controlled by major faults, both normal and strike-slip, that extend into basement. The mineralisation is localised by secondary structures subsidiary to these structural zones.

Within favourable districts, epithermal mineralisation is localised by high-level intrusions and secondary structures and is preferentially developed within appropriate fluid conduits. The geometrical configuration of epithermal deposits is determined principally by the permeability of the host rocks that controls the plumbing of the hydrothermal system that brought fluids from deep sources into the shallow epithermal environment. Enhanced permeability may be related to geological structures, to lithological variations or brecciation by hydrothermal fluids and also open framework, poorly sorted volcaniclastic sandstones and breccias. Particularly favoured structures are second-order faults, fault intersections and fault bends and zones of rapid change of local strike, which are particularly common in the transpressional and caldera environment. The fluid flow is focused along structures, and ore deposition occurs in zones of dilation and extension where physical and chemical conditions are appropriate. Disseminated mineralisation is produced where pervasive flow is permitted by relatively permeable lithologies such as poorly consolidated pyroclastic or volcaniclastic rocks.

Lithological contacts and regional unconformities may also be favoured sites for the development of epithermal mineralisation, especially if the contact juxtaposes rocks of significantly different physical or chemical properties. Various types of breccias, especially of hydrothermal origin, also provide effective fluid conduits that may host mineralisation. Given the shallow depths of their emplacement, typically in the upper 1 km of the crust, preservation from erosion is an important factor in their exploration and discovery. This explains why epithermal deposits are most common in relatively young rocks, mostly of Tertiary or Quaternary age. However the recognition of important epithermal mineralisation in Palaeozoic and older rocks testifies to the efficacy of rapid subsidence and burial as a means of preserving mineralisation of this type. Transpressional regimes result in areas which are simultaneously uplifted in some areas and downthrown in others, facilitating rapid sedimentation and resultant preservation as in Fiji (Colley and Greenbaum, 1980). Where sinters or poorly consolidated and reworked volcaniclastic rocks are preserved in a potentially favourable terrain this indicates that burial was rapid and that underlying mineralisation may have been preserved. The preservation of silica sinter and plant remains in the Lower Devonian basin at Rhynie in Aberdeenshire, north-east Scotland (Rice and Trewin, 1988), provides good evidence for the nearly complete preservation of an epithermal system capped by a hot spring and indicates potential for underlying precious-metal mineralisation. In the Brora district of east Sutherland the present erosion level is close to the Lower Devonian palaeosurface and so high-level epithermal mineralisation may be preserved (Crummy *et al.,* 1997). Silicic alteration in epithermal systems may help to preserve associated mineralisation as it is usually erosionally resistant and is therefore less likely to be removed than associated argillic alteration. This feature is most significant where vuggy silica alteration is extensive, either in stratiform or structurally controlled zones.

4.1.4 Exploration guides and methods in the Northern Highlands of Scotland

Epithermal systems are complex and highly varied in size and shape at both local and prospect scales and consequently the application of models to exploration for epithermal deposits may not be straightforward. The fundamental control on the location of mineralisation in these environments is the palaeohydrology of the parent system. This is determined by numerous factors including: multiple generations of complex structures; variations in host-rock properties such as permeability and chemical reactivity; overprinting of one event by another due to changes in water table and boiling levels; and shifts in the position of active vents. Nevertheless models remain powerful predictive tools, especially when used in conjunction with detailed mapping to determine the controls on palaeofluid flow and hence on the distribution of ores. Processes responsible for the genesis of epithermal deposits have been studied in modern volcanic environments and are relatively well understood. These deposits are the products of large-scale hydrothermal systems operating at high water/rock ratios and can form under a variety of physical and chemical conditions given a suitable heat supply and sources of metals and sulphur. Low-sulphidation systems are related to deeper magmatic bodies than high-sulphidation systems and degas into an overlying groundwater system. Exploration criteria applicable to low-sulphidation epithermal deposits are shown in Table 4.1.

Table 4.1 Exploration criteria for low-sulphidation epithermal deposits

Exploration criteria	Description	Northern Highlands
Known occurrences	Areas with known deposits prospective for new ones.	Occurrence within Devonian outliers at Brora.
Host rock textures	Diagnostic quartz-vein textures – open-space filling, banded and breccias.	Similar textures identifed by Crummy (1997) in Brora area.
Alteration minerals	Typically smectite, illite, adularia, quartz, sericite.	Not known, but identified at Rhynie.
Age of host rocks	Quaternary or Tertiary rocks most common, now recognised in older rocks.	Brora examples in Lower Devonian rocks.
Deposit form	Veins dominant, stockwork ore common, disseminated and replacement ore minor.	Quartz veining and stockwork-like structures noted at Brora.
Tectonic setting	Deposits occur in volcanic-plutonic arcs associated with subduction zones.	Brora examples possibly related to back-arc volcanism, though no volcanic rocks known.
Structural break	Faults allow focused fluid flow	Mapped shear zones in Caithness and Sutherland.
Magnetic anomalies	Aeromagnetics may locate structures and buried high level intrusions.	Regional aeromagnetics used to determine fault linears.
Resistivity anomalies	High-resisitvity silicified caps may occur over low-resistivity clay alteration, obscuring some features.	No studies undertaken in the Northern Highlands.
Radiometric anomalies	Sericite and adularia may be identified. Altered K-rich host rocks may show depletion in radioelements.	Restricted aeroradiometric coverage.
Gravity anomalies	Positive or negative anomalies (dependent on host rocks) may be produced by alteration.	Only useful over known deposits or their immediate vicinity.
Regional Geochemistry	Au, Ag, As, Sb, Tl, Hg, Bi, Te, Se and Co may be anomalous, dependent on position within the system.	G-BASE regional geochemistry shows subtle anomalies.
Lithological associations	Andesite – rhyodacite – rhyolite and associated epiclastic rocks. Some associated with alkaline or sub-alkaline (shoshonitic) volcanics.	No Devonian volcanic rocks proved in the area

The effects of supergene processes on the distribution of gold in surficial materials should be taken into account when designing any exploration programme for epithermal gold. The long-held view that gold is inert in the weathering environment and is dispersed only by mechanical processes has been challenged in recent decades and there is now good evidence from a variety of sources which supports supergene chemical mobility of gold (Nichol *et al.,* 1994). This mobility is ascribed principally to the transport and precipitation of gold in chloride, thiosulphate and organic complexes (Lawrance, 1995). In the UK, relicts of Mesozoic and younger tropical weathering have survived to the present day. The influence of these earlier periods of deep weathering on the distribution of gold in the surficial environment and consequently on the effectiveness of target recognition should not be overlooked. Glaciation has affected large parts of the northern hemisphere, including Britain, during the Pleistocene, most recently in the last 10 000 to 20 000 years. The impacts of glacial processes on the underlying land surface and hence on exploration procedures are diverse and may be highly significant. Extensive erosion, reworking and deposition remote from the original source may be involved. Subsequent glaciofluvial and alluvial processes may also lead to further disturbance of element distribution patterns and hence hinder identification of a mineralised source in bedrock. Elsewhere depositional processes may lead to masking of bedrock mineralisation by exotic deposits. In the UK integrated geochemical and geophysical methods have been developed for precious metal exploration in prospective terrains characterised by thinner overburden cover, including glacial deposits. Panning and geochemical analysis of basal overburden samples have been successfully used to identify drilling targets (e.g. Coats *et al.,* 1991; Gunn *et al.,* 1991; Shaw *et al.,* 1995).

The Brora area shows some similarities with the Ochil Hills in central Scotland which were investigated by a previous study (Gunn and Rollin, 2000). There, alluvial gold had been found over a wide area, and was especially abundant in the western part of the central Ochils, but no discrete bedrock source of ore-grade material had been identified. Crummy (1993) suggested that this may be explained by gold remobilisation under tropical weathering conditions of an extensive area without discrete gold concentrations, followed by glacial, fluvioglacial and fluvial reworking. However, the existence of economic epithermal mineralisation in bedrock in the Ochil Hills and the Brora area of Sutherland cannot be ruled out.

4.2 VOLCANOGENIC MASSIVE SULPHIDE (VMS) DEPOSITS

4.2.1 Introduction

VMS deposits are synvolcanic accumulations of base-metal sulphide minerals that are formed by the discharge of hydrothermal solutions into the sea floor. They occur in rocks of many ages and processes similar to those that led to their formation can be observed today. VMS deposits form part of a larger grouping of concordant hydrothermal submarine ore deposits with the other major grouping normally termed sedimentary-exhalative (SEDEX), sediment-hosted or shale-hosted massive sulphides. SEDEX deposits include the world-class deposits at Sullivan, Mt Isa, Rammelsberg and are represented in Britain by the Foss-Duntanlich baryte deposits in Perthshire.

A typical economic VMS deposit contains 1 to 10 Mt of ore with an average grade of 2–10% combined Cu, Pb and Zn. Examples of such deposits include those in the classic Hokuroko district of Japan, the Abitibi Greenstone Belt of Canada, and the Tasman Geosyncline of Australia. The world's largest VMS deposits contain in excess of 100 Mt of ore (e.g. Kidd Creek, Ontario), whilst a few are termed as supergiant deposits such as Rio Tinto in Spain that was originally over 500 Mt. British examples include Parys Mountain in North Wales, Vidlin in the Shetland Isles, and Gairloch in north-west Scotland.

Many extensive reviews of VMS deposits are available, including Sangster, (1972), Klau and Large (1980), Franklin (1993), Lydon (1984, 1988) and Swinden *et al.* (1988). Some geologists prefer the term "volcanic-hosted deposit" as this does not imply that the deposits themselves are an integral part of the volcanic process. Because of the large number and range of VMS deposits, several classification systems defining sub-groups have been proposed based on tectonic setting, host rock or ore composition. A summary is given in Table 4.2. In Britain two styles are represented: the Besshi-style Cu-Zn type occurs at Gairloch and Vidlin while the Kuroko-style of polymetallic Zn-Pb-Cu-Ag-Au deposit occurs at Parys Mountain in Anglesey.

Table 4.2 Characteristic features of volcanic-associated massive sulphide deposit types. (Modified from Evans, 1993)

Type	Mineralisation	Volcanic Rocks	Clastic Sedimentary Rocks	Depositional Environment	Tectonic setting	Known age range	Examples
Besshi (Kieslager)	Cu-Zn +/- Au +/- Ag	Intraplate basalts	Continental-derived greywackes and other turbidites	Deep marine sedimentation with basaltic volcanism	Rifting in epicontinental or back-arc	Early Proterozoic - Palaeozoic	Besshi, (Japan), Windy Craggy, (Canada), Gairloch (NW Scotland), Vidlin (?), (Shetland Islands)
Cyprus	Cu (+/- Zn) +/- Au	Ophiolitic suites, tholeiitic basalts	Minor or absent	Deep marine with tholeiitic volcanism	Tensional, minor subsidence associated with oceanic rifting at accreting margin	Phanerozoic	Troodos Massif, (Cyprus), Bay of Islands, (New Zealand)
Kuroko	Cu-Zn-Pb +/- Au +/- Ag	Bimodal suites, tholeiitic basalts, calc-alkaline lavas and pyroclastics	Shallow to medium depth clastics, few carbonates	Explosive volcanism, shallow marine to continental sedimentation	Rifting and regional subsidence, caldera formation associated with back-arc rifting	Early Proterozoic - Phanerozoic	Kuroko deposits, (Japan), Ambler District, (North Alaska), Iberian Pyrite Belt, (Spain), Parys Mountain, (Wales)
Primitive	Cu-Zn +/- Au +/- Ag	Fully differentiated suites, basaltic to rhyolitic lavas and pyroclastics	Immature greywackes, shales, mudstones	Marine, <1km depth. Mainly developed in greenstone belts	Major subsidence associated with: fault-bounded troughs or back-arc basins?	Archean - early Proterozoic	Noranda, (Canada), Yilgarn block deposits, (Australia)

4.2.2 Geological Setting

Although the basic model for VMS mineralisation was established more than 30 years ago (Sangster, 1972), the understanding of how these deposits form has been greatly aided by the discovery and study of sea-floor hydrothermal vent systems from which massive sulphide deposits are currently forming. Many of the basic principles are now well established although some problems remain. For example the size and nature of associated geochemical haloes, as well as precisely which hydrothermal systems form the large ore deposits. Table 4.3 lists the main characteristics for the four major types of deposit.

The fluids that vent from the hydrothermal system are derived from cold, dense, descending seawater reacting with the heated crust as it passes through. Some contribution from magmatic waters may also be involved in at least some systems, and it is possible that modified seawater may enter high-level magma chambers. The fluids begin to circulate within the crust as they are heated by a thermal anomaly (an intrusion) that provides the energy for the fluids to be drawn into the crust, circulate and then migrate back to the sea floor in a convective cell. These fluids leach metals from the surrounding rock as higher temperatures (c. 350°C) are reached and the buoyant, superheated metal- and silica-rich fluids then rise to the surface through fracture zones produced by tectonic activity and vent onto the seafloor (Figure 4.1). As the fluids rise they cool and react with the surrounding wall rocks causing silicification and copper is also preferentially precipitated with respect to Pb, Zn and Ba prior to venting, forming stringer zones within the surrounding host rocks. When the fluids vent into the cold seawater, many different minerals rapidly precipitate due to the temperature contrast. Anhydrite, derived entirely from ambient seawater is the first mineral to precipitate and forms structures such as chimneys that are infilled and replaced by precipitating metal sulphides. Individual vents and chimneys have short lives and the sulphide-rich mound builds as they collapse and/or are overgrown. Zonation develops continually by overgrowth and replacement at the surface and within the mound, while tectonic activity will trigger slump deposits. Baryte forms regardless of source rock, but its presence appears to be dependent on the discharge temperature, with low temperature discharges being rich in baryte and low in metals. Therefore systems that were abruptly terminated while venting high-temperature fluids would not have formed significant baryte accumulations. At relatively shallow seawater depths boiling may occur which is likely to enhance precipitation at or near the surface in the vent zone, and there is some evidence to suggest that Au-rich deposits form in such conditions (where the water depth is <1900 m) (Kappel and Franklin, 1989).

The uppermost strata of a deposit appear to have diverse origins but they probably fulfill an important role in sealing the deposit. In modern oceans, particulate sulphides from vents are commonly rapidly dispersed and oxidised unless protected by sedimentation or volcanic strata. Some ferruginous caps are probably the result of syn-depositional oxidation, while a ferruginous-siliceous zone may arise from low-temperature discharges. Baryte and Mn-oxide layers could only form if the bottom waters were oxidising, while if the bottom water is reducing then sulphide precipitation could form distal concentrations that have significant implications for exploration. Ancient deposits suggest that preservation is enhanced by sheltering in sea-floor depressions or by the flanks of rhyolitic domes. Topographic features and substrate structures such as syn-volcanic faults and regional-scale fractures on the ocean floor dictate the locations of these deposits at the time of formation. Frequently deposits are spatially associated with felsic volcanic rocks, particularly rhyolite domes or fragmental deposits (breccia units), even in successions dominated by mafic volcanics.

4.2.3 Mineralisation

Mineralisation within VMS deposits tends to occur within a single stratigraphic interval, within which several individual deposits may be developed. Ore bodies are typically well zoned, massive and bulbous in form and are underlain stratigraphically by stringer ore.

A generalised and widely applicable zonation model of VMS deposits from base to top is as follows (Figure 4.1):

(i) discordant stockwork or veins of pyrite, chalcopyrite and quartz;

(ii) chalcopyrite-pyrite zone (copper-rich);

(iii) pyrite-sphalerite-galena (zinc-rich);

(iv) sphalerite-galena-pyrite baryte (lead-baryte-rich).

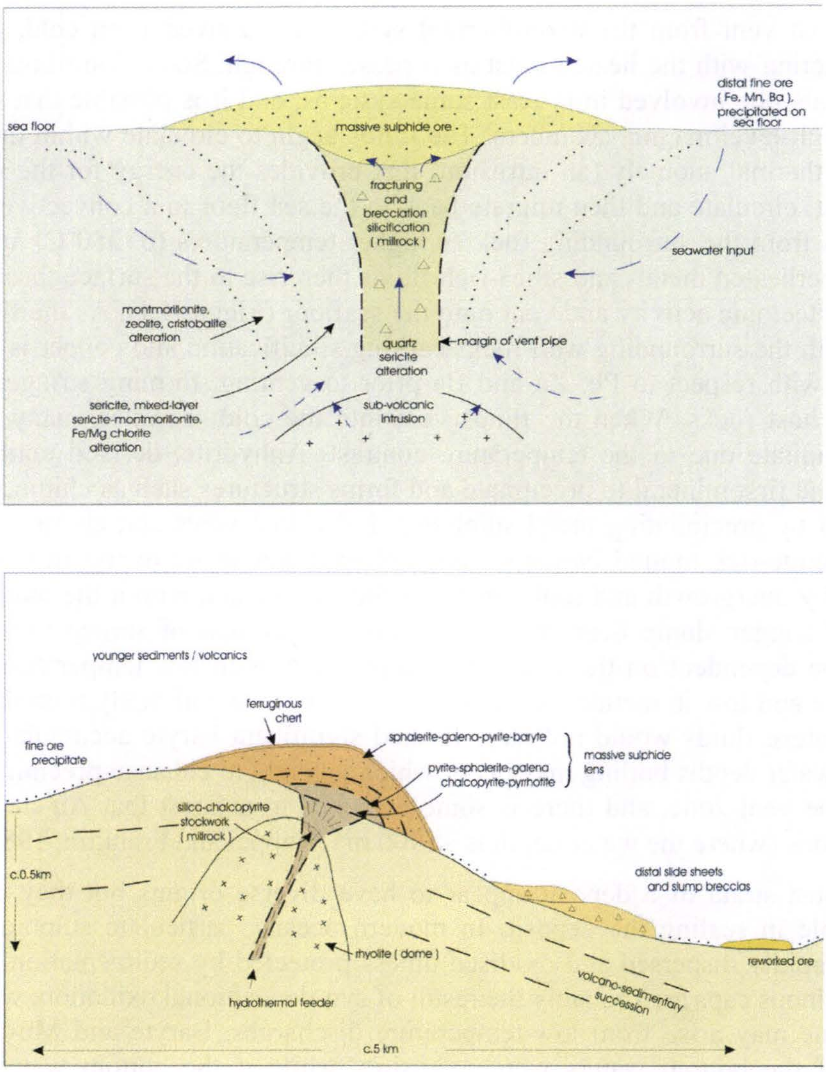

Figure 4.1 Schematic model for volcanogenic massive sulphide deposits (based on Franklin, 1993; Lydon, 1988)

In the ore zone the Cu/Zn ratio decreases upwards and outwards. Massive, rubbly and brecciated textures predominate towards the centre of the deposit and clastic sulphide rocks, often containing spectacular sedimentary structures arising from slumping, are common at the periphery. Mechanically transported breccia ore is also characteristic of some deposits (e.g. Buchans, Newfoundland). The upper contact of the orebodies is usually sharp but the lower is usually gradational into the stringer zone.

In sediment-dominated successions orebodies tend to be more tabular and laterally extensive with less-prominent zoning. The ore is typically a fine-grained and intergrown mixture of the principal sulphides (pyrite, sphalerite, galena and chalcopyrite). Baryte is common and a range of other minerals such as arsenopyrite, pyrrhotite, sulphosalts, cassiterite, stannite, hematite and magnetite may be present in individual deposits. Gangue minerals are quartz, carbonates, gypsum and chlorite.

4.2.4 Alteration

Hydrothermal alteration of the host rocks around VMS deposits is often intense, with large-scale movement of many elements into, out of, and within the hydrothermal system. It is also well zoned with a sericitic halo to a chloritic core. The chloritic zone is typically depleted in Si, Na, K and Ca, reflecting the destruction of feldspar, and enriched in Fe and Mg with the sericitic zone also being enriched in K. Strong silicification is common around the upper part of the stringer zone in the core of several deposits. The chemical signatures of some deposits related to alteration (e.g. Na depletion) may be detected more than a kilometre from the deposit, including stratigraphically below the mineralised horizon. This concept has important implications for exploration. However, some deposits do not have well-developed alteration, while other strong hydrothermal alteration zones in volcano-sedimentary successions contain little or no ore. Local variations are common within the generalised framework described above in Figure 4.1, and four zones have been defined around the classic Kuroko deposits: (i) outer montmorillonite, zeolite and cristobalite, (ii) sericite, mixed sericite-montmorillonite, Fe-Mg chlorite and minor feldspar, (iii) sericite clays, and (iv) quartz and sericite in the core.

Since zonal alteration is a common feature associated with many VMS deposits, alteration indices, such as the Ishikawa alteration index (AI) and the chlorite-carbonate-pyrite (CCPI), have been developed to measure the intensity of hydrothermal alteration in close proximity to the orebodies (Large *et al.,* 2001). These indices can be important in the exploration for VMS deposits because they prevent expenditure of exploration capital on unrelated alteration assemblages and focus attention on the areas likely to host sulphide orebodies. Both the AI and CCPI give a quantitative estimate of the intensity of alteration around the orebodies, and plotted against each other in an alteration box plot they enable the relationship between alteration mineralogy and lithogeochemistry to be explored and to place samples within the context of a hydrothermal alteration system. This provides a powerful exploration tool in assisting the exploration and understanding of VMS deposits when used in combination with petrographic and mineralogical studies.

4.2.5 VMS deposits in the Northern Highlands

In this study, attention was focused on deposits occurring within Proterozoic terranes. The sulphide mineralisation discovered near Gairloch (Section 3.2.3) is believed to represent a Besshi-style (Table 4.3) VMS deposit that is formed in volcano-sedimentary successions in an epicontinental or back-arc setting. Besshi-style deposits are generally copper dominant with some zinc, but no lead. The eponymous deposit in Japan contained about 30 Mt of ore at 2.5 % copper. Besshi-style VMS mineralisation often occurs in clusters along strike. At Gairloch the mineralisation occurs in a volcano-sedimentary succession that includes mafic lavas, sills and tuffs with varying quantities of interbedded clastic sediments, typically greywackes. Strong alteration and/or metamorphism often accompanies VMS deposits and may locally severely modify the host-rock lithologies to the extent that their original composition and textures are almost totally obscured (e.g. at Parys Mountain which has been affected by metamorphism). At Gairloch, for example, the host rocks for the mineralisation (quartz-carbonate schists), have been metamorphosed to amphibolite facies and have also undergone a complex structural history including polyphase faulting and shearing.

A VMS deposit also occurs at Vidlin in the Shetland Islands (Section 3.2.3). Outcropping mineralized samples taken from the area have recorded values of up to 12.2% Cu, as well as significant values of zinc and lead (Garson *et al.,* 1976). The orebody was shown from drilling to continue north and thicken under the sea. However a geophysical survey to the south of the outcrops has indicated the possibility of the orebody also continuing further south, though this has yet to be proven with drilling. The characteristics of the mineralisation at Vidlin are also thought to be similar to a Besshi-style VMS deposit, and therefore there is the potential for further deposits to be located in the same stratigraphic unit elsewhere in the area.

Table 4.3 Exploration guidelines for VMS deposits

Guideline parameter	Description	Northern Highlands
Known occurrences	Deposits often occur in clusters over a large strike length, e.g. Kuroko deposits - 100 known occurrences over 800 km in 8 districts.	Gairloch district - several occurrences known, Vidlin - outcrops of mineralisation recorded
Gossanous outcrops	A gossan at surface may indicate mineralisation at depth.	Gairloch discovered by an outcropping gossan.
Association with volcanic domes	Noted in Kuroko, Japan and the Noranda deposits in Canada, but not present in all areas	Not recognised
Stringer zones	Stringer zones, commonly Cu rich, may occur below massive sulphide mineralisation	Not recognised
Structural break	Fluid flow focused along faults	Many NW trending faults in Gairloch area
Magnetic anomalies	Pyrrhotite and magnetite detected using magnetic methods	High amplitude anomaly at Gairloch identified by Coats *et al.* (1997). Anomalies also recorded at Vidlin.
EM / electrical response	Sulphide lenses usually display EM or IP response depending on style of mineralisation.	Anomaly recorded at Vidlin
Stratigraphic interval	Deposits often cluster within a limited stratigraphic horizon and can be laterally extensive.	Potential along strike at Gairloch and Vidlin
Alteration	Geochemical alteration indices used. PIMA potentially useful to identify alteration minerals such as chlorite and sericite.	No data
Regional Geochemistry	Anomalies in Cu, Pb, Zn, Ag common. Mn halos sometimes present.	
Changes in lithology	Deposits often occur at a sudden change in lithology e.g. acid to basic	Gairloch and Vidlin at contact of basic volcanics and sediments
Lithological associations	Mafic volcanic rocks associated with clastic rocks. Possible association with ultramafic rocks.	Mafic volcanics, clastics and ultramafic rocks present at Gairloch and Vidlin.

4.2.6 Exploration

The discovery of VMS-hosted mineralisation at both Gairloch and Vidlin proves that mineralisation can be located within Proterozoic rocks in Scotland, and that, because Besshi-style mineralisation often occurs in clusters, there is good potential for the discovery of further, larger deposits along strike from the initial discoveries. Sangster (1980) analysed eight VMS districts of Precambrian to Miocene age and found that they average c. 30 km in diameter and contain between 4 and 20 deposits. The use of alteration indices as described above allows certain types of alteration to be examined and their position determined within hydrothermally altered VMS systems. Table 4.3 shows typical characteristics of VMS deposits and details important criteria that can be used to locate new orebodies.

4.3 PGE IN ALKALINE INTRUSIONS

4.3.1 Introduction

Precious metal enrichments associated with mafic and ultramafic rocks have been documented in many parts of the world (e.g. Mutschler *et al.,* 1985). The most important are epithermal gold-silver and porphyry copper-precious metal deposits, with the platinum-group elements (PGE) notably enriched in alkaline suite porphyry systems in the North American Cordillera e.g. in the Allard stock, Colorado (Werle *et al.,* 1984). Copper-PGE mineralization also occurs in the Coryell alkaline intrusions of southern British Columbia (Hulbert *et al.,* 1988; Shaw *et al.,* 1994), and in the Proterozoic Coldwell alkaline complex in north-western Ontario (Mulja *et al.,* 1991; Good and Crockett, 1994; Page *et al.,* 1983). By analogy with these occurrences, the BGS identified enrichments in PGE and a range of platinum-group minerals (PGM) in bedrock at Loch Borralan and Loch Ailsh in north-west Scotland in 1989-90 (Gunn and Styles, 2002).

4.3.2 PGE in the Northern Highlands of Scotland

Limited investigations into the PGE potential of the Loch Ailsh and Loch Borralan complexes were carried out by the MRP during 1989-90 (section 3.2.2). Widespread elevated Pt and Pd values were discovered over the Borralan complex, however, drilling was restricted to satellite parts of the complex and the more promising main area remains untested. Drainage and bedrock sampling in the south-east and northern parts of the Loch Ailsh Complex also indicated localised PGE enrichment in mafic and ultramafic rocks. The source of these anomalies was not discovered however, and further work could be undertaken in this area to determine the cause and location of any further enrichment.

Mineralogical and petrographic studies have been carried out to elucidate the origin of the high PGE values in the clinopyroxenites and melagabbros from Loch Borralan and Loch Ailsh (Styles *et al., in prep).* Both complexes show a long and complex history of magmatic crystallisation and post-magmatic deformation, recrystallisation, fracturing and veining. Many of these phases were accompanied by crystallisation and recrystallisation of sulphide minerals and PGE.

In both complexes an early magmatic stage formed a framework of coarse clinopyroxene crystals with interstices filled with a range of late magmatic phases including feldspar, apatite, biotite, magnetite, sphene and sulphides. In some places this was followed by a phase of high-temperature shearing and recrystallisation. At Borralan this was followed, or possibly accompanied, by a phase of ‘metasomatic’ andradite garnet formation, while at Ailsh amphibolitisation is more widespread. A later phase of low-temperature deformation and retrograde alteration is widespread in both intrusions. It is characterised by the presence of carbonate, both in discrete veins and as a more pervasive alteration of feldspar. Chlorite, sericite and minor epidote and barite often accompany the carbonate.

Studies of the ore minerals present in rocks with Pt+Pd values greater than about 50 ppb have identified sulphide minerals with two main modes of occurrence. Relatively coarse-grained sulphides, up to 0.5 mm, occur at Borralan as a late magmatic interstitial phase, with magnetite, apatite and sphene. These minerals, generally less than 2 % by volume of the rock, are mainly chalcopyrite and pyrite, with lesser pyrrhotite and pentlandite. Fine-grained sulphides, less than 0.1 mm, are common and occur as trails and clusters of grains, around the grain boundaries of the coarse early minerals, in micro-shear zones, veins and late brittle fractures. Chalcopyrite and pyrite are most abundant, with subordinate galena and sphalerite, occurring in association with calcite, chlorite and barite.

Most of the PGE located are very small, 5 µm or less, and often occur in clusters with other PGM or sulphides. The mode of occurrence of the PGM is similar to that of the sulphide minerals. In Loch Borralan samples a few grains of PtS, cooperite, and PtPbS, possibly braggite, occur as rounded crystals within early-formed silicates such as garnet and clinopyroxene. This suggests that the PGE sulphides form at the same time as the garnet and the early sulphides at a late magmatic-metasomatic stage. The majority of PGE are located in late brittle fractures and along grain boundaries, commonly associated with barite and calcite.

This evidence shows that the PGE were introduced during the late magmatic-metasomatic phase, but significant PGE remobilisation occurred during the later low-temperature deformation and hydration phase that also remobilised the sulphides. The As-, Sb- and Te-bearing PGM deposited from alteration fluids occur along brittle fractures and grain boundaries along with chalcopyrite, pyrite, galena, sphalerite, hessite, calcite and barite. This low-temperature hydrothermal origin for the majority of the PGE is comparable with hydrothermal PGE occurrences described in alkaline complexes such as the Coldwell Complex in Ontario (Watkinson and Ohnenstetter, 1992) but also from a wide range of geological settings including the New Rambler deposit, Wyoming (McCallum *et al.,* 1976), Lac des Isles, Ontario (Talkington and Watkinson, 1984), the Labrador Trough (Beaudoin *et al.,* 1990), and the Fifield complex, New South Wales (Johan *et al.,* 1989). These are summarised in Table 4.4.

The micro-scale distribution of PGE in the Borralan and Ailsh ultramafic rocks is controlled by late fractures and remobilisation. The secondary PGM assemblage is found alongside the primary assemblage that may indicate that the distance of migration is not large, possibly on a metre or centimetre scale. The fact that the richest samples are dominated by secondary PGM suggests that remobilisation plays an important role in upgrading PGE concentrations. On the basis of the limited work on PGE carried out by the MRP in the Loch Ailsh and Loch Borralan complexes, potential exists for the discovery of economic PGE mineralisation in both areas. At Loch Borralan the most promising sector of the marginal pyroxenite has not been tested, except by very shallow boreholes. It is also important to note that the high Pd and Pt values occur over a distance exceeding 2 km in both pyroxenites and melagabbros along the south-western margin of the Loch Borralan complex. At Loch Ailsh the sources of drainage and bedrock PGE anomalies have not been identified.

The PGE potential of alkaline intrusions from the Northern Highlands is restricted to the Loch Ailsh, Loch Borralan and Ben Loyal complexes. The Ben Loyal complex is of limited interest due to its lack of an ultrabasic component, and previous work has shown no enhanced PGE values (Shaw and Gunn, 1993). For this reason it is not appropriate to carry out mineral prospectivity mapping for this style of mineralisation in the Northern Highlands.

Table 4.4 A comparison of selected PGE occurrences in alkaline intrusive rocks (adapted from Mutschler and Mooney, 1993)

Deposit or camp	Metals	Grade	Mineralisation style	Age	Host rocks
Coldwell, Ontario, Canada	Cu (Ni, Co, PGE)	0.42% Cu, 1.85 ppm Pd, 0.68 ppm Pt, Au trace, Ag trace	Disseminated and massive sulphides in gabbro	Precambrian (1188 Ma)	Zoned gabbro-syenite complex
Giant Mascot, British Columbia, Canada	Ni, Cu, (Cr, Co, PGE)	1.35% Ni, 0.45% Cu, 9 ppm PGE	Magmatic-hydrothermal Ni-Cu (Au, PGE, Cr, Co)	Cretaceous (122-97 Ma)	Zoned ultramafic pluton
Nickel Mountain, British Columbia, Canada	Ni, Cu (PGE)	0.80% Ni, 0.62% Cu, 0.34 ppm Au, 6.8 ppm Ag, no PGE data	Magmatic disseminations, veins, massive sulphides	Cretaceous (<185 - >110 Ma)	Olivine gabbro stock, plugs, dyke swarm
Allard Copper, Colorado, USA	PGE	0.40% Cu, 0.07 ppm Au, 5.14 ppm Ag, no PGE data	Porphyry Cu-Ag-Au-PGE related to complex syenite pluton	Upper Cretaceous (65-70 Ma)	Alkaline syenite complex (shoshonite)
Franklin Camp, British Columbia, Canada	Cu, Pb, Zn (PGE)	3.29 ppm Au, 102.85 ppm Ag	Vein, disseminated, pegmatitic	Jurassic (150 ± 5 Ma)	Zoned pyroxenite-diorite-monzonite-syenite complex

4.4 PGE IN OPHIOLITE COMPLEXES

4.4.1 Introduction

An ophiolite is a suite of mafic and ultramafic rocks representing a segment of oceanic crust that has been obducted onto continental crust. Ophiolite complexes typically occur in areas that have undergone plate collision that has enabled oceanic crust to be emplaced onto continental crust rather than being subducted as normally occurs. They are most likely to be preserved in small marginal basin areas, rather than large ocean floor systems such as the Atlantic or Pacific. Well-known examples of ophiolite complexes include the Troodos Ophiolite Complex in Cyprus (Prichard and Lord, 1990), the Oman ophiolite (Page *et al.,* 1982), and others in Newfoundland and California, (Page and Talkington, 1984; Page *et al.,* 1986).

4.4.2 PGE in ophiolites

PGE concentrations in ophiolites are typically low (up to a few tens ppb for combined Pt and Pd) and show a general pattern of high Os, Ir, and Ru relative to concentrations of Pt and Pd. However, recent studies have revealed high concentrations of Pt and Pd relative to other PGE in some ophiolites. Examples of Pt- and Pd-enriched ophiolites include the Zambales Ophiolite Complex in the Philippines (Bacuta *et al.,* 1990), the Leka Ophiolite Complex in Central Norway, (Pedersen *et al.,* 1993), the Herbeira Massif at Cabo Ortegal, NW Spain, (Moreno *et al.,* 1999 and 2001), the Pirogues Ophiolite Complex, New Caledonia (Augé and Legendre, 1994), and the Unst Ophiolite Complex of Shetland, (Prichard *et al.,* 1981).

Drilling in olivine cumulates of the layered series of the Leka ophiolite has yielded an average of 1 ppm PGE + Au over intervals between 0.5 to 1 m thick that can be traced over distances of more than 1.5 km (Pedersen *et al.,* 1993). The Pt- and Pd-enriched horizons resemble in some respects PGE deposits such as the UG 2 and Merensky Reef of South Africa in that they occur at the base of macro-rhythmic-cyclic units. Their occurrence in the Leka Ophiolite demonstrates that orthomagmatic stratiform Pt-Pd-Au deposits may also be present within other ophiolites.

In the New Caledonian ophiolite very high concentrations of platinum (up to 25 ppm) have been reported in massive chromitite bodies as well as in laterite and sediment derived from the complex (Augé and Legendre, 1994). The high values appear to be related to intense lateritisation affecting magmatic mineralisation associated with chromite seams.

In the ultramafic Herbeira Massif at Cabo Ortegal in Spain, high concentrations of PGE (>13 ppm) have been recorded in chromitites (Moreno *et al.,* 1999). The PGE have been strongly fractionated and occur in chromitites within the upper dunite unit of the ophiolite above a strongly PGE-depleted harzburgite unit with associated dunite lenses. The chromitites are interpreted as having crystallised from a sulphide-poor, mantle derived suprasubduction melt deep within an arc massif subsequently thrust over the Gondwanan continent during Variscan collision (Moreno *et al.,* 2001).

High PGE values have also been reported from podiform chromitites within ophiolite sequences from the Sierra Nevada range in the USA (Page *et al.,* 1986). Maximum values of 2.53 ppm Pt have been recorded from the Rattlesnake Creek terrane. Table 4.5 compares features of ophiolite complexes enriched with PGE with more typical PGE-poor ophiolites.

Table 4.5 Comparison of selected PGE-rich ophiolite complexes

Ophiolite	Setting/Age	Concentration
Zambales, Philippines	Eocene island-arc complex	Highly variable distribution of PGE up to ~6 ppm Pt and 8.3 ppm Pd in basal cumulate peridotites
Leka, Norway	Lower Ordovician Caledonian island-arc/arc-basin	up to 1 ppm total PGE + Au over 1 m.
Herbeira Massif, Spain	Emplaced during Devonian in Variscan orogeny	up to 13 ppm PGE
Voilar-Syninsky, Russia	Palaeozoic complex thrust over platform sequence	480 ppb total PGE in samples within mafic/ultramafic cumulate section
Semail, Oman	Upper Cretaceous	200 ppb total PGE in chromitite samples
Troodos, Cyprus	Upper Cretaceous	up to 100 ppb total PGE over 35 m in gabbros
Sierra Nevada, USA	Palaeozoic to Mesozoic	up to 2.53 ppm Pt
New Caledonia	Oligocene	up to 25 ppm Pt in massive chromitite, most values 2-10 ppm Pt
Bay of Islands, Newfoundland	Late Precambrian - early Palaeozoic arc-basin complex	up to 120 ppb Pt and 77 ppb Pd
Unst, Scotland	Lower Palaeozoic emplaced during Caledonian orogeny	up to 25 ppm Pt and 46 ppm Pd

4.4.3 PGE in the Unst Ophiolite

The presence of platinum and associated elements in Unst was first established by Phillips (1927). Discrete PGM were first identified by Prichard *et al.* (1981) who found grains of laurite and Os-Ir alloy in chromite from two localities. Since then Prichard and various co-workers have carried out extensive mineralogical and geochemical studies to examine the distribution and abundance patterns of PGE throughout the Unst ophiolite (Prichard *et al.,* 1986; Prichard and Lord, 1993; Prichard *et al.,* 1994). Gunn *et al.*(1985) and Gunn (1989) reported the results of exploration carried out by BGS for PGE in the complex, including rock, overburden and drainage geochemical surveys and limited mineralogical investigations.

The chromite mineralization on Unst occurs in thin layers and bands, massive schlieren and locally as larger pods in the dunite cumulates and in dunite lenses in the harzburgite unit. The form and chemistry of the chromite is typical of the podiform type developed in alpine or ophiolite complexes (Prichard *et al.,* 1982). The largest chromite deposits occur as series of near-vertical lenses concentrated near the harzburgite-dunite transitional boundary.

High PGE concentrations have been identified in several different stratigraphical settings summarised by Prichard and Lord, (1993).

1. chromite-rich dunites and associated chromite-poor sulphide-bearing dunites in dunite lenses in harzburgite
2. sulphide-bearing dunites associated with chromitite layers in the cumulate dunite
3. sulphide-bearing pyroxenites and wehrlites
4. high-level ultramafic lenses in the gabbro

Os-, Ir- and Ru-bearing PGM occur in samples from several chromite workings to the north of Balta Sound, while PGM of all six PGE have been documented at two localities in chromitites and chromite-rich dunites (Prichard and Tarkian, 1988). At these two sites, Cliff and Harold's Grave, the Os-, Ir- and Ru-bearing PGM are found within chromite grains, while the Pt-, Pd- and Rh-bearing PGM occur as apparently later phases within the altered serpentinised silicate matrix interstitial to the chromite. Pt- and Pd-bearing PGM were also reported in sulphide-bearing dunite from Cliff. In most cases, where the PGM are not enclosed in chromite grains, they occur in close association with a range of base-metal sulphides, arsenides and antimonides. The PGM are dominated by sperrylite and stibiopalladinite, although a wide range of other species has been reported (Prichard *et al.,* 1994). The stratigraphic settings of the high PGE values within the ophiolite are illustrated schematically in Fig. 4.2.

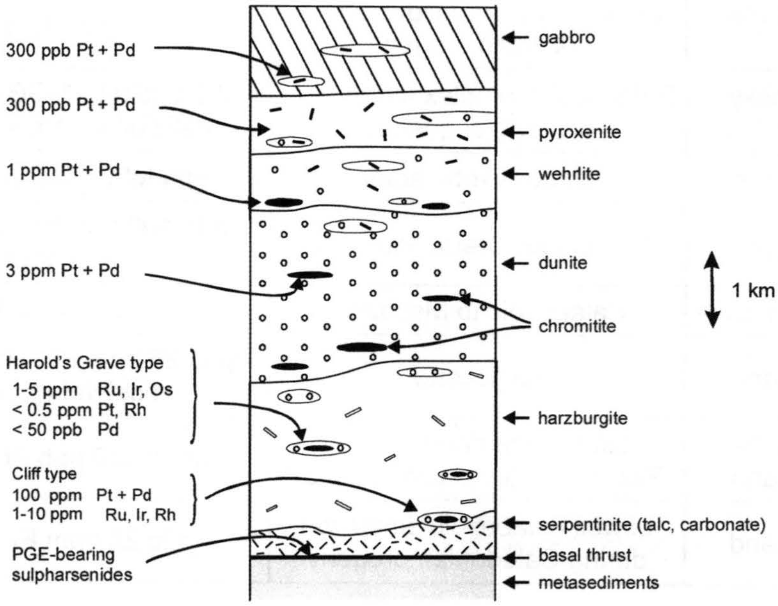

Figure 4.2 Stratigraphic settings of PGE in the Unst ophiolite (modified from Prichard *et al.,* 1994)

The Cliff occurrence has several distinctive features:

1. Very high contents of all six PGE, dominated by Pd and Pt. Gunn *et al.*(1985) report average values of 46 ppm Pd and 25.6 ppm Pt in three samples of chromite-rich dunite, while Leicester Diamond Mines Ltd reported values in a single sample of 273 ppm Pd and 138 ppm Pt.

2. PGE are restricted to the dunite pod, either in close association with disseminated chromite or in sulphide-bearing dunite. The presence of ppm levels of Pd and Pt in dunite with 'background' Cr values suggests that the association of PGE with chromite ores is not necessarily of primary magmatic origin.

3. Anomalous values, significantly greater than normally found in ultramafic rocks, of Cu, Ni, As, Sb and Te occur in the PGE-mineralised chromitites and dunites.

4. The Cliff occurrence is located close to the basal emplacement thrust, approximately 300 m from the exposed thrust plane.

Elevated PGE values reported higher in the succession are also dominated by Pd and Pt (Prichard and Lord, 1993; Gunn *et al.,* 1985). Pt+Pd values up to 4 ppm occur in chromite-rich sulphide-bearing dunite from the dunite unit, while Pt+Pd values up to 1 ppm occur in pyroxenites and wehrlites in the upper part of the ultramafic sequence. The maximum value of Pt+Pd in pyroxenites and wehrlites within the gabbro is 310 ppb.

In summary Pt-Pd dominated enrichment in the PGE has been documented at various localities at several stratigraphical levels in the complex, including dunite pods within the harzburgite, chromite in the dunite unit, in the pyroxenite and wehrlite cumulates. In all cases the PGE are associated with small volumes of sulphide, arsenide and antimonide mineralization.

4.4.4 Genesis

Lord *et al.* (1994) and Prichard *et al.* (1996) proposed a genetic model for the PGE mineralization in the Unst ophiolite involving predominantly magmatic processes. In this model the PGE-enriched magmas are formed by a high degree of partial melting occurring in the early stages of subduction where the water-rich descending slab of oceanic crust facilitates the removal of very refractory PGE from the mantle into a boninitic magma. However, primary magmatic Pt- and Pd-bearing PGMs on Unst are rare and have been observed only in a single unaltered clinopyroxene crystal (Prichard *et al.,* 1994). The vast majority of PGMs occur in altered silicates in close association with a range of nickel, iron and cobalt sulphides, arsenides and antimonides. These minerals are interpreted as products of low-temperature hydrothermal alteration involving the introduction of fluids carrying large amounts of As, Sb and Te. The Pt and Pd are considered to have been released from magmatic sulphides during alteration and redeposited very close (10–100 µm) to their primary PGE source. Later modification by low-temperature processes including weathering result in the loss of As, Sb and Te, leading to the development of Pt and Pd alloys and oxides and ochres.

Gunn *et al.* (1985) proposed a model that stressed the importance of late hydrothermal processes in effecting large-scale upgrading of Pd and Pt concentrations. The role of structures in focusing flow of fluid containing PGE liberated from a large volume of rock is important in the production of the widely observed high concentrations of Pd and Pt. The observation by Prichard *et al.* (1994) of minor enrichment of Pt and Rh along the basal thrust provides evidence of large-scale movement of PGE from the inferred primary source at Cliff about 300 m away. Whether Cliff is in fact the primary source of PGE at this site and also the identity of the primary source of PGE at Cliff itself remain unclear. However the widespread occurrence of Pd-Pt-dominant PGE assemblages associated with hydrothermal base metal sulphides, arsenides and antimonides demonstrates the efficacy of this process and the scale of its operation. Further support for this model is presented by Gunn *et al.*(1985) who documented the variation in geochemistry with alteration in samples of dunite from the Cliff area. 'Fresh' dunite contains <10 ppb Pt, Pd, Ru, Ir and Rh, accompanied by Cr, Ni, Cu and As values typical of ultramafic rocks. Dunites with minor relic olivine and those that have undergone one or two phases of serpentinisation contain elevated values of PGE, especially Pd and Pt (average contents of 200–250 ppb Pd and 100–150 ppb Pt), accompanied by significant enrichments in Cu, As and, to a lesser extent, Ni. In carbonate and talc-carbonate altered dunites the concentrations of these elements are much lower, with about 15–30 ppb each of Pd and Pt. These patterns suggest that the PGE, Cu, As and Ni are introduced into the dunites by fluids associated with serpentinisation and are flushed out as alteration proceeds with the passage of fluids of differing chemistry.

Prichard and Lord, (1990) and Gunn *et al.* (1985) have shown that high levels of Pt and Pd can occur in ophiolites. However, there are many ophiolites that do not exhibit enriched PGE values and display a negative chondrite normalised slope for PGE. It is therefore important to understand the circumstances that may cause this enrichment and to separate the barren complexes from those with economic potential.

4.4.5 Exploration guidelines and methods

The PGE enrichment in the Unst ophiolite demonstrates that PGE occur in association with podiform chromite mineralisation in ultramafic rocks as well as in cumulate lithologies without discrete chromite mineralisation. Gunn *et al.* (1985) have shown that potentially economic concentrations of PGE mineralisation may be produced by alteration and remobilisation of these elements in certain structurally-controlled zones. This has obvious implications for PGE exploration in ophiolite complexes worldwide, and more specifically in the Unst Ophiolite.

Gunn (1989) noted a good correlation between Ni/MgO and the PGE in chromitite samples at Unst, confirming the PGM association with Ni sulphides and arsenides. This suggests that this ratio could potentially be used as a pathfinder for PGE-bearing mineralisation. Additionally, weaker correlations were also noted between the PGE and Cu, As, Sb and Te.

Individual geological units were found to be well characterised by using partially-panned concentrate sampling of streams. This technique was used in a drainage survey over the complex that revealed a major discordant north-trending structure enriched in Fe, Cu, Ni, As, Pt and Pd which indicates its potential for locating hyrdrothermal PGE-bearing mineralisation (Gunn, 1989).

Further exploration for PGE in the Unst ophiolite is justified by the highly anomalous PGE values reported to date, and the possibility of more extensive mineralisation in the complex. Specific localities that could be looked at in more detail include the Cliff area, the basal thrust and structural discontinuities along the western edge of the ophiolite complex. This zone would require drilling due to the scarcity of outcrop in the area.

As the Unst body is the only ophiolite in the study area, mineral prospectivity analysis it was not appropriate to carry out for this type of target.

5 Field Surveys

Geochemical field surveys were carried out during two weeks in April and May 2002. This was intended to check the extent of the area of possible epithermal gold in the Upper Strath Brora, previously identified by Crummy *et al.* (1997), and to provide additional data for the prospectivity analysis of the Lower Devonian outcrop. The areas and location of samples are shown in Figure 5.1 as well as the locations of previous MRP and MEIGA exploration areas.

Sampling was undertaken in the following areas: Strath Brora, to the north of Lairg; near Ben Griam [280 930]; and around Strathy and Reay on the north Caithness coast. The four areas were investigated using stream-sediment and panned-concentrate sampling, together with a small amount of rock sampling. A total of 49 stream samples and 40 rock samples were analysed using ICP-ES for 35 elements by Acme Analytical of Vancouver, Canada. The elements analysed were: Ag, Al, Au, B, Ba, Bi, Ca, Ce, Co, Cr, Cu, Fe, Ga, Hg, K, La, Mg, Mn, Mo, Na, Nb, Ni, P, Pb, S, Sb, Sc, Sr, Tl, Ti, U, V, W, Zn, Zr. Au, Pt and Pd analysis was conducted on the same samples by lead fire assay. The samples were collected using the techniques described by Gunn (1989). Panned-concentrate samples were collected by wet screening through a 2 mm nylon mesh sieve in the field, followed by washing to remove clays and a final reduction by panning to a standard final volume. The standard reduction was from 4 litres of wet-sieved material down to 150 ml panned concentrate. Stream-sediment samples were obtained by wet screening to -100 mesh (150 microns). The sediment was allowed to settle in the pan prior to decanting into a Kraft bag.

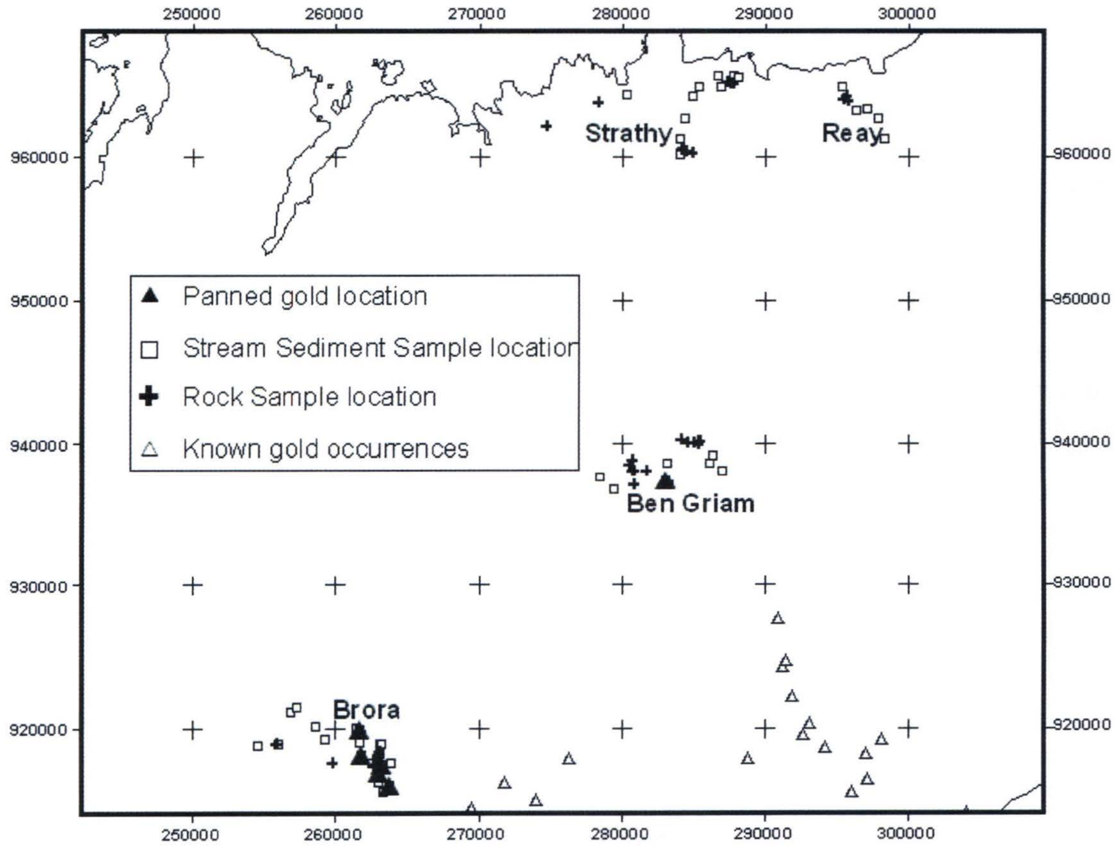

Figure 5.1 Fieldwork areas

5.1 STRATH BRORA

In this area Crummy *et al.* (1997) reported visible gold and localised hydrothermal alteration in bedrock. It is underlain by Lower Devonian Langwell conglomerates to the west and by granite intrusions to the east, which were emplaced into variably metamorphosed psammites, mica schists and migmatitic country rock of the Moine Series.

Investigations were based on the resampling of localities identified by Crummy *et al.*(1997) and of adjacent catchments, with the systematic collection of samples to provide coverage of the drainage courses of the area. Bedrock samples were collected where alteration or veining was developed.

The area is remote, with most of the ground given over to sparse sheep grazing and deer stalking over upland wet heath vegetation. The vicinity of the sampling area comprises the broad, gentle-sided Brora valley, containing the Brora river and its upper tributaries. The valley is flanked by elongate, flat-topped ridges which locally exceed 400 m elevation. In the upper Brora headwater area a more extensive wet upland plateau exceeds 500 m elevation, and is extensively covered with thick raised peat which exceeds 5 m thickness over most parts. Both the hill flanks and the Brora valley tract contain patchy hummocks and swathes of glacial material. This material attains its greatest thickness, in excess of 10 m, in an excellent streamside exposure in the upper reaches of the Allt a Bhaid Leathain [263 920].

Access to the hill flanks and summits is made difficult due to the boggy terrain which precludes the use of road vehicles. Vehicle access is however provided by private track to the remote steading of Dalnessie [263 915] and from there northwards on foot along the narrow drover's track.

Visible gold was noted in the pan at six localities, with a count of one or two grains (of less than 0.5 mm diameter) at each locality; no base metal sulphides or pyrite were seen. The presence of Moine migmatites or Caledonian granites could be inferred by the presence or absence of zircons. There are few bedrock exposures due to the extensive peat cover. Some of the streams flowed through marshy areas, reducing the sites available for sampling. Forty rock outcrop and float samples were taken. A float sample of vuggy quartz vein was collected from the banks of the Allt a Bhaid Leathain [263 920].

5.2 BEN GRIAM

Outliers of Lower Devonian Conglomerate (flysch) occur on the distinctive, isolated summits and marginal flanks of Ben Griam Mor and Ben Griam Beg. The lithologies comprise dominantly conglomerates, with lesser amounts of reddened relatively coarse arkose, which dip gently north-east. They form a stepped and sometimes massive, ramparted sequence of exposures, especially on the east-facing slopes of both hills. In broad terms, the sequence commences with coarse cobble and boulder-supported conglomerates, with clast and matrix material derived from granitic and migmatitic sources. These pass upwards into conglomerates of similar coarseness and appearance, but with a mixed clast suite of granitic and Moine-derived variants.

Access to the foot of Ben Griam Beg is via off-road vehicle along the private estate track to Greamachary [285 939]. From here a footpath runs westwards through the lower ground between Ben Griam Beg to the north and Meall a' Bhurich to the south. From this path the western side of Ben Griam Mor may also be accessed.

On Ben Griam Beg the sequence of bedrock exposures may be traced from the hill flank to the north-west of Greamachary [284374 940706], where the distinctive pink. exposures of conglomerate indicate high proportions of both granite cobbles and granite-derived matrix. The high proportion of pink feldspar forming the hard interstitial cement points not only to rapid erosion and deposition but also possibly subsequent burial. There are no indications of tectonic fabric development in any of these sediments and it is therefore inferred that they were laid down after the peak of Northern Highland orogenic compression. The extreme hardness is characteristic of the Lower Devonian throughout the Northern Highlands, and is probably the main reason for the preservation of the conglomerates as outliers on the Moine basement.

Upslope the conglomerates pass into a sequence of conglomerates and pink arkoses rich in plagioclase and K-feldspar and quartz-poor. The arkoses continue to [283596 940952], where they become more distinctly thin-bedded. From [283207 941116] the sequence comprises quartz-pebble conglomerate, interbedded with matrix-supported conglomerate. The latter is pink, friable, and contains much granite-derived detritus.

Downslope from the summit, on the western side of the hill, the exposure passes down-sequence through arkoses (flags). On this side of the hill exposure is poor, but the use of arkosic flags for construction of the fort, and its presence as float material, indicates its abundance in this area. From here there is no exposure, and little float other than the bounding enclosures to the hill fort, until [283233 940649] where the basal conglomerate recurs. There is no more exposure from here until [283584, 940195] - where a good exposure of Moine psammite/ granulite occurs.

5.3 BEN GRIAM MOR

Sampling of Ben Griam Mor was carried out using the track access south of the Garvault Hotel at [2786 9379]. The lower slopes of the hill are extensively but mainly thinly drift covered, as far as [279433 939298] and bedrock is not exposed. Only sporadic occurrences of Moine-derived float are seen at surface, and mixed Moine/ granite-derived cobbly and pebbly drift in the trackside ditch. The first confirmed exposure, which is of Lower Devonian arkose, is seen at [279610 939311] which is at the foot of the west-facing flank of a low hog's-back ridge. It is probable that the entire ridge comprises a basal part of the Lower Devonian succession as excellent exposures occur on its eastern flank around [279731, 939520].

Flaggy arkoses continue upslope to the summit on Ben Griam Mor [280654, 938917]. They vary from flaggy to massive arkose and are widely evident around the summit as sporadic exposure and widely-distributed float.

The same flags were followed downslope, on the western flank of Ben Griam Mor, to the base of the succession at 280898, 939061]. Here the base of the succession occurs as reddened medium-grained, generally well-bedded flags without pebbles. This passes downwards into a mixed sequence of quartz/ Moine pebble 'clast-supported' conglomerates [280941, 939079], with arkosic matrix, and thin arkoses - especially common near the top.

Six bedrock samples were taken in order to evaluate the possibility of palaeo-placer gold derived through the rapid exposure and weathering of the Caledonian mountains.

5.4 STRATHY

The Strathy outlier forms a 6 km long by 1 – 3 km wide north-trending elongate ridge which extends almost to the coast at Strathy Bay, on the north coast of Caithness. Along its western and south-eastern flanks the outlier rests unconformably on basic gneisses of the Kirtomy Group, which forms part of the Moine Supergroup. Along its south-west margin the outlier is fault-bounded. The Baligill Fault is the most conspicuous internal contact, dividing arkose-dominant rocks in the west from basal breccio-conglomerates in the east, although nowhere is the exposure good. The bulk of the eastern part of the outlier comprises basal breccio-conglomerate. It is intruded close to its eastern margin by a Caledonian granite. The granite is poorly exposed, particularly over its broader, southern part. Contact alteration of the host conglomerates can be seen along the southward-running track just to the east of the Baligill Burn.

The shallow contact between Moine basement and the overlying Devonian sediments is best seen in the south of the area, around [283450, 960250], where a small outlier of breccio-conglomerate forms a gently-rolling capping to the basement gneisses. Here the coarse, clast-supported cobble and boulder conglomerate comprises clasts of pink K-feldspar, quartz, altered biotite which are coarse-grained and unfoliated.

The western contact of the conglomerate is not exposed. The contact runs part-way down the north-trending flank of a shallow, hog's back ridge about 20 m high. Towards the east the ground is nearly flat, featureless wet heath moorland with old peat diggings. To the west the ground is flattish for c. 100 m, and then shelves more steeply into the valley of the Baligill Burn.

In the north-western part of the area the Devonian sediments are in contact with granite. The rocks here are generally discoloured, mainly reddened, and locally show signs of fluid movement along joint surfaces with black Mn-staining.

5.5 REAY AREA

Access to the Reay area is along the private track opposite Sandside House, to the west of the village of Reay. The track runs south through muted, hummocky terrain, to a fence point at [2947, 9636]. The landscape is one of low to medium relief, with the conspicuous ridge of Beinn Ratha (242 m) bifurcating the otherwise expansive landscape of dry and wet heath vegetation.

Access is by foot to the sporadic outliers which crop out to the west and south-east. Exposure is generally poor, although at [294304 963638] there is good exposure of the typical pebble/cobble conglomerate, in this case matrix-supported. To the west of the western outlier, in the catchment of the Allt Achadh na Gaodha, massive to flaggy arenites are exposed, which are locally worked (e.g. [293910, 963650]. Three samples were collected along roadside exposures to test a zone marked on the map as having intense veining (in Moine gneisses).

5.6 RESULTS

Gold grains were noted at six sites, all except one in the Strath Brora area, confirming the presence of gold noted by Crummy (1997). The grains were very fresh, around 0.2 mm in size and generally platy in form. The single grain from Ben Griam Mor area was cigar shaped and may have travelled a short distance. The others are likely to be near the original source. Four of the sites with recorded gold show anomalous gold values in the panned concentrate analyses, but only one has slightly elevated gold in the fine fraction stream sediment analyses. Three sites without recorded visible gold show anomalous gold values in the panned concentrate analyses and one in the fine fraction stream sediments. There is general agreement between the ICP-ES and the fire assay results for gold. The fire assay results are generally lower and the highest ICP-ES value of 3144 ppb reports as 11 ppb by fire assay. This variation is not unexpected given the 'nugget effect' which makes representative sub-samples difficult to obtain from samples containing particulate gold.

Sulphur, platinum and palladium results were all below detection levels in all sample types apart from a few low values of sulphur (max 0.17 %) in stream-sediment samples. There were no significant anomalous results in base metal values with the highest being 939 ppm Pb in a rock sample from a psammitic gneiss in a road cutting on the north Caithness coast. The stream sediments had generally much higher Fe and Mn contents than the panned concentrates reflecting the amount of organic matter in the finer fraction of the stream sediments. Arsenic, antimony and bismuth values are low with maxima of 62, 11 and 0.5 ppm respectively.

Summary statistics for geochemical data are shown in Tables 5.1 to 5.3 below. Full results are given in Appendix 2.

Table 5.1 Summary statistics for stream sediment samples

Stream sediments

Element	Mo ppm	Cu ppm	Pb ppm	Zn ppm	Ag ppm	Ni ppm	Co ppm	Mn ppm	Fe %	As ppm	U ppm
Max	4.4	56.1	291.4	182	0.1	67.7	84.4	29994	16.24	62.7	13.4
Min	0.1	3.2	9.8	28	0.1	7.3	6	229	1.26	1.5	1.2
Median	0.8	10.5	23.8	69	0.1	16.5	17.2	2542	3.96	5.6	2.8
S D	0.86	10.96	44.34	32.42	0.00	13.33	19.78	6211.11	3.43	9.07	2.71
Element	Au ppb	Th ppm	Sr ppm	Cd ppm	Sb ppm	Bi ppm	V ppm	Ca ppm	P %	La ppm	Cr ppm
Max	497.2	26	115	0.9	1.1	0.5	131	1.58	0.596	95	92.6
Min	0.5	4.5	14	0.1	0.1	0.1	22	0.22	0.055	16	13.2
Median	1.45	11.3	33	0.2	0.3	0.1	51	0.54	0.133	38	27.3
S D	74.92	4.71	21.13	0.14	0.22	0.07	26.08	0.25	0.10	14.89	20.63
Element	Mg %	Ba ppm	Ti %	B ppm	Al %	Na %	K %	W ppm	Hg ppm	Sc ppm	Tl ppm
Max	1.94	601	0.26	5	2.32	0.045	0.71	0.7	0.48	11.5	0.8
Min	0.22	34	0.037	1	0.51	0.013	0.11	0.1	0.01	1.7	0.1
Median	0.48	128	0.121	2	1.26	0.025	0.26	0.1	0.035	3.1	0.3
S D	0.31	133.33	0.05	1.05	0.39	0.01	0.12	0.13	0.08	2.07	0.18
Element	S %	Ga ppm									
Max	0.17	15									
Min	0.06	3									
Median	0.09	7									
S D	0.03	2.61									

Table 5.2 Summary statistics for panned concentrates samples

Panned concentrates

Element	Mo ppm	Cu ppm	Pb ppm	Zn ppm	Ag ppm	Ni ppm	Co ppm	Mn ppm	Fe %	As ppm	U ppm
Max	0.8	42.4	411.1	30	0.4	23.2	8.5	1216	4.67	6.1	8.5
Min	0.1	0.6	2.5	6	0.1	1	0.9	48	0.31	0.5	0.4
Median	0.1	1.7	3.3	11	0.15	3.4	2.6	287	0.74	0.8	1.3
St. Dev.	0.13	5.91	58.18	5.26	0.11	3.62	1.85	199.27	0.94	1.18	1.39
Element	Au ppb	Th ppm	Sr ppm	Cd ppm	Sb ppm	Bi ppm	V ppm	Ca ppm	P %	La ppm	Cr ppm
Max	3144.8	60.7	27	0.1	11.2	0.5	119	0.79	0.091	174	49.4
Min	0.6	2.1	6	0.1	0.1	0.1	4	0.04	0.008	8	2
Median	1.7	7.6	10	0.1	0.1	0.15	13	0.15	0.023	26	8.8
St. Dev.	632.23	10.04	3.76	0.00	3.19	0.19	24.99	0.14	0.02	28.55	9.56
Element	Mg %	Ba ppm	Ti %	B ppm	Al %	Na %	K %	W ppm	Hg ppm	Sc ppm	Tl ppm
Max	0.59	658	0.154	3	0.66	0.089	0.26	0.3	0.01	3.9	0.1
Min	0.03	14	0.009	1	0.17	0.025	0.04	0.1	0.01	0.3	0.1
Median	0.12	31	0.059	1	0.32	0.04	0.09	0.1	0.01	1.2	0.1
St. Dev.	0.10	89.91	0.03	0.47	0.12	0.01	0.04	0.08	0.00	0.85	0.00
Element	Ga ppm	Au** ppb									
Max	5	2284									
Min	1	2									
Median	2	3									
St. Dev.	0.93	372.44									

** Au by Fire Assay

Table 5.3 Summary statistics for rock samples

Rock samples

Element	Mo ppm	Cu ppm	Pb ppm	Zn ppm	Ag ppm	Ni ppm	Co ppm	Mn ppm	Fe %	As ppm	U ppm
Max	2.10	102.00	939.40	197.00	4.60	55.10	19.80	14791.00	7.58	23.40	6.20
Min	0.1	0.8	1	4	0.1	2.6	0.9	22	0.36	0.5	0.1
Median	0.1	3.8	6.8	18	0.2	8.7	3.7	148.5	1.15	1	0.8
S D	0.42	17.31	150.95	36.53	1.64	12.30	4.57	2345.89	1.29	9.18	1.12
Element	Au ppb	Th ppm	Sr ppm	Cd ppm	Sb ppm	Bi ppm	V ppm	Ca ppm	P %	La ppm	Cr ppm
Max	55.50	15.20	785.00	0.20	5.60	0.20	64.00	39.17	0.08	61.00	45.40
Min	0.6	0.8	3	0.1	0.1	0.1	3	0.01	0.004	3	3.5
Median	1.5	7.85	8	0.1	0.1	0.1	14.5	0.05	0.023	26.5	13.2
S D	8.91	3.26	122.65	0.04	1.14	0.03	15.04	6.43	0.02	12.59	10.83
Element	Mg %	Ba ppm	Ti %	B ppm	Al %	Na %	K %	W ppm	Hg ppm	Sc ppm	Tl ppm
Max	0.98	570.00	0.27	5.00	2.52	0.12	1.21	0.60	0.21	5.70	26.70
Min	0.02	15	0.002	1	0.13	0.004	0.03	0.1	0.01	0.6	0.1
Median	0.19	37.5	0.022	2	0.57	0.0305	0.2	0.2	0.01	1.6	0.1
S D	0.24	101.54	0.06	1.18	0.52	0.03	0.20	0.17	0.05	1.20	4.77
Element	S %	Ga ppm	Au** ppb								
Max	4.45	11.00	55.00								
Min	0.06	1	2								
Median	0.07	4	3								
S D	1.958834	2.51	11.16								

6 Mineral prospectivity mapping

The prospectivity of an area for specific types of mineral deposit is one of the central interests of the exploration geologist. Certain lithologies or regions have long been known to be more prospective than others: for example Archean greenstone belts are more likely to host lode gold deposits than the surrounding granites. Prospectors therefore concentrate their efforts in those areas. This knowledge was largely empirical and was not predictive. However, over the last century there has been a growth in the cumulative knowledge of all types of mineral deposit and this has been codified in mineral deposit models, such as those produced by Cox and Singer (1986). These give the specific parameters which encompass the chemical and physical characteristics of the particular deposit type. The development of remotely sensed data such as magnetics and satellite imagery, and more particularly its availability on digital form has vastly increased the amount and range of parameters which can be measured. The parallel development of sufficient computing power to combine and analyse this data has created the ability to produce mineral prospectivity maps. Mineral prospectivity or potential maps are classes of map objects that share similar general properties. Any map is a response theme which represents the combination of spatial information with generic or empirical concept or inference model used to interpret the data (Figure 6.1). The suitability of the model used to create the map product and the availability and utilisation of the spatial data are the main causes of uncertainty in the map product. The map product is generally subjective because of the extent and content of data selected for inclusion and in the type of model used. Objective data is often used to present a subjective map.

Although Figure 6.1 relates to production of a geological map or geological theme, these have traditionally been generated by direct interaction of the field geologist with observed data to generate the geological linework (model). Consequently the digitisation of geological map linework has captured the interpretation of the field data acquired over a long period of time, using a variety of observational schemas and convolved with numerous models which were used to produce the geological map. It is important to recognise therefore that the linework is an interpretation.

Uncertainty in the geological map linework is inevitable since we have incomplete data (extent and content) and incomplete records of the inference model used to generate each map.

6.1 METHODS

Knowledge-based or data-driven prospectivity is based on a series of procedures:

1. Selection of target mineralisation and area for prospectivity analysis
2. Review deposit model(s) to determine key exploration indicators
3. Assessment of capability of available data to provide the key indicators
4. Data processing, interpretation and analysis to extract key indicators
5. Assignment of weightings, zones and styles of influence to key indicators (expert parameterisation)
6. Calculation of prospectivity using Binary Weights of Evidence, Fuzzy logic model

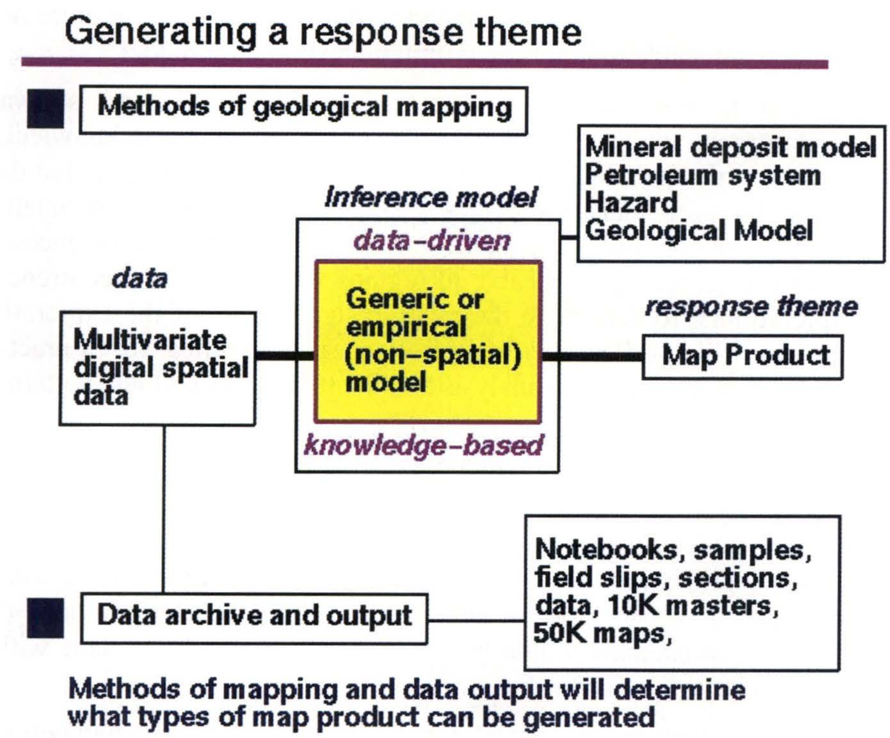

Figure 6.1 Map products as a response theme from data and inference model

Generic or empirical mineral deposit models (MDM) can be used to identify the exploration criteria for a particular type or model of occurrence. These criteria form the basis of a prospectivity analysis of a region for exploration potential. In its simplest form prospectivity analysis would involve appraisal of the region for the presence or absence of the identified criteria. Often this analysis would be subjective, depending on the preferences given to particular criteria and on the availability of data to assess the criteria. In some cases crucial geological, geophysical or geochemical data might be absent or incomplete. In other cases, there may be several phases of data collection, possibly collected for other deposit types, and the explorationist has to decide which of the data are suitable to include in the prospectivity appraisal. In some cases a plethora of data will mean that the traditional exploration methods of visual inspection and transparent overlays are impractical.

Table 6.1 Examples of various spatial data used to map favourability

Classes and layers of multivariate data		
Geological data	**Geochemical data**	**Geophysical data**
Digital 1:250000 chronostratigraphy	G-BASE regional stream sediments	Gravity data/residuals
Digital 1:250000 contacts	detailed stream sediments	Magnetic data/residuals
Digital fault vectors	detailed panned concentrates	Susceptibility data
Dip/strike observations	Recorded gold occurrences	IP/SP/Resistivity/EM data
Photo interpretation	Rock geochemistry	Lineament analysis
Mineral occurrences	Pathfinder composites	Lineament intersections
Source rock subcrops	Fluid chemistry	Seismic structures
Reservoir rocks	Reservoir cements	Seismic velocity
Trap structures	Seal properties	WELLOG properties
Maturity maps	HC phases	Geothermal

Elements of the MDM may be directly or indirectly mapped to existing data, may require new data to be acquired or may not be amenable to inclusion within the exploration model

Modern prospectivity appraisal is generally carried out using digital data and software applications devised for a data-driven analysis of the occurrence relationships or a knowledge-based analysis using exploration expertise. Data-driven analysis aims to relate all specified data layers to known occurrences of the particular deposit type within the region and by association highlight those data relationships which closely mimic the patterns at the known occurrences. A knowledge-based system, which is generally applicable to regions with no known occurrences, uses expertise from the explorationist to determine the relative significance of the exploration data and then search for patterns which reflect the total effect of such significance. In practice this means selecting what data layers to use in the analysis and the relative weight and pattern of influence for each data layer.

Various *classes* of multivariate geoscience data are frequently available in digital form: geological maps, geochemical analyses and geophysical data. Within each class there are often numerous *layers (themes)* of data which might be used for analysis. These various layers consist of several *types* of data: points, grids, vectors, and sets. In addition particular *relationships* between data *layers (themes)* can give rise to *event* occurrences which the explorationist can include in a prospectivity model. An example would be the intersection of a fault plane with a particular geological unit or boundary.

Data themes can be of several types. Primary geological data might be used as attributed polygon vectors where the attributes include selectable parameters such as chronostratigraphy, lithology, and reservoir properties. In other cases, geological data in a topological form (if available) might be more appropriate for identification of contacts between a particular lithologies and formations. Many of the data layers will be point data with [x,y,(z)] attributes. Other data layers are vectors or grids derived from random point data. Several layers of point data might be combined into sets which represent a group of points with a common composite attribute. Event data can be considered as an [x,y] occurrence defined by the interaction of other data layers typically the intersection of faults/lineaments/geological contacts.

In past projects involving mineral potential mapping (Cooper *et al.,* 2000, Gunn and Rollin 2000, Rollin *et al.,* 2001) BGS have used a knowledge-based prospectivity system to integrate multivariate data. The system used simple Fuzzy Logic (FL) models to assess prospectivity scores across a region. Fuzzy Logic analysis allows data layers to have a 'range of uncertainty' within which the significance of the data will range from [0.0-1.0]. Each individual data parameter is treated as a layer of evidence in the subsequent analysis. Each data layer has associated parameters which determine the significance of the data elements and the style of influence they exert.

This system is knowledge-based in that the user provides the parameters for the relative weight of influence, zone of influence and style of influence for a particular input data layer and the system responds with expertise in the form of a pixel based prospectivity grid. Exploration criteria (logic model, data parameters) are defined on the basis of generic and empirical mineral deposit models modified by specific features of known local mineralisation. Multivariate data are analysed using these criteria to define the relative weight for occurrence events of any particular data layer. Combination of the data layer weight arrays provides a prospectivity map to assist decision-making in mineral exploration. Buffering is used to decrease the influence of particular data layers away from its acyual occurrence. Thus faults may have buffers at 500 m and 1000 m distance on either side from the mapped trace of the fault. The fault trace may have a significance of 1 while within the 500 to 1000 m buffer it will have a lower influence of say 0.4.

The degree of confidence and value attached to all prospectivity maps depends on the availability, quality and relevance of data together with the reliability of the exploration model. Many analyses will use only a few data layers and might only represent 20-50% of the exploration criteria of the deposit model.

This report uses Arc-SDM (Spatial Data Modeller) to calculate prospectivity themes. Arc-SDM is an extension to ArcView developed by the Geological Survey of Canada in association with the United States Geological Survey and provides tools for performing quantitative favourability mapping, especially in relation to mineral potential. The Arc-SDM extension runs on ArcView 3+ and requires the Spatial Analyst extension.

The main steps in any prospectivity or potential study are:

1. Build and populate a spatial digital database.
2. Identify and extract predictive evidence for the occurrence.
3. Generalise or classify the selected evidential themes.
4. Combine the evidential themes to produce a potential map.

Arc-SDM is essentially a tool to allow steps 3 and 4 to be realised. Step 1 is taken to be part of the strategic core of BGS work and expertise. Step 2 is the conversion of the target deposit model/petroleum system/hazard to characteristics which can be identified in the strategic database.

Arc-SDM provides 6 methods of prospectivity analysis:

- Weights of evidence Normal #
- Weights of evidence Expert
- Logistic regression #
- Neural Network Supervised # $
- Neural Network unsupervised
- Fuzzy Logic

needs a deposit training point theme

$ needs a non-deposit training point theme

Deposit training themes are occurrences of the target proposition, such as a base-metal mine. For propositions where no target has yet been identified then alternative data might be used as a proxy target or a method not requiring target occurrences such as Fuzzy logic (FL) should be used. For example, occurrences of gold in rock might be used as a proxy for economic gold mineral deposits. All methods require a missing data definition and a cell size for analysis. All methods except FL require a unit area to be specified and use a unique conditions table. Neural Network (NN) analysis uses a separate module called DataXplore which can run independently from ArcView using other data sources. It provides two NN algorithms: radial based functional link (RBFLN) and fuzzy clustering (FC).

1. Exploration datasets are required to be digital, they might be derived or primary and may be interpreted in relation to an exploration model.
2. Exploration model refers to those aspects of the mineral deposit model (MDM) which can be identified within the data available. It is important to realise that many characteristics of the MDM are not visible in exploration data and conversely negative aspects of exploration data are often not part of the MDM.

6.2 FUZZY LOGIC

Classic set theory defines membership as true (T) or false (F). Membership of a fuzzy set is defined on a continuous scale from 0.0 (non-membership) to 1.0 (full membership). An example would be the definition of an amplitude population by means of percentile analysis (Figure 6.2). Values above the 75% level in the cumulative population might be considered anomalous (Fuzzy set membership = 1.0), while values below the 25% level might be considered not anomalous (Fuzzy set membership = 0.) Many evidential themes can have fuzzy membership values for the same or a different proposition and can be combined using various Fuzzy Logic (FL) operations to provide a response theme for a particular proposition e.g. the favourability for a gold deposit.

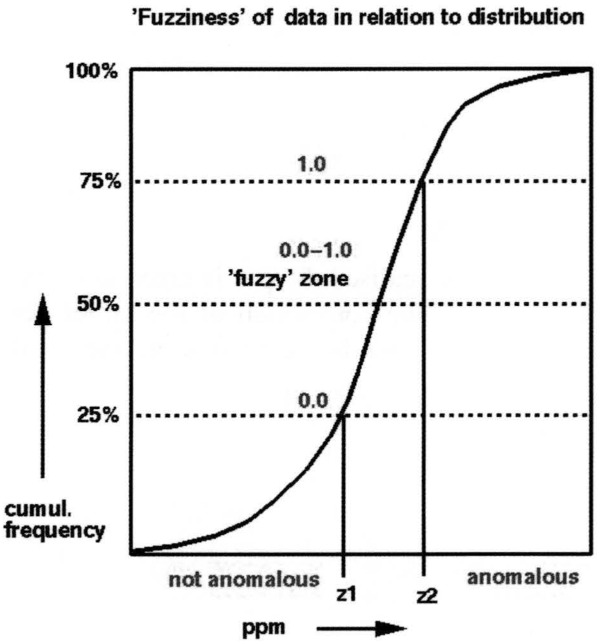

Figure 6.2 The idea of fuzzy class membership

Fuzzy class or sets can be combined using several operators.

Fuzzy AND of a group of fuzzy memberships (μ) is:

$f_{AND} = \text{MIN } \{\mu_i\}$ i =1, n eg [0.4,0.7] > 0.4

Fuzzy OR of a group of fuzzy memberships is:

$f_{OR} = \text{MAX } \{\mu_i\}$ i =1, n eg [0.4,0.7] > 0.7

The Fuzzy Algebraic Product is the product of all fuzzy membership functions:

$F_{PROD} = \prod \mu_i$ for i =1, n eg [0.4,0.7] > 0.28

The Fuzzy Algebraic Sum is one minus the product of the complement of fuzzy membership functions:

$F_{SUM} = 1 - \prod (1 - \mu_i)$ for i =1, n eg [0.4,0.7] > 0.82

F_{PROD} is decreasive and always less than or equal to the smallest of the fuzzy memberships while F_{SUM} is increasive and always greater or equal to the maximum.

The Fuzzy Gamma ($0. < \gamma < 1.0$) function is given by

$$F_\gamma = (F_{SUM})^\gamma * (F_{PROD})^{1-\gamma}$$

The FL operator used to combine fuzzy sets will depend on the relationships of the sets and on the interdependence of the data. For example, with a proposition regarding favourability for base metal deposits, although copper, lead and zinc in geochemical data might all be suitable pointers, these data are likely to be inter-dependent. In such cases a first part of the FL inference model might be to evaluate the Fuzzy OR for all these fuzzy sets. The output of this logic operation could then be used in a higher level of the inference model using either a Fuzzy SUM or a Fuzzy Gamma.

6.3 FUZZY LOGIC MODEL FOR EPITHERMAL AND MESOTHERMAL GOLD DEPOSITS IN THE NORTHERN HIGHLANDS

Epithermal gold is characteristically associated with high-level acid to intermediate volcanic rocks of the andesite-rhyolite suite (Table 6.2). These rocks are present in the Midland Valley and the South-West Highlands of Scotland and have been the subject of gold prospectivity appraisal (Gunn *et al.,* 1999). In the Northern Highlands there are no epithermal economic gold deposits, although the Brora occurrence (Crummy *et al.,* 1990) shows textural characteristics of low-sulphidation epithermal types and the gold occurrence at Rhynie is clearly associated with epithermal activity. Gold occurrences are not common in the Northern Highlands but the terrane includes several characteristics that are associated with mesothermal gold deposits worldwide (Table 6.3).

Table 6.2 Field characteristics of low-sulphidation epithermal deposits

Feature	Field characteristic
Volcanic rocks	Andesite-rhyodacite-rhyolite
Alteration zone	Widespread
Alteration minerals	sericite; illite; roscoelite; chlorite; adularia
Quartz gangue	chalcedony/quartz with crustiform, colloform, bladed texture with carbonate replacement
Carbonate gangue	present with Mn
Other gangue	barite/fluorite locally often above mineralisation
Suphide abundance	typically < 5% mainly pyrite
Key sulphide species	sphalerite; galena; tetrahedrite; chalcopyrite
Metals present	Au, Ag (Zn, Pb, Cu)
Metals locally	Mo, Sb, As, (Te, Se, Hg)

Table 6.3 Simplified deposit model for mesothermal lode gold deposits

Tectonics	In accreted, deformed and metamorphosed continental margin or island arc terrains. Close to major structures, commonly transcurrent faults or major shear zones
Size and grade	Up to a few million tonnes, typically 5–25 ppm Au
Host lithology	Widely variable; greywackes-pelites, chemical sediments, volcanics, plutons, ultramafics. Local control by competence contrasts in host succession
Metamorphism	Variable; commonly greenschist
Relations to plutons	Variable; characteristic of granite-related sub-class
Regional geochemistry	Prospective belts regionally enriched in As, and locally Sb, relative to average crustal abundances
Local structure	Ores in dilatant zones controlled by folds and faults; where fault controlled, mineralisation commonly associated with second-order faults related to major structures. Shear zone / fault intersections and bends particularly favoured
Timing	Late; post-date main deformation
Ore morphology and textures	Quartz veins, typically banded, occasionally vuggy with high-grade ore shoots; vertically continuous

Mineralogy and paragenesis	Early phases with quartz, Ca-Mg-Fe carbonates, arsenopyrite, pyrite, albite, sericite, chlorite, scheelite, stibnite, pyrrhotite, tetrahedrite, chalcopyrite, tourmaline. Late phases with gold, galena, sphalerite, tellurides
Hydrothermal alteration	Carbonatization, albitization, sericitization, silicification, sulphidation, chloritization; listwaenite development
Lithogeochemistry	Au/Ag typically > 1; associated elements Ag, Sb, As, W, Hg, Bi, Mo, Pb, Zn, Cu, Ba.
Fluid inclusions and isotopes	Low salinity, T = 250–350°C. Crustal sources.

6.4 EVIDENTIAL DATA

6.4.1 Geology

The UK has complete coverage of the solid geology of the onshore region at 1:50,000 as part of the DigMapGB database. These data are currently available as attributed polygons for use within a GIS application. There is also coverage of the UK onshore region at 1:250,000 scale.

At Rhynie, a suite of minor intermediate-acidic igneous intrusions have been identified and are believed to be directly related to the epithermal mineralisation (Parry and Rice, 2002). Integrating this evidence with the deposit models for epithermal gold and granite-related mesothermal gold, high-level alkali-rich felsic to intermediate igneous intrusions of Caledonian age were selected from the 1:250,000 geology. Descriptions and formation names extracted from the 1:50,000 geology were joined to the 1:250,000 table for ease of interpretation. Filtering of the selected igneous intrusions was performed such that bodies with a surface area greater than 20 km^2 were removed from the dataset to eliminate effects caused by large bodies. The remaining igneous intrusions were buffered at 500 m intervals for a distance of 1000 m (Figure 6.3) and assigned a fuzzy membership of 0.4 and 0.2, decreasing outwards from the intrusions (Table 6.4).

Table 6.4 Igneous bodies - buffer distance and fuzzy membership

Buffer distance (m)	Fuzzy membership
0 – 500	0.4
500 – 1000	0.2

6.4.2 Faults

Epithermal deposits typically develop along structures, such as faults, that localise the movement of fluids. The location of the Siluro-Devonian hydrothermal activity at Rhynie was strongly influenced by active major extensional fault systems, along which strike-slip can be demonstrated (Parry and Rice, 2002), and are hosted in a succession of Lower Devonian fluvio-lacustrine sediments and andesitic lavas (Rice at al. 1995, 2002). Crustal-scale structures and associated faults are widely recognised as important controls on the location of mesothermal gold deposits (Plant *et al.,* 1998).

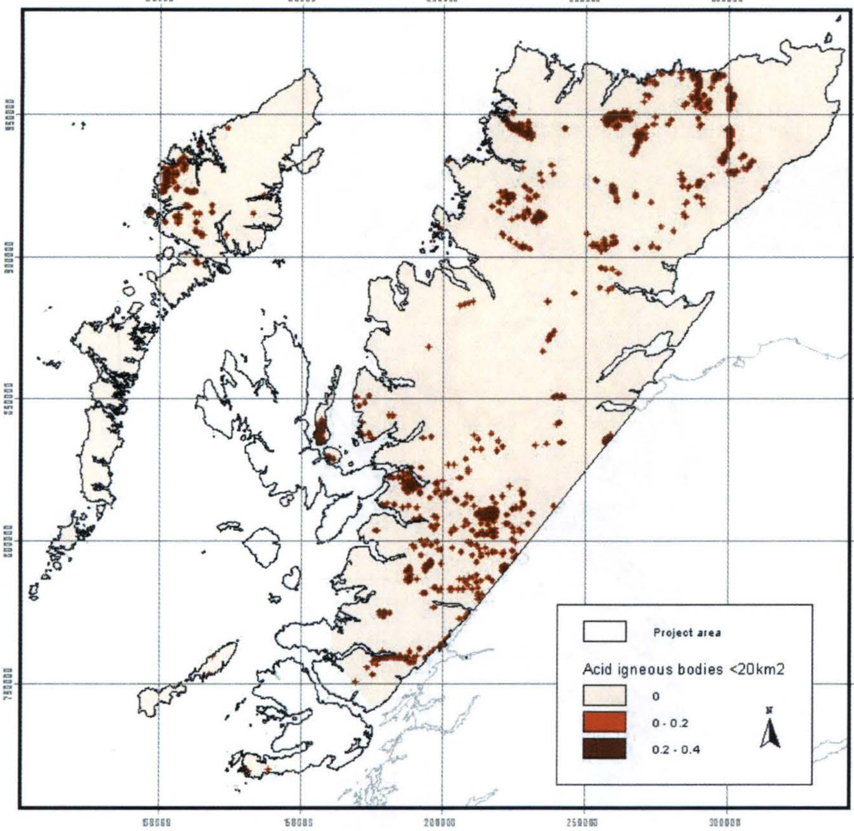

Figure 6.3 Igneous bodies <20km^2 and fuzzy memberships

The age of a fault is an important criterion for relating faults to tectonic events, therefore the faults were evaluated to determine their age based on cross cutting relationships. The 1:250,000 scale-mapped faults were filtered to remove those related to the Moine Thrust and then buffered at 500 m intervals for a distance of 2 km (Figure 6.4). Each buffer was assigned a fuzzy membership value, as shown in Table 6.5, reflecting the importance of faulting as evidence for defining the regional tectonic setting and as loci for the movement of metal bearing hydrothermal fluids in both epithermal and granite-related mesothermal mineral deposit systems.

Table 6.5 Faults - buffer distance and fuzzy membership

Buffer distance (m)	Fuzzy membership
0 – 500	0.4
500 – 1000	0.3
1000 – 1500	0.2
1500 – 2000	0.05

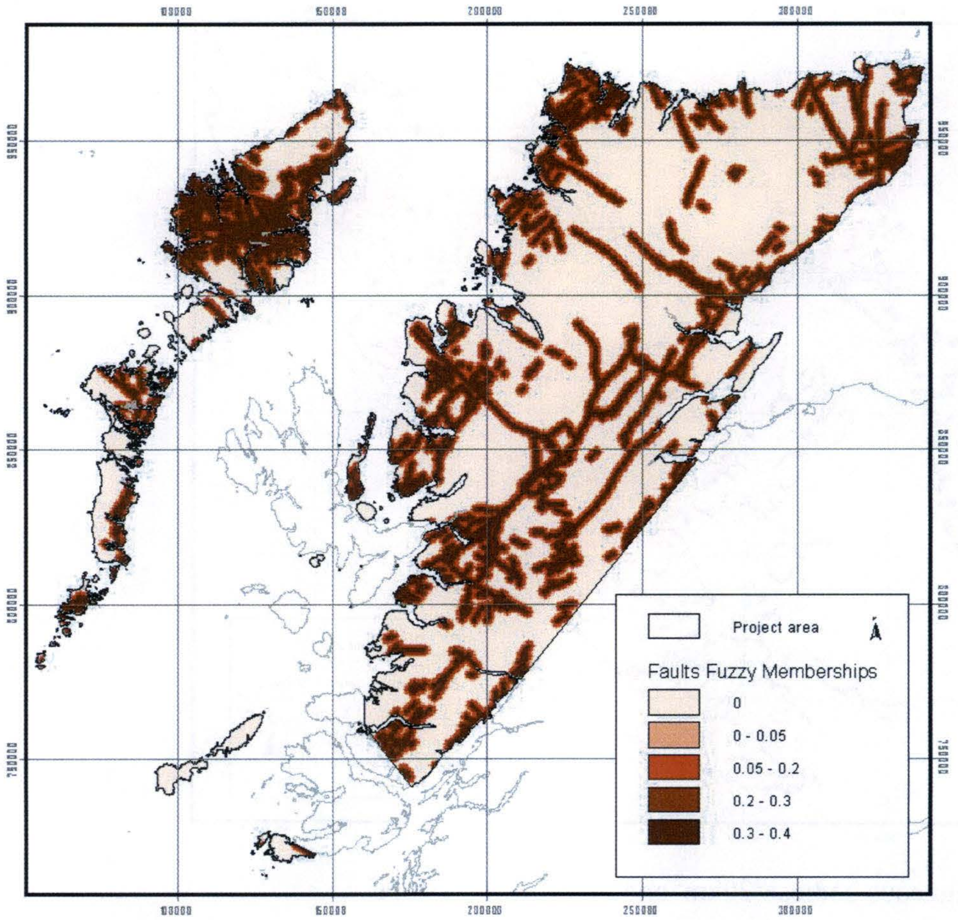

Figure 6.4 Buffered 1:250,000 scale faults and fuzzy memberships

6.4.3 Drainage Geochemistry

Drainage geochemistry is frequently used to identify areas of mineralisation. The eastern part of the Northern Highlands has been covered by various drainage geochemical surveys, conducted by both public sector and commercial organisations. The most extensive coverage is provided by the BGS regional geochemical survey (G-BASE), which systematically covered the Northern Highlands region. Detailed follow-up surveys have also been carried out in a few selected areas by BGS under the Mineral Reconnaissance Programme.

For the present study, G-BASE data for the study area were retrieved from the BGS UK Geochemical Database. Within this area, data for 14240 stream sediment samples were available for up to 35 major and trace elements. The study area comprises parts from four of the G-BASE regional sampling programmes which used differing analytical techniques as follows:

- Caithness Sampling programme (1969): with the exception of Cu, Pb, Zn and U, all elements were determined by Optical Emission Spectroscopy (OES). Zn and Pb were determined by Atomic Absorption Spectroscopy (AAS) and U by delayed neutron activation.
- Great Glen Geochemical programme (1974): elements were analysed by Direct Reading emission spectrometry with the exception of U, Pb and Zn. Pb and Zn were determined by AAS and U was determined using delayed neutron activation.
- Outer Hebrides Geochemical programme (1975): all elements were analysed using Direct reading emission spectroscopy with the exception of U which was determined using delayed neutron activation.

- Argyll Geochemical programme (1976 and 1977): all elements were analysed using Direct reading emission spectroscopy except U, As and Sb. As and Sb were determined by ASS with detection limits of 5 ppm and 0.5 ppm respectively. Uranium was determined using delayed neutron activation.

G-BASE regional sampling programmes carried out in the 1970s, with the exception of Argyll did not analyse for the critical pathfinder elements for gold exploration, Au, As, Sb and Bi. A programme of re-analysing excess material for As, Sb and Bi by Atomic Absorption Hydride Generation from the Caithness, Great Glen and Outer Hebrides sampling areas was undertaken in 2001. The new As, Sb and Bi data were merged with the Argyll data to form near complete coverage for these elements in the project area. All the recent data is currently being normalised with the rest of the G-BASE data for these elements to provide seamless coverage of these elements across Britain. However, this was not available to the current project so the values used may change slightly when the full datasets are released by the G-BASE programme. The distribution of sample sites is shown in Figure 6.5. and summary statistics for the dataset are shown in Table 6.6.

Table 6.6 Summary statistics for G-BASE stream-sediment samples (ppm)

Element	No. of samples	mean	Min.	Max.	50%	75%	90%	95%	98%
Ba	13989	770	7	19160	732	887	1101	1302	1688
Co	13993	28.7	0	668	20	36	66	85	101
Cu	13972	24.6	0	788	13	26	65	97	122
Fe	13982	59482	6085	537139	52385	77353	100154	114953	138481
Mn	13981	3979	0	180000	1857	3380	8500	14400	28100
Mo	13991	0.58	0	160	0.1	0.1	0.1	3	8
Pb	14055	26.7	0	3180	20	30	51	71	108
Zn	14011	122.6	0	2668	92	150	231	299	406
Bi	1043	1.19	0	116	1	1	3	4	7
As	1281	3.15	0	25	5	5	5	10	10
Sb	1283	0.008	0	4	0	0	0	0	0

The critical pathfinders for epithermal gold mineralisation are Au, Ag, and Cu, with Bi, Sb, As and Mo occurring locally. Mesothermal gold pathfinders are similar, although more pronounced As and Sb and locally occurring W, Bi, Mo and base metals.

At Rhynie, pronounced enrichments of Au (maximum 0.2 ppm), As (maximum 650 ppm), Mo (maximum 250 ppm) and W (maximum 230 ppm) are notable in the Rhynie Chert and in the intensely silicified and altered basin margin fault zone (Parry and Rice, 2002). Elevated W and Mo suggest the involvement of a 'granitic source' and elevated As is a positive indication of epithermal gold mineralisation. Parry and Rice also note heavy metal mineralisation akin to that at Rhynie developed elsewhere in Scotland and of similar age. Of particular interest in Argyll, is the commercially significant quartz vein hosted gold at Cononish, near Tyndrum that may represent a mesothermal equivalent of Rhynie.

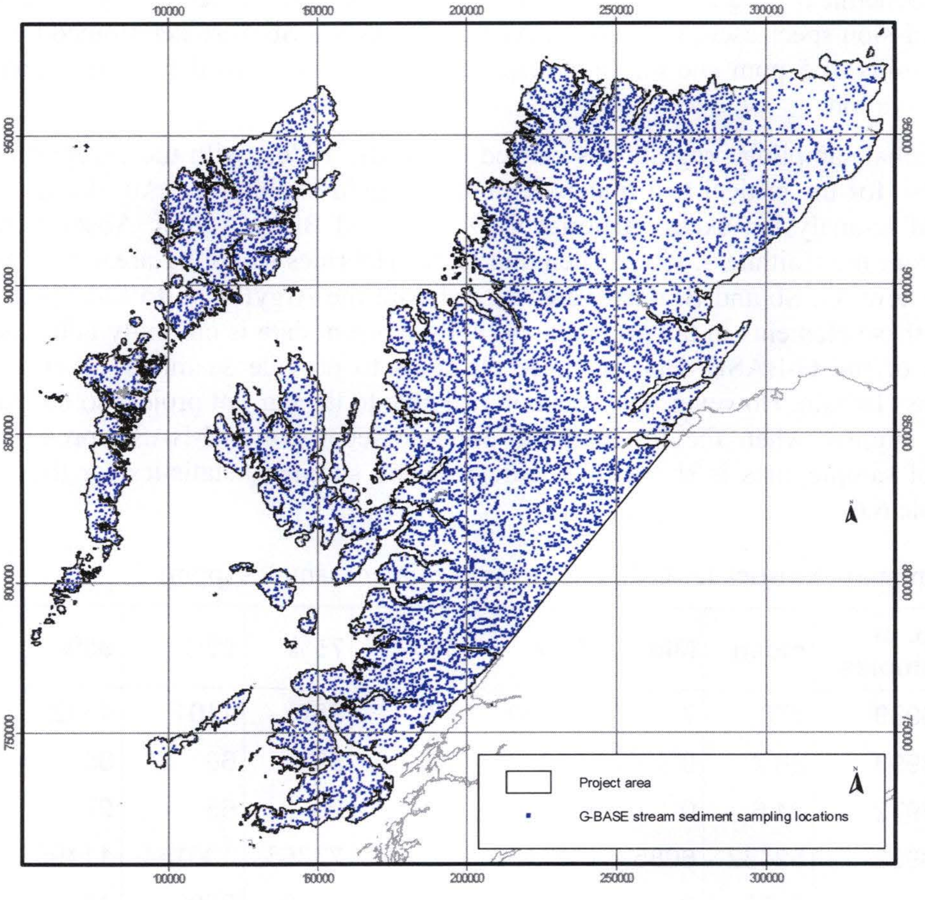

Figure 6.5 G-BASE stream-sediment sample location points

As, Sb, Bi, Cu and Mo were selected from G-BASE for use in the prospectivity modelling. Au and W are not determined in the G-BASE programme and the coverage of Ag is incomplete. Data for each element have been interpolated onto a square grid of mesh size 0.5 km and symbolised using quarter standard deviation breaks with incremental fuzzy membership values (Table 6.7). Figure 6.6 shows fuzzy logic values for arsenic.

In sedimentary environments, As is readily sorbed by organic matter and secondary Fe-Mn oxides, and syngenetic pyrite has been shown to take up As relative to the host rock (Raiswell and Plant, 1980). The Devonian sediments and surrounding lithologies in the Caithness area demonstrate this supergene concentration effect over a wide area which is clearly not related to mineralisation and hence the elevated As values overlying the Devonian sediments were removed from the dataset. Although this supergene affect appears to extend westwards from the outcrop of the Devonian sedimentary rocks the reason for this is not clear.

Table 6.7 Geochemistry – Standard deviation and fuzzy membership

Standard Deviation	Fuzzy Membership
< Mean	0
Mean	0
0.00 – 0.25	0.1
0.25 – 0.50	0.1
0.50 – 0.75	0.2
0.75 – 1.00	0.2
1.00 – 1.25	0.3
1.25 – 1.50	0.3
1.50 – 1.75	0.4
1.75 – 2.00	0.4
2.00 – 2.25	0.5
2.25 – 2.50	0.5
2.50 – 2.75	0.6
2.75 – 3.00	0.7
> 3 St Dev	0.8

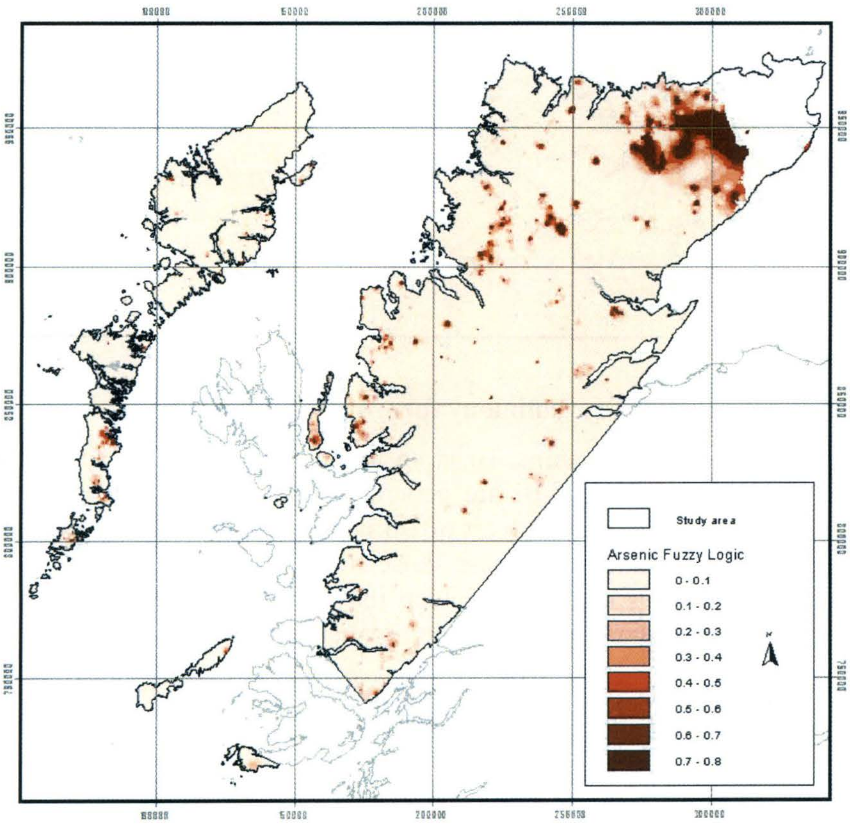

Figure 6.6 Stream-sediment geochemistry: arsenic fuzzy memberships

The distribution pattern of antimony in the region (Figure 6.7) is broadly similar to that of arsenic (Figure 6.6). The anomalous area is the northwest overlies the Loch Eil vein complex and the Stath Halladale Granitic intrusion. These anomalies may relate to either pyritic zones in these lithologies or reflect hydrothermal mineralisation associated with the igneous intrusions. To the east of this, a broad elevated area reflects the underlying shales and sediments of the Devonian. The Sb content of shales is highly variable, often related to pyritic zones, but they are broadly enriched in Sb relative to igneous rocks.

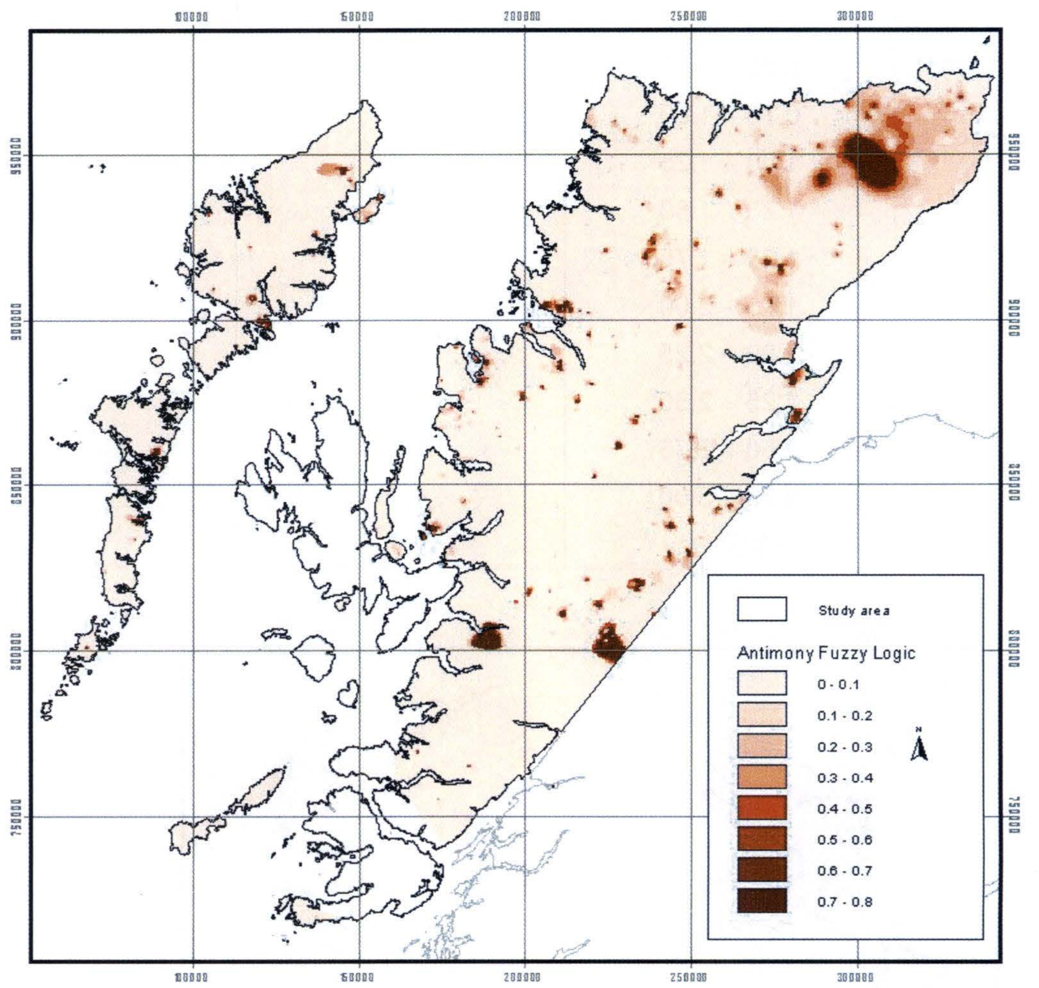

Figure 6.7 Stream-sediment geochemistry: antimony fuzzy memberships

Figure 6.8 shows bismuth fuzzy memberships. Bi is an important pathfinder element for gold mineralisation. In the study area, levels of Bi are generally low with the exception of a few pronounced enhancements, in particular to the west of Dornach at A and the Knoydart peninsula at B. Both are associated with Moine sediments; those at A are also intruded by granites. Numerous small, scattered anomalies also occur which may reflect the presence of pyritic or graphitic metasediments or of hydrothermal sulphide mineralisation.

The distribution of copper in the region mainly reflects lithology. The strongest copper anomalies occur over the Palaeocene rocks in the west of the area and have been eliminated as they are not of interest in this study. Generally high levels of Cu occur over the Lewisian on both the western mainland and on the Hebrides. Particularly high values over the Glenelg-Attadale inlier and the Loch Maree Series at A, relating to concentrations in metabasic rocks (Figure 6.9). The major Loch Maree Fault which cuts the Lewisian supracrustal assemblage hosts the Gairloch deposit 30 km to the west. Isolated high values may be related to metalliferous mineralisation or to contamination.

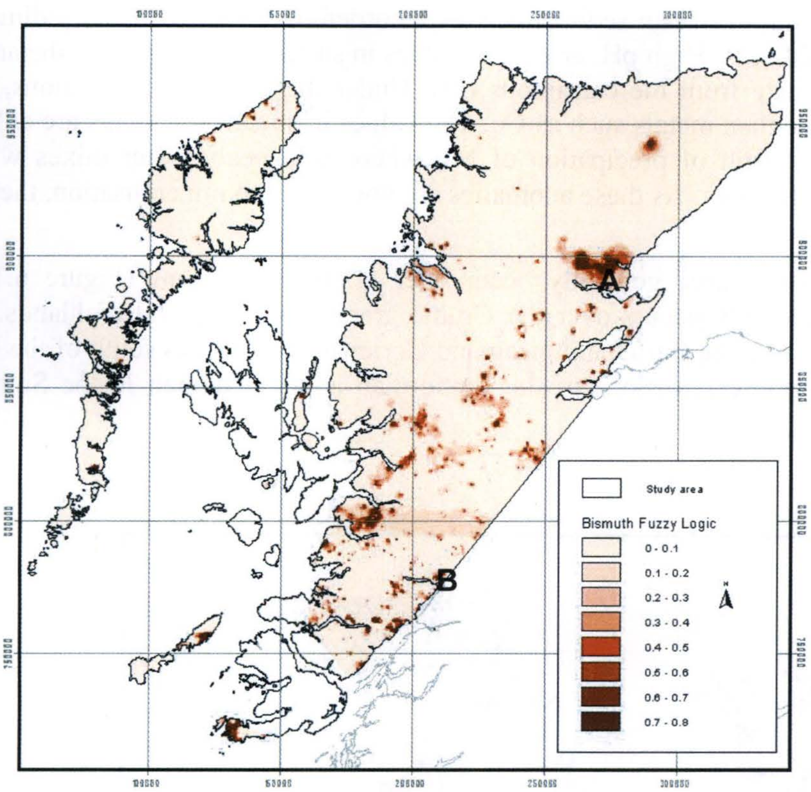

Figure 6.8 Stream-sediment geochemistry: bismuth fuzzy memberships

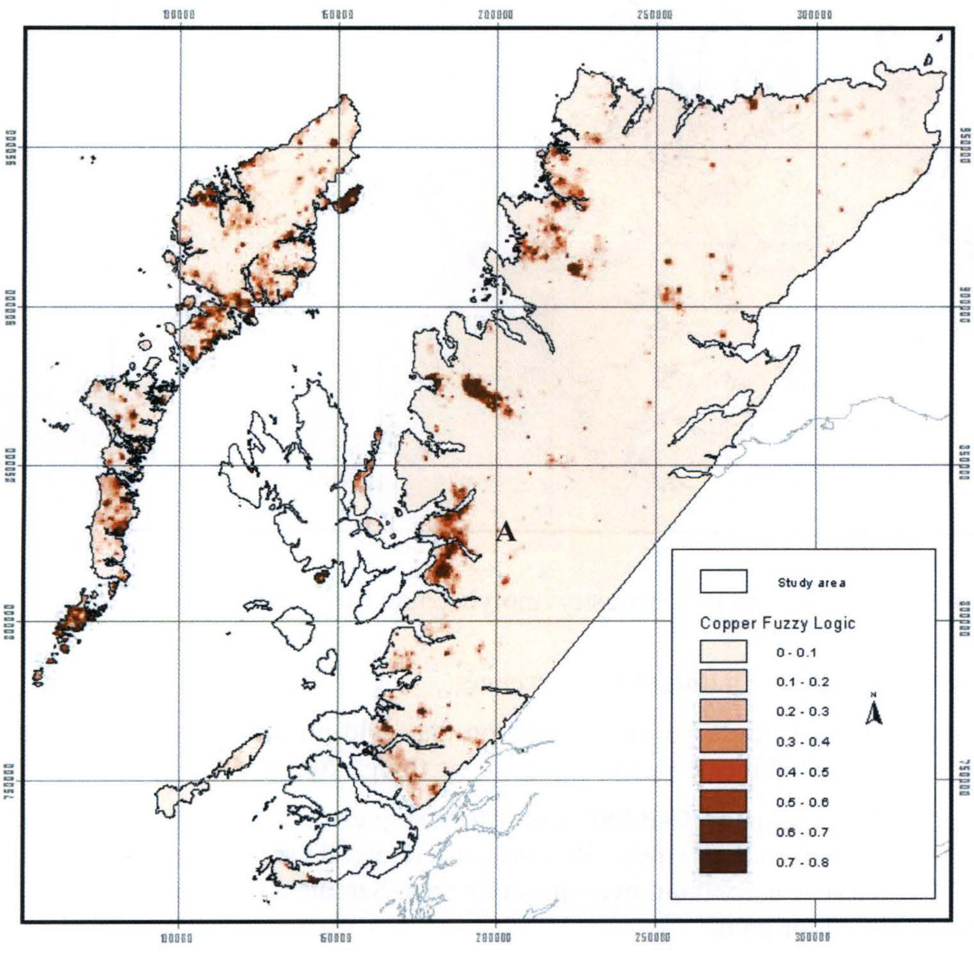

Figure 6.9 Stream-sediment geochemistry: copper fuzzy memberships

High levels of molybdenum in stream sediments were recorded over the Devonian sediments in the north-east area of Caithness. High pH, around 8, values in surface water occur in the area due to the leaching of carbonate from the calcareous tills. Under these alkaline conditions, Mo is considerably more soluble than metals such as Cu. The values in stream sediments are enhanced relative to bedrock as a result of precipation of Mo where acid peaty water mixes with the alkaline groundwaters in the area. As these anomalies are not related to mineralisation, they were eliminated from the dataset.

Mo anomalies in the study area generally occur over granitic intrusions (Figure 6.10). In particular, a large Mo anomaly occurs over the Grudie granite in the central highlands. Other notable anomalies occur over the Carn Chuinneag and Corieyairack granites south of the Grudie Granite and over late granitic intrusions of the Laxfordian and Caledonian in the Sutherland region.

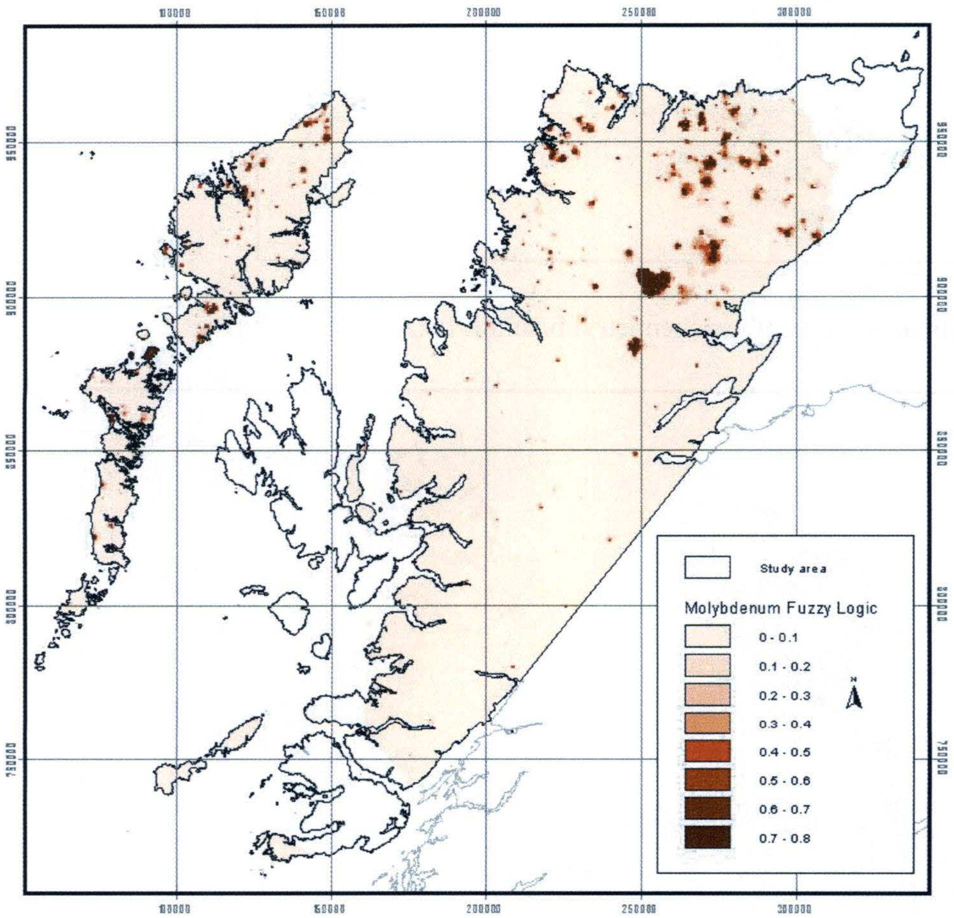

Figure 6.10 Stream-sediment geochemistry: molybdenum fuzzy memberships

6.4.4 Proximity to placer gold/gold occurrences

Known gold occurrences are a positive indication that gold mineralisation exists in an area. A gold occurrence evidential theme was compiled using three existing datasets:

1. Visible gold observations in G-BASE and MRP samples or gold values in analysed panned concentrates greater than 50 ppb. Panned-concentrate datasets were compiled from the various MRP surveys carried out over the study area. Samples from some of the later surveys were also analysed for gold.

2. Gold occurrences from the BGS Mineral Occurrence Database (MOD). Gold occurrences in bedrock were extracted and filtered to remove gold occurrences in non-epithermal or -mesothermal deposit types.
3. Visible gold observed in panned concentrate or gold values > 50 ppb from reconnaissance fieldwork for this project. Gold in panned concentrates was determined on 30g splits by two methods, lead collection fire-assay and ICP-MS by aqua Regis. Detection limits for gold were 1 ppb and 0.5 ppb respectively. Values from the two methods were combined and halved and values greater than 50 ppb were selected for inclusion.

The three datasets were combined to produce one point dataset, buffered at 500 m intervals. Fuzzy membership was assigned to the buffered points, with decreasing weighting with distance from the occurrence (Table 6.8).

Table 6.8 Geochemistry – Point buffer distance and fuzzy membership

Buffer distance	Fuzzy membership
0 – 500	0.6
500 – 1000	0.5
1000 – 1500	0.4
1500 – 2000	0.3
2000 – 2500	0.2
>2500	0.0

6.4.5 Geophysics

The UK has complete coverage of the onshore and offshore region with regional gravity and aeromagnetic data as part of the national geophysical database. These data provide first order visualisation of the distribution of density and magnetisation within the crust of the earth (BGS, 1998, 1999).

Gravity data have been collected at Ordnance Survey benchmarks and spot heights onshore at a nominal distribution of about 1 per km^2 in lowland regions and about 1 station per 2.5 km^2 in upland areas. These data have been interpolated onto a square grid of mesh size 0.5 km. The observed Bouguer gravity anomaly has been upwardly continued to 5km above observation level and a residual gravity anomaly derived as the resultant of these two fields.

Amplitude variations in the field reflect the bulk density of the crust while gradient features in the Bouguer gravity anomaly can generally be associated with the margins of the density structures. Consequently lineament analysis based on shaded-relief images of the gravity data highlight gradient zones, which can be associated with mapped and unmapped geological structures. For this analysis lineaments picked from images of the gravity data and its derivatives have been used as an indication of crustal structures which are potentially important zones for fluid transport and mineralisation.

The gravity lineaments in North Scotland show two important complementary sets with strikes of 020°/110° and 060°/150° (Figures 6.11 and 6.12). These two sets have been extracted from the population and show a clear relationship to localities were gold has been observed. Both these lineaments sets have been considered as evidence for gold mineralisation (Table 6.9).

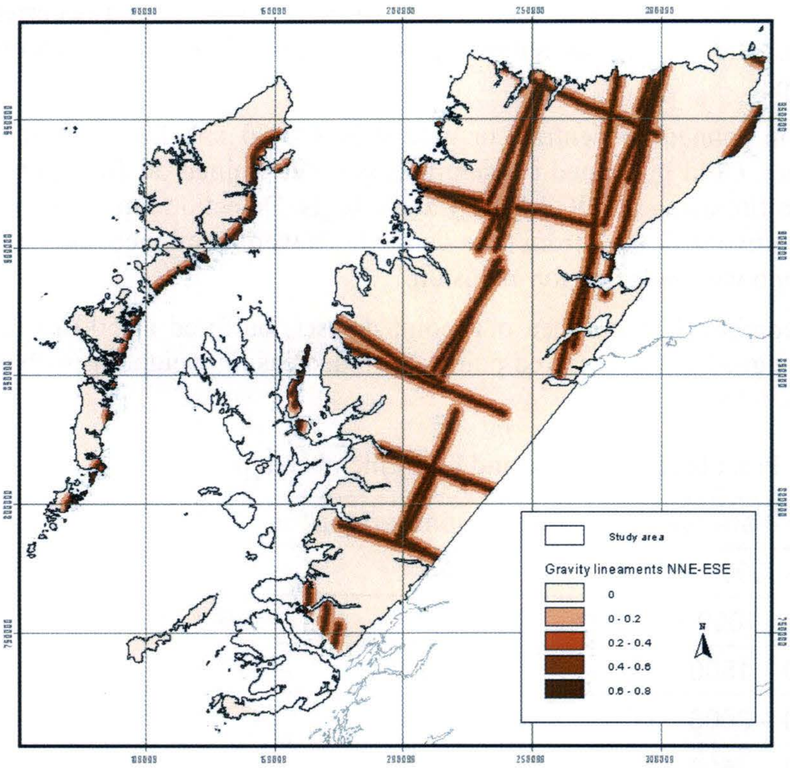

Figure 6.11 Gravity lineaments NNE-SSE

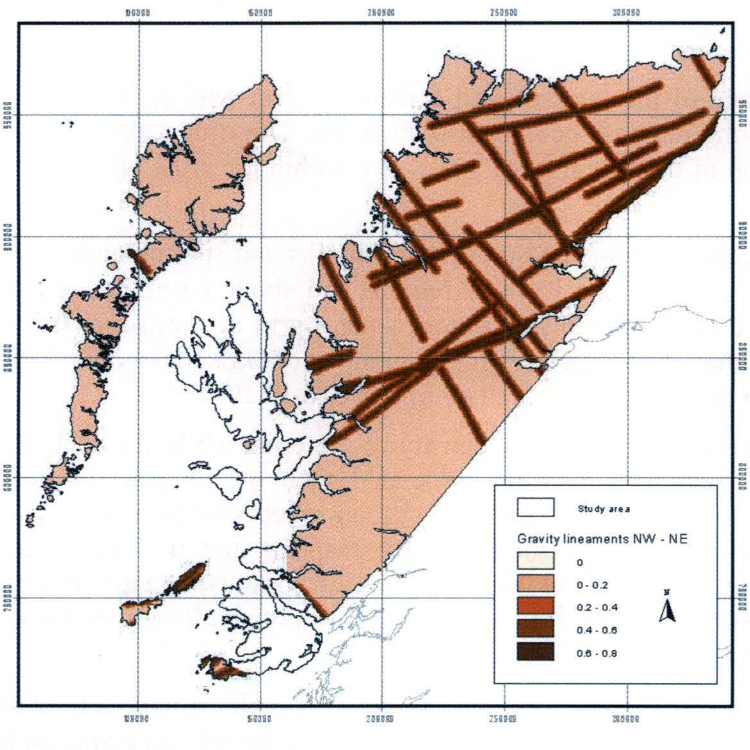

Figure 6.12 Gravity lineaments NW-NE

Table 6.9 Gravity lineaments - Buffer distance and fuzzy membership

Buffer Distance (m)		Fuzzy Membership
020/110	060/150	
1 – 1000	1 – 1000	0.2
1000 – 3000	1000 – 3000	0.1
> 3001	> 3001	0

The aeromagnetic data for North Scotland were collected along east-west flight lines spaced approximately 2 km apart. The mean terrain clearance was 305 m. Data have been converted to digital points at contour cuts and inflexion points along the flight lines, interpolated onto a square grid of mesh size 0.5 km and analysed for lineaments and signature. The observed field has also been transformed to the 'reduced to the pole' field, and upwardly continued to 2 km above observation level. A residual polar magnetic anomaly has been generated as the resultant of these two fields.

The magnetisation distribution of a rock is generally more complicated than the density distribution, with a wide range of induced magnetisation and a variable Natural Remnant Magnetisation (NRM). Thin structures with a strong magnetisation such as dykes are prominent in the magnetic data but invisible in the gravity data. Many of the lineaments observed from magnetic data reflect discrete magnetisations in small volumes of rock and may be related to dykes, metasedimentary strata with magnetite or intrusive bodies.

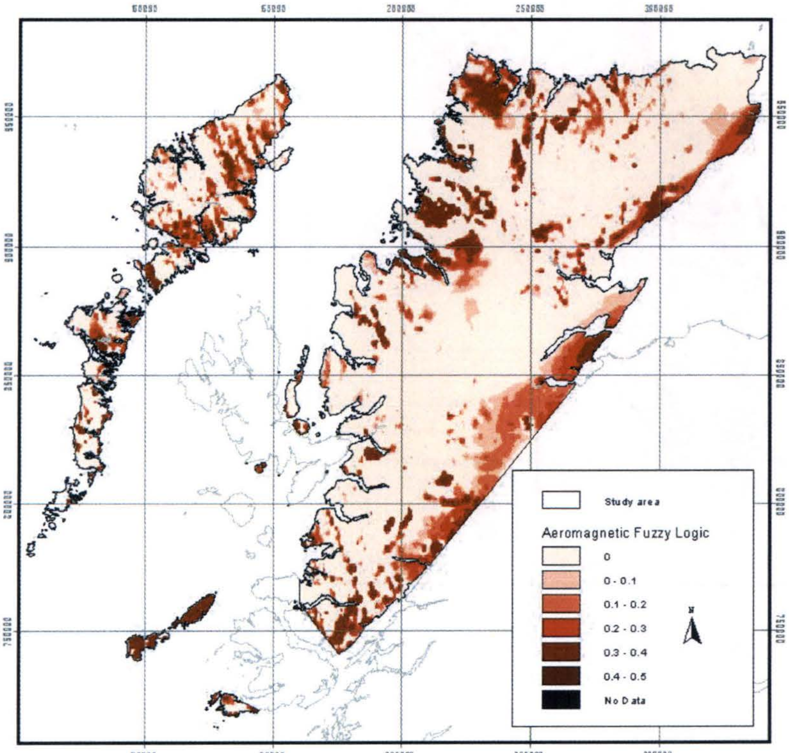

Figure 6.13 Magnetic residual, grid

Mesothermal and epithermal gold deposits can often be associated with small or medium-sized, late permissive intrusions of coarse-grained granite and granodiorite. Known outcrops of these bodies commonly have clear residual magnetic anomalies. A potential evidential layer for gold deposits is therefore the residual magnetic anomaly map (Figure 6.13). It is clear, however, that the positive anomalies can be caused by numerous sources in addition to intrusions.

Table 6.10 Residual magnetic anomalies – Anomaly value and fuzzy membership

Magnetic Residual	Fuzzy Membership
-2778 – 9	0
10 – 19	0.1
20 – 29	0.2
30 – 49	0.3
50 – 999	0.4
999 – 1790	0.5

6.4.6 Landsat TM Images

Landsat TM images provide a false-colour image of the earth's surface and can be interpreted for lineaments and signature. These lineaments reflect structures at the surface but often show a good correlation with geology. Many of the picked features are relatively short in length but when analysed for direction, linked structures and continuity can be observed (Figures 6.14 and 6.15). The east-north-east lineaments observed in Landsat TM images are used as an evidential theme (Table 6.11).

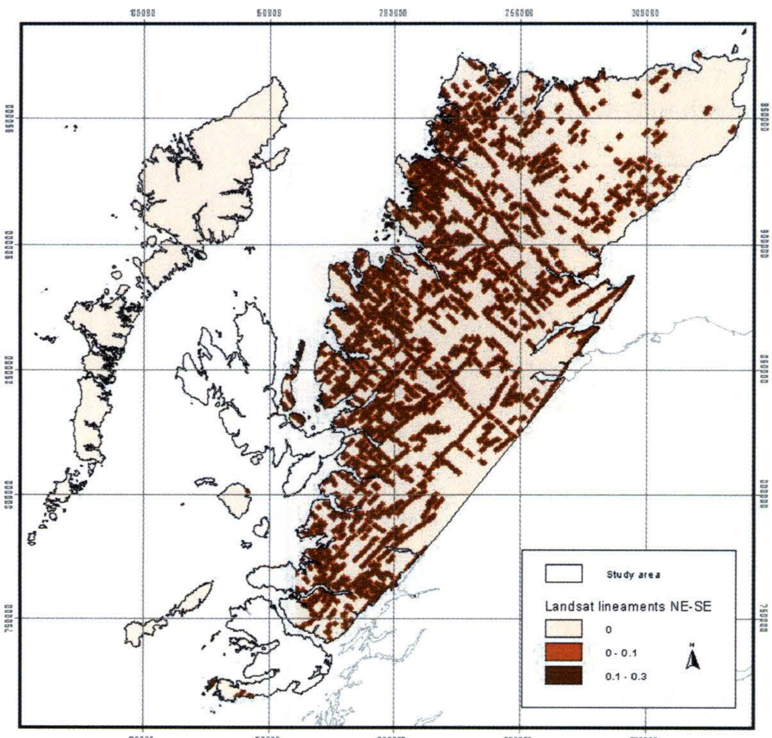

Figure 6.14 Landsat TM lineaments NW-SE

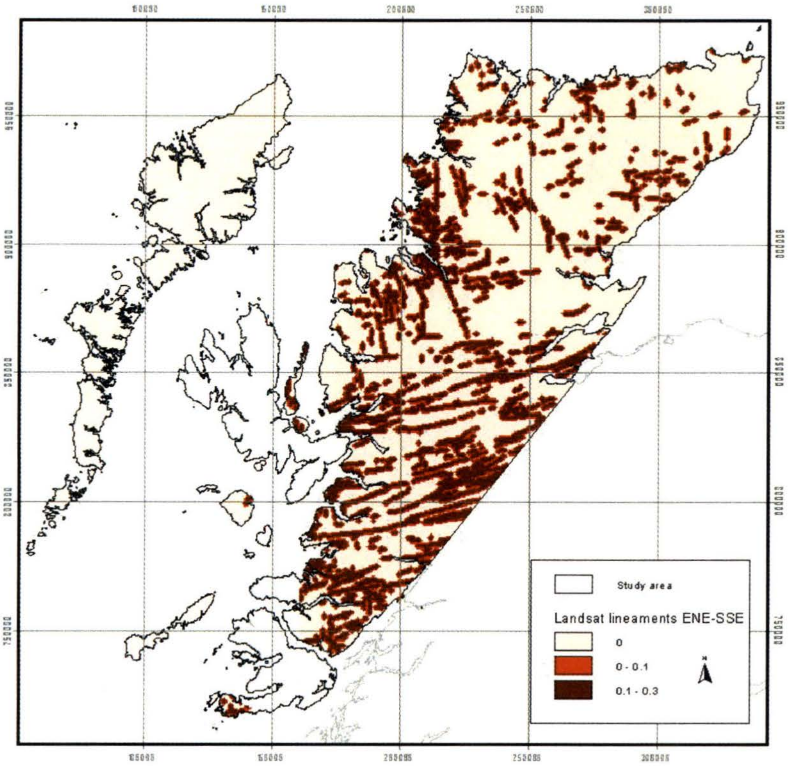

Figure 6.15 Landsat TM lineaments ENE-SSE

Table 6.11 Landsat TM lineaments - Buffer distance and fuzzy membership

Buffer Distance ENE lineaments	Fuzzy Membership
1 – 500	0.3
501 – 1000	0.1
>1001	0

6.5 FUZZY LOGIC MODEL RESULTS

The prospectivity model was produced using Fuzzy Logic operators. The geochemistry themes were combined as follows:

- copper **OR** molybdenum
- arsenic **OR** bismuth **OR** antimony

The outputs from these OR operators were combined with the other fuzzy evidential themes using Fuzzy Algebraic Sum. The result of the prospectivity modelling is shown in Figure 6.16 for Fuzzy Algebraic Sum > 0.88. Eight areas (A to H on Figure 6.16) are characterised by the coincidence of various parameters which indicate favourability for the occurrence of gold mineralisation of granite-related mesothermal or epithermal types. The features of each area are summarised in Table 6.12.

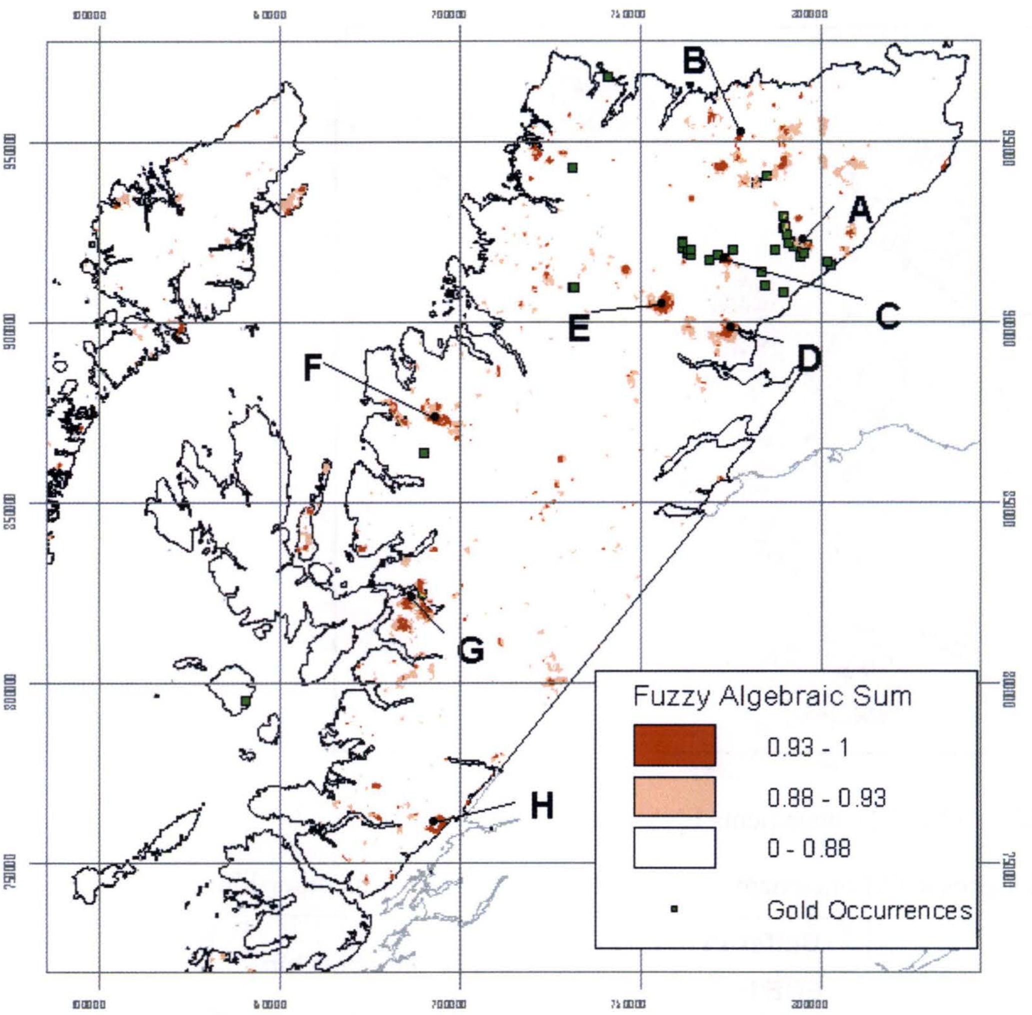

Figure 6.16 Prospectivity and target areas for epithermal and granite-related mesothermal gold mineralisation

Table 6.12 Summary of prospective areas

Area/Name		A Helms-dale	B Strathy	C Upper Brora	D Loch Fleet	E Lairg	F Loch Maree	G Loch Duich	H Loch Linnhe
Areal extent km^2		42	37	**35**	90	81	108	158	34.5
Geology	Moine	■	■	■	■	■		■	■
	Lewisian						■	■	
	Granite	■				■			
	Igneous		■	■	■	■		■	■
Gold Occurrences		9		3				5	
Geochemistry	As	■	■	■		■	■		■
	Bi		■		■			■	■
	Cu					■	■	■	■
	Mo	■	■	■	■	■			
	Sb	■	■	■	■	■			
Landsat TM Lineaments	NE-NW	■	■	■		■	■	■	■
	NNW-ENE				■	■	■		■
Gravity Lineaments	NE-NW	■	■	■	■	■		■	
	NNE-WNW		■	■	■			■	
Mineral Occurrences	Au	■							
	Cu						■	■	
	Mo							■	
	Pb						■	■	
	Zn						■	■	

6.6 NEW TARGET AREAS FOR EPITHERMAL AND GRANITE-RELATED MESOTHERMAL GOLD MINERALISATION

A. – Helmsdale.

This area, centred on [295000, 922000], is underlain by Caledonian Helmsdale Granite and Moine sediments. It also contains the placer gold deposit worked in the 1880s. The Helmsdale area is situated on a NE trending gravity lineament and NE-NW intersecting Landsat TM lineaments.

B. – South of Strathy Forest in the Strathy catchment.

This area, centred on [280000, 950000], is underlain by Moine sediments with some minor intrusions. Two intersections of gravity lineaments occur in the area: NE-NW and NNE-WNW. In addition, NW and NE trending Landsat TM lineaments also occur.

C. – Upper Brora.

This area, centred on [275000, 918000], is underlain by Moine sediments with a number of minor intrusions. Two gravity lineaments occur in the vicinity: NE and NNE trending. There is an intersection of NE and NW trending Landsat TM lineaments and the catchment contains several panned gold occurrences.

D. – Loch Fleet.

This area, centred on Ben Tarvie 5 km west of Loch Fleet, around [272000, 897000], is underlain by Moine sediments with minor basic intrusions and Lewisian gneiss inliers. There are a number of lineaments in the area of interest: an intersecting NE and NW gravity lineament; a NNE trending gravity lineament; and an ENE and NW trending Landsat TM lineaments.

E. – Lairg.

This area, centred 8 km northeast of Lairg at [260000, 908000], is underlain by Moine metasediments and minor intrusives, with a larger granite body in the south of the area. There are also two NE trending gravity lineaments and NW and NNW trending Landsat TM lineaments

F. - Loch Maree.

This area, centered on [197000, 872000], is underlain by Lewisian supra-crustal metasediments and volcanics, of the same age as those hosting the Gairloch Cu-Zn-Au deposit 15 km to the west. The area is bordered by the Loch Maree fault which extends for over 50 km to the southeast in the Scardroy area. A number of intersecting NW and NW trending Landsat TM lineaments also occur.

G. - South-west of Loch Duich.

This area, centred on Balvraid [187000, 817000], is underlain by Lower Moinian Morar Group psammites in Lewisian gneisses and with some small areas of acid volcanic rocks. The Ratagain gold mineralisation (Alderton 1988) is on the eastern margin of the area. WNW and NE trending gravity lineaments are present in the area and intersecting NE and NW trending Landsat TM lineaments.

H. – North side of Loch Linnhe.

This area, centred on [190000, 760000], is underlain by Moine metasediments with minor intrusives. Two sets of intersecting Landsat TM lineaments occur: NNW and ENE, and NE and NW.

No attempt has been made to prioritise these occurrences as the study was carried out at a regional scale. No further local investigations have been carried out.

6.7 ENVIRONMENTAL CONSTRAINTS OVER TARGET AREAS.

There are a number of local, national and international environmental constraints covering parts of the study area. Many of these are coincident. Figure 6.17 shows the interaction of the potential target areas and Sites of Special Scientific Importance (SSSI) and National Scenic Areas (NRA). These include areas covered by other designations, such as RAMSAR sites, and thus encompass all the natural environment and scenic designations.

Several of the target areas (B, C and F) are largely covered by environmental constraints and thus any form of development is unlikely to be permitted. However the remaining five areas (A, D, E, G and H) are almost entirely free of constraints, such that statutory environmental constraints would not preclude applications for mineral development projects.

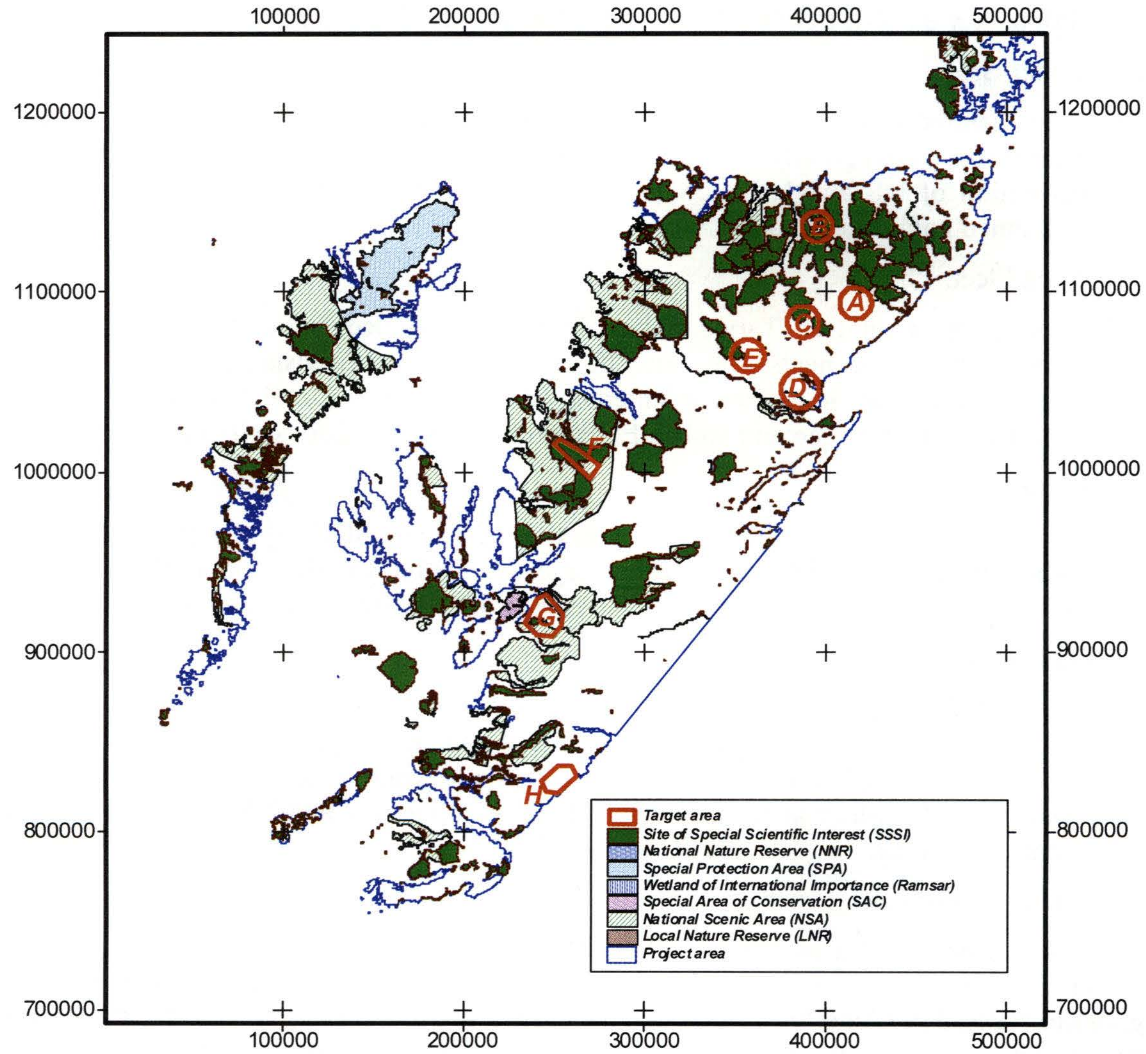

Figure 6.17 Target areas with environmental constraint areas

7 Discussion

Mineral exploration has traditionally been a field-based activity and it still requires the physical recognition of mineralisation by drilling to prove a deposit. However, the recent increased availability of high-quality digital geoscientific data of potential exploration significance allows the possibility of identifying the more prospective areas remotely, thus cutting down on the expensive process of eliminating unfavourable ground by traditional fieldwork. This has become possible with the development of GIS-based mineral prospectivity analysis systems, such as ArcSDM™, which can manipulate, analyse and output scenarios based on the information with which they have been supplied. Although the systems rely on the input of geological and exploration experience, and the analysis can be manipulated widely within certain parameters, they will give a consistent, quantitative and objective output, which can be replicated and understood.

In this study, a wide variety of geological and cultural datasets, including a summary of existing mineralisation, have been collected for the Northern Highlands of Scotland. A set of models for the main styles of mineralisation developed or expected in the area has been compiled. From these models parameters have been selected to input into ArcSDM to produce maps of the potential for epithermal and granite-related mesothermal gold mineralisation. The following key datasets have been used

i. geology: lithology, age.

ii. geochemistry: trace-element distributions in drainage geochemical samples, especially As, Sb, Bi and locally Mo, Ag, Cu, Pb and Zn.

iii. geophysics: lineations derived from regional aeromagnetic and gravity survey data; residual magnetic and Bouguer gravity anomalies from the same datasets.

iv. remote-sensing: lineations taken from satellite images and topographic maps.

v. mineral occurrences: metalliferous mineralisation in bedrock and in mine workings; incidence of alluvial gold grains in heavy mineral concentrates.

The results show that a number of areas meet the criteria set for the occurrence of epithermal or mesothermal gold. It must be emphasised that no follow-up field work has been possible to prove the existance of epithermal mineralisation on the ground at these localities. It should also be emphasized that the exploration criteria utilised are the most logical from the information available for the mineralisation models used. They are not based on information deduced from existing mineralisation in the area, because none has been reported so far.

The prospectivity analysis in Figure 6.16 shows that the most favourable areas are generally dominated by the intersection of lineaments. This is not surprising, as structural controls exert important influence on the location of both epithermal and mesothermal gold mineralisation. It is encouraging that gold occurrences also occur in most of the target areas. MRP and G-BASE sampling has provide most of the recorded occurrences.

8 Conclusions

1. A wide range of metallic mineral deposit types are present in the Northern Highlands, represented by more than 300 known occurrences. Those with potential for the discovery of economic mineralisation include: PGE in basic and ultrabasic igneous rocks; VMS base and precious metal mineralisation associated with volcanic and sedimentary rocks; and gold in epithermal and mesothermal vein deposits.
2. Minor mineral occurrences include widespread low-grade uranium mineralisation in Caithness and Orkney, baryte and base metal vein mineralisation at Strontian, low-grade disseminated tin mineralisation at Carn Chuinneag and numerous minor lead and copper veins. These occurrences have little economic potential.
3. Areas prospective for PGE are restricted to small areas of the Loch Ailsh and Loch Borralan complexes and the Unst ophiolite, Shetland.
4. In contrast, gold mineralisation of epithermal and mesothermal types may occur more widely in the Northern Highlands. Deposits of this type tend to be small and high-grade. This reduces the capital expenditure required for development and minimises the mine's environmental 'footprint'. They are therefore particularly amenable to exploration and development by small companies. Examples of recent discoveries of this type elsewhere in the UK include the Cononish deposit near Tyndrum in central Scotland and the Cavanacaw and Curraghinalt deposits near Omagh, Co. Tyrone in Northern Ireland. These deposits contain resources ranging from 500 000 to 2 million tonnes with gold grades of between 7 and 10 grams per tonne and accompanying high silver values. Cononish and Cavanacaw have received full planning permission for development of an underground and open-pit gold mine respectively.
5. Prospectivity mapping using Arc-SDM and based on the integrated analysis of multivariate regional digital datasets available from BGS databases, has identified eight new target areas varying in size from 35 km^2 to 150 km^2 in the region. Five of these new target areas have few environmental constraints and are, therefore, recommended for follow-up surveys. They are located mainly in the north of the region. The target areas cover 2.7 % of the total area investigated.
6. Knowledge-based prospectivity mapping using GIS technology provides a powerful technique for identifying and ranking exploration targets. However, this analysis is critically dependent on the availability of relevant, high-quality digital data and well-founded mineral deposit models. The analysis should not be regarded as producing final, definitive maps: as more data becomes available and our understanding of the genesis of mineral deposits improves, so the analysis can be reworked and improved.
7. Improved knowledge of the prospectivity of a region can increase inward investment by mineral exploration companies. Exploration is a global industry and the relative attractiveness of different areas, commodities and deposit types is frequently monitored. Rapid access to information is vital in enabling companies to make exploration investment decisions.

9 Recommendations

1. Follow-up surveys are recommended over the new targets, A, D, E, G and H which extend over areas between 35 and 158 km^2. The investigations should include detailed geological mapping and alteration studies using mineralogical and geochemical techniques. Detailed drainage and overburden sampling should also be carried out together with ground geophysical surveys to investigate the extent and form of hydrothermal alteration. The areas B, C and F have severe environmental constraints and are therefore likely to be inaccessible to commercial development.

2. The methodology used in this study can be applied elsewhere in Britain. Knowledge-based prospectivity mapping is a powerful generic tool which can increase exploration efficiency by focusing expensive field programmes. It can be used to map the potential for the occurrence not only of epithermal gold mineralisation, but also of a wide range of other mineral-deposit types.

3. Knowledge-based systems are dependent on the availability of appropriate expertise and well-founded deposit models for their effective application. Continued research on mineral-deposit genesis is required in order to define more reliable exploration criteria and hence to apply the methodology with greater confidence to a range of deposit types, both in the UK and overseas.

4. Prospectivity analysis requires high-quality, relevant digital datasets such as those held in various national geoscience databases by BGS. The continued maintenance and enhancement of these databases are therefore vital. Digitising of archived paper records should continue to ensure their long-term availability for strategic applications such as mineral-potential mapping.

5. The application of new technologies (e.g. PIMA, 3-D modelling) and genetic concepts to existing datasets or archived reference materials is recommended practice. This may provide significant additional information and new insights into the processes responsible for mineralisation and the location of deposits.

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Appendix 1 Mineral localities in the Northern Highlands

MOD ID	Occurence Name	Easting	Northing	Elements / commodity of interest	Style	Occ. Type
5275	Achanarras	314900	954600	Pb	Vein/Lode form	7
30208	Achfarry	229200	941600	Mo	Vein/Lode form	7
30245	Achvarasdal	298600	964700	Fe	Breccia infill	8
30113	Aith Voe 1	444300	1128300	Ankerite	Vein/Lode form	7
30129	Aith Voe 2	442200	1129100	Co, Ni	Unclassified	8
30121	Aith Wick	444500	1129700	Cu	Vein/Lode form	7
3793	Akers Houll	454400	1199920	Au	Placer	6
3510	Allt Airigh Chearnachain	184710	820320	Au	Placer	6
3204	Allt an Fhionnfhuaraidh	290500	923800	Au	Placer	6
3208	Allt Breacich or Allt Breac	295400	920000	Au	Placer	6
3515	Allt Cathair Bhan 1	232770	912380	Au	Placer	6
30327	Allt Cathair Bhan 2	233100	912450	PGE	Unclassified	6
3507	Allt Coire Thorrlaich	189460	819740	Au	Placer	6
3508	Allt Coire Thorrlaich	189390	819640	Au	Placer	6
3209	Allt Duibh or Duible Burn	292700	920500	Au	Placer	6
3509	Allt Grannda	190400	818040	Au	Placer	6
30269	Allt Iarairiah	232600	817100	Pb, Zn	Vein/Lode form	7
3506	Allt Lionagan	189190	818680	Au	Placer	6
5382	Allt nam Ba	140820	794500	Cr	Layer/cumulate	2
30310	Allt nam Ba	140700	794500	Ni, Cu, Cr, Au and PGE	Layer/cumulate	2
30303	Allt nam Peathrain	219100	810900	Pb, Ba	Breccia infill	8
3207	Allt Torrish	296500	921000	Au	Placer	6
3008	Allt-Smeoral	283500	913500	Au	Placer	6
30299	Ardross Castle	260500	873900	Fe	Vein/Lode form	5
30244	Arkle	231500	942600	Au	Placer	6
30235	Armadale Burn 1	279800	962900	Cu	Unclassified	8
30236	Armadale Burn 2	279800	963100	Cu	Unclassified	8
30212	Arscaig	250900	914000	Mo	Unclassified	8
30308	Askival	139000	795000	Cr	Vein/Lode form	2
30227	Aultnager Lodge	257800	899100	Fe	Unclassified	8
5293	Bad an Dobhrain	166400	774400	Pb	Unclassified	8
30209	Badnabay	221400	946000	Mo	Vein/Lode form	7
30305	Bail an Or	291300	921300	Au	Placer	6
30226	Balblair Wood	258500	895000	Pb, Ba	Unclassified	8
5375	Barrapol	95220	742205	Fe	Layer/cumulate	2
30196	Bay of Clachtoll	204100	926700	Cu	Unclassified	8
30164	Bay of Creekland	323700	1004400	Fe	Vein/Lode form	7
30160	Bay of Navershaw	326500	1008900	Pb	Disseminated	5
30194	Bay of Stoer	203600	927200	Fe, Cu	Bed	8
30329	Bearreraig River	151700	852800	Fe	Stratabound	8
5377	Beinn a Chaisil	178200	747690	Pb, Zn	Unclassified	8
30330	Beinn an Dubhai	158900	820400	Fe, Cu	Replacement (skarn)	4
5374	Bellsgrove Lodge	182400	765200	Pb	Vein/Lode form	7
5715	Bellsgrove or Corrantee or Middleshop	183100	765800	Pb, Ag, Ba, Zn	Vein/Lode form	7
30232	Ben Loyal 1	261500	946000	Th	Unclassified	8
30233	Ben Loyal 2	256900	948700	U	Unclassified	8
30112	Beosetter, Bressay	449200	1144300	Ca	Vein/Lode form	7
30117	Bight of Vatsland	446700	1146200	Cu	Vein/Lode form	7
30126	Bight of Vatsland	446700	1145800	Pb	Unclassified	8
30169	Blackhall	323800	1014500	U	Unclassified	5
3007	Blackwater	273500	917000	Au	Placer	6
30231	Blackwater River 2	282300	911600	Pb	Unclassified	8

30241	Blackwater River 3	271400	918200	Au	Placer	6
30242	Blackwater River 4	269200	916500	Au	Placer	6
30255	Blar Cnoc na Gaoith	300510	962320	Mo, Ag, Pb, Zn, Cu, Ba and U	Unclassified	5
30131	Blue Geo	443800	1124700	Cu	Unclassified	8
30183	Borve	102900	894900	Sulphides	Unclassified	8
30256	Brawlbin	306000	956000	Mo, Ag, Pb, Zn, Cu, Ba and U	Unclassified	5
30111	Brei Wick	447700	1140500	Ca	Vein/Lode form	7
3000	Breiwick	463600	1217700	Au	Placer	6
30252	Bridge of Westfield	305900	963900	Cu, Pb, Zn, U	Breccia infill	8
30313	Brora	290000	904000	Coal	Bed	8
30251	Broubster	301900	962400	U	Vein/Lode form	7
5289	Bualoinn	218200	806500	Pb	Unclassified	7
3804	Burn of Breitoe	440500	1125430	Au	Placer	6
3806	Burn of Fitch	442630	1139390	Au	Placer	6
3792	Burn of Gutcher 1	452830	1200420	Au	Placer	6
3794	Burn of Gutcher 2	452970	1200720	Au	Placer	6
3795	Burn of Gutcher 3	465640	1216280	Au	Placer	6
3796	Burn of Skaw	465120	1216120	Au	Placer	6
3799	Burn of Voesgarh 1	461310	1206630	Au	Placer	6
3801	Burn of Voesgarh 2	461680	1208030	Au	Placer	6
3813	Burragarth	458000	1203250	Au	Placer	6
30258	Caen Burn 1	302000	919000	U	Unclassified	8
30261	Caen Burn 2	301600	918900	Pb, Mo, Zn, As	Unclassified	8
30276	Carn Chuinneag 1	247100	884500	Fe	Layer/cumulate	8
30277	Carn Chuinneag 2	246500	883800	Sn	Vein/Lode form	7
30278	Carn Chuinneag 3	246300	887100	Pb	Vein/Lode form	7
30279	Carn Chuinneag 4	248600	887900	Cu, Mo	Breccia infill	8
30324	Carr Brae	190140	824650	Fe (Au?)	Stratabound	8
5276	Castle of Old Wick	337000	948800	Cu	Unclassified	8
5290	Ceanacroc	219000	811000	Pb	Unclassified	7
30262	Ceann Ousdale	307600	918500	Pyrite-Qtz	Breccia infill	8
30306	Cill Chroisd	161800	820700	Fe	Replacement (skarn)	4
30152	Cleber Geo	437800	1194300	Soapstone	Unclassified	8
30145	Clibberswick	465200	1212100	Talc	Unclassified	8
30094	Cliff	460770	1211416	Cr PGE	Layer/cumulate	2
30098	Clothister Hill	434200	1172900	Fe	Lensoid	8 or 4
3203	Clyne-Milton Burn	289600	908000	Au	Placer	6
30264	Cnoc na Stri	307000	918000	U, As, W, Mo and Be	Disseminated	8
30109	Colla Firth	435700	1184400	Serpentine	Unclassified	8
5355	Copper Geo	420300	1072800	Cu	Vein/Lode form	7
30290	Coulags	195700	846200	Fe	Unclassified	8
3206	Craggie Water / Craggie Burn	287600	919700	Au	Placer	6
3205	Crask	294500	917500	Au	Placer	6
30237	Creag Dalveghouse	271200	955800	Cu, Mo	Unclassified	8
30302	Creag nan Damh	198400	811700	Qtz	Breccia infill	8
5298	Croggan	170700	727300	Pb	Unclassified	7
30122	Croo Tang	442900	1126900	Cu	Vein/Lode form	7
30260	Culgower Burn	297000	912000	U	Unclassified	8
30148	Cunningsburgh	442500	1127100	Talc	Unclassified	8
30154	Dale	437200	1148200	Kaolin	Replacement	8
5282	Dalelea	272300	869400	Pb	Unclassified	7
5294	Dalelea	173500	769400	Pb	Unclassified	7
3790	Dales Voe	445730	1145310	Au	Placer	6
3817	Dales Voe	445000	1144590	Au	Placer	6
30127	Dales Voe 1	445600	1145500	Zn	Unclassified	8
30128	Dales Voe 2	445500	1145000	Zn	Unclassified	8
5347	Deerness Hyso	357200	1008700	Pb, Au	Unclassified	8
30312	Dididii River	140000	792500	Cr	Unclassified	8
30283	Dochfour Burn	260800	840200	Cu, Pb, Mo	Replacement	8

3011	Dornie	189530	824320	Au ?	Unclassified	8
30125	Durey Voe	444600	1148600	Pyrite	Stratabound	8
3003	Durness	241000	967600	Au	Unclassified	8
30108	Duttfield	422200	1072200	Cu	Unclassified	8
30116	E. Fetlar	467000	1191400	Fe	Unclassified	8
3807	Easter Loch	460120	1201310	Au	Placer	6
30114	Eastern Fetlar	465600	1191300	Ankerite	Vein/Lode form	7
30189	Eilean Mhuire	143200	899200	Fe	Unclassified	8
30178	Eilean Glas	124600	894900	Talc	Unclassified	2
5292	Eilean Shona	165200	775000	Pb	Unclassified	8
30137	Esha Ness	420300	1178000	Agate	Unclassified	8
30272	Falls of Rogie 1	244600	858400	Cu	Unclassified	8
30273	Falls of Rogie 2	244200	858600	U, Cu	Unclassified	7
5718	Fee Donald	186200	766500	Pb, Ag, Ba	Vein/Lode form	7
30191	Foindle	218000	948000	Cu, Ni	Layer/cumulate	3
3009	Gairloch 1	183980	872200	Cu, Zn, Au	Stratabound	3
30314	Gairloch 2	183800	872300	Cu, Zn, Au	Stratabound	3
30315	Gairloch 3	183500	874500	Cu, Zn, Au	Stratabound	3
30316	Gairloch 4	183950	870100	Cu, Zn, Au	Stratabound	3
30317	Gairloch 5	184750	869600	Cu, Zn, Au	Stratabound	3
30318	Gairloch 6	182400	873400	Cu, Zn, Au	Unclassified	3
30319	Gairloch 7	180650	876650	Cu, Zn, Au	Unclassified	3
30320	Gairloch 8	181200	877400	Cu, Zn, Au	Unclassified	3
3810	Gallow Hill	457100	1201330	Au	Placer	6
5373	Garbh Bheinn	191780	761810	Ba, Pb	Unclassified	8
30172	Garthna Geo	322000	1015180	U, P	Unclassified	5
5353	Garthsness	436800	1112700	Cu	Lensoid	3
30259	Gartymore Burn	298000	915000	U	Unclassified	8
3800	Gerragarth	461320	1209780	Au	Placer	6
5280	Glen Calvie	246300	887100	Pb	Unclassified	7
5281	Glen Diebidale	247200	884300	Sn	Unclassified	7
5372	Glen Fordan-Loch Shiel	177000	771100	Cu, Ni	Unclassified	8
30298	Glen Glass	254900	867700	Pb	Vein/Lode form	7
30268	Glen Moriston	236070	817710	Cu, Pb, Zn, Ag	Multiple	8
30335	Glen Moriston 2	232960	817100	Pb, Zn	Vein/Lode form	7
30338	Glen Oykel 1	231150	909000	Au	Unclassified	8
30339	Glen Oykel 2	231725	909000	Au	Unclassified	8
3012	Glenelg	184300	820100	Rare pyroxenes	Unclassified	8
30247	Glenuisg Geo	301100	969500	Cu, Pb, Zn	Vein/Lode form	7
3816	Gossawater Burn	443550	1161730	Au	Placer	6
30225	Grudie Burn	255300	905800	Mo, Bi, W	Vein/Lode form	7
30213	Grudie granite 1	255200	903400	Cu, Pb	Vein/Lode form	7
30214	Grudie granite 2	254700	903500	Pb, Ba	Multiple veins	7
30215	Grudie granite 3	251400	904400	Mo	Vein/Lode form	7
30216	Grudie granite 4	251500	905200	Mo	Vein/Lode form	7
30217	Grudie granite 5	252900	903400	Cu, Bi, Mo	Vein/Lode form	7
30218	Grudie granite 6	252700	903400	Cu, Bi, Mo	Vein/Lode form	7
30089	Hagdale	463800	1210200	Cr PGE	Layer/cumulate	2
5383	Hallival	139300	796680	Cr	Unclassified	2
30090	Hamarberg	459600	1203700	Dolomite	Unclassified	2
30096	Hamnavoe	450300	1179800	Pb	Vein/Lode form	7
5338	Hardhill	339800	1012900	Pb	Vein/Lode form	7
30095	Harold's Grave	462929	1211274	PGE	Layer/cumulate	2
30311	Harris	133500	793700	Cr	Unclassified	8
5385	Harris Bay	134000	795600	Cr	Unclassified	8
30146	Hesta Ness	466200	1192500	Talc	Unclassified	8
30147	Hesta Ness	466300	1192700	Cr	Unclassified	8
30246	Hill of Sour	311500	961300	Pb, Ba	Vein/Lode form	7
30133	Hirdie Geo	414900	1160800	Ba	Unclassified	8
30132	Honga Ness	465500	1191300	Cu	Unclassified	8
30106	Hoswick	441800	1123700	Cu, Fe ?	Unclassified	8

30257	Houstry of Dunn	320000	954000	Mo, Ag, Pb, Zn, Cu, Ba and U	Unclassified	8
30280	Inchbae	237400	871100	Mo	Unclassified	1
5288	Inchnacardoch	238100	810300	Pb	Unclassified	8
30307	Kilbride	158900	820400	Fe	Replacement (skarn)	4
3227	Kilcalmkill	284500	909800	Au	Placer	6
30334	Kilchoan	148500	763500	Rare silicates	Replacement	4
3579	Kildonan	302100	916200	Au	Vein/Lode form	7
3004	Kildonan Burn	291700	922000	Au	Placer	6
5283	Kiltearn	254000	867000	Pb	Vein/Lode form	7
3210	Kinbrace Burn	289600	929000	Au	Placer	6
30135	Kirk sand	417800	1159800	Ba	Unclassified	8
30297	Knoydart	178800	796100	Be	Vein/Lode form	7
5350	Lang Taing	345600	995600	Cu	Vein/Lode form	7
30265	Langwell Valley	308800	922600	U	Unclassified	5
30184	Laxadale Burn	119500	902200	Sulphides	Unclassified	8
30163	Lead Geo	318600	1003200	Mn	Unclassified	8
30150	Leagarth	462800	1190400	Talc	Unclassified	2
30285	Learnie	275000	861000	Cu, Pb	Breccia infill	8
30200	Ledmore	224000	911000	Cu	Unclassified	2
30267	Letterewe House	195905	872440	Pb	Vein/Lode form	7
30105	Levenwick	440900	1121700	Cu, Fe ?	Unclassified	8
30201	Loch Ailsh 1	232700	912300	Cu	Unclassified	1
30202	Loch Ailsh 2	232800	912400	Cu	Unclassified	1
30203	Loch Ailsh 3	232500	912700	Cu, Pb	Unclassified	1
30204	Loch Ailsh 4	232900	912200	Pb	Vein/Lode form	7
30205	Loch Ailsh 5	230100	908700	Pb	Vein/Lode form	7
30206	Loch Ailsh 6	233400	912700	Pb	Vein/Lode form	7
30294	Loch Ailsh 7	181900	828700	Ba	Placer	6
30186	Loch Airligh Iain Oig	113400	893900	Mo	Vein/Lode form	8
30177	Loch a'Sgurr	100600	886000	U, Th	Vein/Lode form	7
30182	Loch Bearasta Mor	112400	894800	Sulphides	Unclassified	7
30301	Loch Bruicheach	246000	836600	Ba, F	Vein/Lode form	7
30291	Loch Carron	198000	846400	Pb	Disseminated	8
30188	Loch Cleit a Ghuib Choille	131200	909700	Olivine	Unclassified	8
30336	Loch Cluanie	219000	810900	Pb	Vein/Lode form	7
30240	Loch Crocach	264500	959400	Cu, Mo	Unclassified	8
30292	Loch Dughaill	197800	846100	Ba	Placer	6
5287	Loch Duich Trials	189500	824300	Au, Ag (Cu, Ni)	Unclassified	8
30266	Loch Gharbaig 1	199590	871020	Pb, Zn, Cu	Vein/Lode form	7
30325	Loch Gharbaig 2	198758	871420	Cu, Pb, Ni, Ag, As, Zn, Sb, U	Vein/Lode form	7
30197	Loch Kirkaig	207300	917800	Fe, Cu	Unclassified	8
30304	Loch Lochy	210900	802900	Pb, Zn	Vein/Lode form	7
30234	Loch Loyal	262300	950700	Ba, Sr	Unclassified	8
30293	Loch Maree	201700	863100	Ba	Placer	6
30326	Loch Maree	193360	872680	Ag?	Vein/Lode form	7
5371	Loch Moidart	167000	774200	Pb	Unclassified	7
30321	Loch na Beinne 1	190164	863468	Au, Cu	Unclassified	8
30322	Loch na Beinne 2	190164	863467	Au	Unclassified	8
30323	Loch na Beinne 3	190139	863486	Au	Unclassified	8
30192	Loch na Claise Fearna	220000	946000	Cr, Ni	Unclassified	3
30254	Loch nan Clachan Geala	300900	958800	Pb	Unclassified	8
3814	Loch of Bottoms	432780	1164450	Au	Placer	6
3798	Loch of Cliff	460480	1211030	Au	Placer	6
3809	Loch of Stour	458220	1201800	Au	Placer	6
30190	Loch Roag	109400	933300	Saphire / Diamonds	In high-level felsic plutons (porphyry)	8
30219	Loch Shin 1	256300	906600	Zn, Cu, Pb	Multiple	7
30223	Loch Shin 2	252200	912200	Cu	Unclassified	8
30224	Loch Shin 3	250700	914300	Cu	Unclassified	8
30239	Lochan Leacach	268700	957500	Cu, Mo	Unclassified	8
30199	Lochinver 1	207400	921000	Pyrrhotite	Unclassified	8

30210	Lochinver 2	207600	918400	Ba, Fe	Unclassified	8
3815	Long Loch	443450	1159600	Au	Placer	6
5296	Lurga	173400	755500	Pb, Zn	Unclassified	8
30138	Maa Loch	429700	1160400	Serpentine	Unclassified	8
30175	Market Stance	80600	853700	Cu, Co (Au)	Layer/cumulate	2
30141	Mavis Grind	434100	1168200	Scapolite	Vein/Lode form	7
5714	Middleshope	183000	764900	Pb	Unclassified	8
30166	Mill Bay	365600	1026700	Pb, Ba	Vein/Lode form	7
30167	Mill of Cairston	325800	1010800	U, P, Zn, Ba, Mo	Breccia infill	7
3802	Mill of Llibberswilk	464550	1212790	Au	Placer	6
30130	Mo Geo	444300	1128300	Cu	Unclassified	8
30284	Moniack Burn	255000	840000	U, Th	Breccia infill	8
30155	Moo Wick	462200	1187700	Kaolin	Replacement	8
5279	Morven or Morvern	300500	928500	Au	Unclassified	8
30118	Muckle Hell	452600	1140000	Cu	Vein/Lode form	7
30091	Muckle Hoeg	462730	1210500	Cr PGE	Layer/cumulate	2
30250	Murkle Bay	317200	969300	U (Cu)	Vein/Lode form	7
30107	N and S Reevas	420000	1070900	Cu	Unclassified	2
30110	Nabb of Lerwick	447900	1140300	Calcite	Vein/Lode form	7
30159	Ness of Ramnageo	462710	1199670	Au	Unclassified	8
30088	Nikka Vord	462500	1210300	Cr	Layer/cumulate	2
30124	No Ness	444500	1121200	Cu	Vein/Lode form	7
30248	North Head	338200	950900	Cu, Pb, Ba	Breccia infill	8
5335	North Hill	370200	1042200	Pb	Vein/Lode form	7
30115	North Roe	438600	1193600	Fe	Unclassified	8
30142	North Roe	433000	1190000	Riebeckite	Vein/Lode form	7
30171	Northern Hoy	326100	1002600	U? Ba	Vein/Lode form	5
5278	Occumster	328800	936000	Ba	Vein/Lode form	7
3001	Ollaberry	436600	1180600	Au	Vein/Lode form	7
30263	Ousdale Burn	306500	920100	Ba, F	Vein/Lode form	7
30193	Poll Inornail	226000	949000	Cu, Ni, Cr	Unclassified	2
30300	Port an Righ	285100	872800	Pb, Zn	Vein/Lode form	7
5297	Port Mine or Crossapol	113005	752930	Ti	Layer/cumulate	2
5354	Quendale	436000	1112000	Cu	Unclassified	8
30195	Quinag	220000	926000	Cu	Unclassified	8
30092	Quoys	461400	1212266	Talc, Mo	Vein/Lode form	7
30093	Quoys West	461600	1212200	Cr PGE	Layer/cumulate	2
30328	Raasay	159000	836000	Fe	Stratabound	8
30173	Rackwick	320300	999300	Ca	Vein/Lode form	7
3812	Ramna Geo	462070	1200220	Au	Placer	6
5285	Rassal	184800	843200	Cu	Vein/Lode form	7
30287	Rassal 2	184000	840500	Cu	Vein/Lode form	7
3010	Ratagain	189600	820000	Cu, Pb, Zn, Ag, Mo	Vein/Lode form	1
30281	Ratagain	193800	819700	Mo	Vein/Lode form	1
30282	Ratagan Village	192300	818800	Sr	Unclassified	1
30198	Rhiconich	225000	952000	Cu	Vein/Lode form	7
3006	River Helmsdale	302800	915100	Au	Placer	6
30337	River Nairn	276700	844700	Mn	Layer/cumulate	8
30151	Robis Geo	461500	1190300	Soapstone	Unclassified	8
30176	Rodel	105000	883000	Pyrrhotite	Unclassified	8
30229	Rosehall	247700	902700	Pb, Ba	Unclassified	8
5337	Rousay	337700	1031200	Cu, Pb	Unclassified	7
5345	Rousay	325000	1004000	Pb	Vein/Lode form	7
30162	Rousay	338700	1028500	Cu	Vein/Lode form	7
5277	Roy Geo	327000	935200	Cu	Unclassified	8
30187	Rubha Cheit	129800	908400	Olivine	Unclassified	8
30119	Rules Ness	452900	1142600	Cu	Vein/Lode form	7
5284	Sanachan	184100	840600	Cu	Unclassified	8
30289	Sanachan	183900	840500	Fe	Unclassified	8
5352	Sandlodge	443800	1124800	Cu	Vein/Lode form	7
30174	Sands Geo	326600	988700	Ba	Vein/Lode form	7

30331	Scardroy 1	223870	848110	Au	Placer	6
30332	Scardroy 2	225190	853680	Au	Placer	6
30333	Scardroy 3	216770	851770	Cu	Placer	6
30134	Scarvi Taing	417500	1159300	Agate, Ba	Unclassified	8
5340	Selwick	323000	1005000	Pb, Ag, Ba	Unclassified	7
5341	Selwick hoy	323100	1005400	Pb, Ag	Unclassified	7
30101	Setter 1	449200	1191400	Cu	Unclassified	7
30103	Setter 2	443500	1125600	Cu	Vein/Lode form	7
30123	Sevenwich Ness	441700	1121400	Cu	Vein/Lode form	7
3811	Shetland	458630	1202790	Au	Placer	6
30220	Shin Granite 1	255800	906900	Cu, Pb	Breccia infill	1
30221	Shin Granite 2	255400	907200	Cu, Pb	Breccia infill	1
30222	Shin Granite 3	255700	907900	Cu, Pb	Breccia infill	1
30211	Shin Limestone	252200	913800	Mo	Unclassified	2
30228	Shin Valley 1	255000	905500	Ba, Fe	Unclassified	8
30270	Shin Valley 2	263000	902200	Ba, Fe	Unclassified	8
30271	Shin Valley 3	263500	899600	Ba, Fe	Unclassified	8
30253	Shurrery	302700	954300	Cu	Unclassified	8
5336	Silver Mine	337200	1030700	Pb, Ag	Unclassified	7
30139	Skelda Ness	430300	1140500	Scapolite	Vein/Lode form	7
30243	Skinsdale	275700	919700	Au	Placer	6
30179	Sletteval ridge	105000	891000	U, Th	Vein/Lode form	1
5348	South Ronaldsay	347300	992050	Pb	Vein/Lode form	7
30170	Sowa Dee	323200	1014500	U	Unclassified	5
30149	Stackaberg	461300	1192800	Talc	Unclassified	2
30249	Staxigoe	338700	952400	Pb, Zn, Ba	Breccia infill	8
30136	Stenness	421400	1177200	Agate, Ba	Unclassified	8
30309	Storr	150000	853000	Cu	Unclassified	8
3577	Strath Ullie	295500	918400	Au	Placer	6
30274	Strathcomair	186900	815800	Pb, Ag	Vein/Lode form	7
5339	Stromness	321900	1015500	Cu, Ba	Vein/Lode form	7
5342	Stromness	323500	1008700	Pb	Vein/Lode form	7
5343	Stromness / Stromness Lead / Stromness Head	323700	1008800	Pb	Vein/Lode form	7
5710	Strontian	180600	765400	Pb	Unclassified	7
5717	Strontian or Sunart	184000	766000	Zn, Ag, Pb	Unclassified	7
5286	Struy	237500	838100	Pb, Ag	Vein/Lode form	7
30286	Struy Bridge	239000	839000	Be	Vein/Lode form	7
5709	Suidhe	180200	765800	Pb	Unclassified	8
3580	Suisgill	290100	926200	Au	Vein/Lode form	7
3005	Suisgill Burn	289900	925800	Au	Placer	6
30144	Swart Houll	464400	1191800	Diopside	Vein/Lode form	7
30157	Swinna Ness	465300	1209300	Talc	Unclassified	8
3805	Swinster	441690	1124980	Au	Placer	6
30153	Tactigill	437300	1151600	Kaolin	Replacement	8
3791	Tagdale	445180	1144480	Au	Placer	6
30156	Taing of Norwick	465200	1214600	Talc	Vein/Lode form	7
30185	Tarbert	115300	900000	Mo	Vein/Lode form	7
30180	Tarbert pier	115800	899800	Mo	Unclassified	8
30165	The Candle of the Sale	327300	1001700	Fe	Vein/Lode form	7
30238	Tom Apigill	270600	957400	Cu, Mo	Unclassified	8
3803	Tongue Field	441780	1130920	Au	Placer	6
30288	Tornapress	184100	842300	Fe	Unclassified	8
30143	Tressa Ness	461700	1194800	Rodingite	Vein/Lode form	7
3808	Trolla water	461400	1209150	Au	Placer	6
30230	Tullich	252000	900200	Pb, Ba	Unclassified	8
30181	Uamasclett	113000	899400	Sulphides	Unclassified	8
3002	Unst	460000	1210000	Au	Placer	6
30084	Vidlin locality 1	448150	1166760	Cu, Pb, Zn	Stratabound	3
30085	Vidlin locality 2	448100	1166610	Cu, Pb, Zn	Stratabound	3
30086	Vidlin locality 3	448070	1166510	Cu, Pb, Zn	Stratabound	3

30087	Vidlin locality 4	448010	1166340	Cu, Pb, Zn	Stratabound	3
30161	Walliwall Quarry	343300	1010400	Pb	Vein/Lode form	7
5344	Warebeth	323500	1008700	Ba, Pb	Vein/Lode form	7
5384	West Rhum	134800	796200	Cr	Unclassified	2
30097	West Sandwick	444100	1190200	Mica	Vein/Lode form	7
5711	West Whitesmith	182300	766000	Pb	Vein/Lode form	7
30140	Wester Wick	428600	1142300	Scapolite	Vein/Lode form	7
30120	Western Noss	453200	1140500	Cu	Vein/Lode form	7
5349	Wha Taing	344500	996100	Cu (U)	Vein/Lode form	7
5346	Whitehouse	326100	1010500	Pb	Vein/Lode form	7
5713	Whitesmith	182500	766200	Pb	Vein/Lode form	7
5716	Whitesmiths or Corrantee or Bellsgrove	183000	766000	Pb, Zn, Sr, Ba, Ag	Vein/Lode form	7
3797	Wick of Grutting	464150	1191970	Au	Placer	6
30104	Wick of Shunni	435000	1115000	Cu	Vein/Lode form	7
5376	Wilderness	140400	728800	Cu	Unclassified	8
30168	Yesnaby	322400	1015900	U, (P)	Disseminated	5

Explanation of Occurrence Type

1. Occurrences associated with acid and intermediate intrusions
2. Occurrences associated with mafic and ultramafic complexes
3. Volcanogenic Massive Sulphide (VMS) deposits
4. Skarn-type occurrences
5. Occurrences associated with Devonian sedimentary and volcanic rocks
6. Alluvial occurrences
7. Vein occurrences
8. Other occurrences

Appendix 2 Fieldwork sampling

Stream sediment samples

Sample No	Easting	Northing	Mo ppm	Cu ppm	Pb ppm	Zn ppm	Ag ppm	Ni ppm	Co ppm	Mn ppm	Fe %	As ppm	U ppm	Au ppb	Th ppm	Sr ppm	Cd ppm	Sb ppm	Bi ppm	V ppm	Ca ppm	P %	La ppm	Cr ppm	Mg %	Ba ppm	Ti %	B ppm	Al %	Na %	K %	W ppm	Hg ppm	Sc ppm	Tl ppm	S %	Ga ppm
NHC 1	254975	920556	0.7	11.4	9.8	28	< .1	14.9	6.7	719	2.07	5.2	1.3	2.6	6.1	23	< .1	0.1	0.5	45	0.58	0.165	41	33.7	0.4	76	0.121	1	0.51	0.023	0.12	0.1	< .01	2.1	0.1	< .05	3
NHC 2	256395	920720	0.7	11.4	25.1	59	< .1	18.8	15.3	3214	3.6	5.3	2.6	5.7	7.1	39	0.1	0.4	0.1	51	0.65	0.17	29	34.1	0.54	81	0.119	1	0.9	0.025	0.16	< .1	0.03	2.2	0.2	0.07	5
NHC 4	257161	922783	0.3	4.1	22.2	97	< .1	17.9	14.4	2907	3.53	7.3	10.8	1	15.7	38	0.2	0.2	0.1	54	0.62	0.139	55	30.5	0.73	78	0.171	2	1.39	0.023	0.19	< .1	0.03	3.5	0.2	0.12	10
NHC 5	257609	923035	0.1	3.2	14.1	49	< .1	10.2	7.4	982	1.58	3.6	2.7	< .5	7.9	19	0.1	0.1	< .1	29	0.28	0.055	29	17.9	0.4	34	0.108	1	0.74	0.027	0.11	< .1	0.02	1.8	0.1	< .05	5
NHC 6	258919	921792	0.4	14.9	18.9	86	< .1	16	13.3	1487	2.8	5.1	3.3	< .5	20	27	0.1	0.4	0.1	48	0.32	0.102	46	23.4	0.56	122	0.166	2	1.52	0.023	0.41	< .1	0.01	3.2	0.4	< .05	9
NHC 7	259509	920937	0.2	6.2	10.6	42	< .1	9.3	6.3	777	1.59	3.8	9.3	3.2	8.9	19	0.1	0.2	< .1	25	0.34	0.108	34	13.4	0.28	60	0.094	1	0.72	0.016	0.19	< .1	< .01	1.9	0.1	< .05	4
NHC 8	261880	919934	0.3	8.9	24.6	61	0.1	9.1	9.7	1354	2.08	2.6	5.2	3.1	12.8	50	0.3	0.2	0.1	45	0.57	0.134	66	24.5	0.44	99	0.118	5	1.28	0.03	0.26	< .1	< .01	1.8	0.2	< .05	7
NHC 9	261622	921647	0.2	11.9	15.5	65	< .1	10.6	8.5	1266	1.78	3	2.6	3.5	8.9	33	0.1	0.5	0.1	29	0.45	0.085	28	22.9	0.38	81	0.114	< 1	0.89	0.025	0.23	< .1	0.02	2.1	0.2	0.13	5
NHC 10	261904	921342	0.5	8.8	18.2	60	< .1	13.2	13.6	1832	2.31	4.4	4	0.7	18.3	34	0.2	0.3	0.1	40	0.41	0.132	62	26.1	0.44	106	0.127	1	1.31	0.045	0.32	< .1	0.02	3.2	0.2	< .05	7
NHC 11	261644	921688	0.4	9.6	19.9	72	< .1	13.9	13.1	1766	1.94	4.1	2.5	1.9	12.3	27	0.2	0.6	0.1	36	0.4	0.085	36	21.4	0.4	77	0.146	1	1.09	0.024	0.28	< .1	0.03	2.7	0.3	< .05	6
NHC 12	261854	920776	0.4	6.2	19.5	52	< .1	11	12.6	2132	2.34	4	2.7	0.5	12.3	38	0.2	0.2	0.1	34	0.44	0.122	35	20.1	0.4	94	0.126	2	1.01	0.028	0.27	< .1	0.03	2.5	0.2	< .05	6
NHC 13	261773	921654	0.3	5.1	25	60	< .1	14.1	17.2	1623	2.69	3.4	1.9	< .5	11.3	29	0.2	0.2	0.1	46	0.32	0.087	28	26.5	0.57	108	0.188	< 1	1.31	0.022	0.49	< .1	0.02	3.5	0.4	0.1	8
NHC 14	262966	918753	0.4	10.5	17.2	65	< .1	14.5	11	1833	2.36	4.7	4.7	0.6	18.3	39	0.2	0.2	0.1	40	0.57	0.167	61	28.2	0.49	107	0.137	1	1.28	0.03	0.33	0.1	0.04	3.5	0.2	< .05	7
NHC 15	263076	918137	0.6	10.9	17.5	94	< .1	21	14.1	2079	3	4.2	4.5	1.3	20.9	47	0.2	0.2	0.1	49	0.74	0.23	68	37.2	0.67	128	0.173	1	1.5	0.034	0.42	< .1	0.01	4	0.3	< .05	9
NHC 16	262627	919436	1.2	15.9	20.5	102	< .1	24.9	24.1	5080	6.02	5.5	3.7	2.8	15.9	47	0.2	0.5	0.1	53	0.65	0.176	43	36.9	0.57	170	0.15	2	1.46	0.022	0.44	0.1	0.03	4.4	0.4	< .05	8
NHC 17	263019	918758	0.8	12.2	21.6	82	< .1	45.3	23.6	4417	3.8	4.7	4	1.5	15.7	82	0.2	0.3	0.1	55	1.21	0.47	68	64.7	0.85	156	0.173	2	1.44	0.029	0.4	< .1	0.04	4.5	0.4	< .05	9
NHC 18	263059	919453	0.7	13.4	24.4	69	< .1	28.1	22.9	3510	4.08	5.6	3.2	0.9	16.6	48	0.2	0.3	0.1	57	0.67	0.161	52	45	0.62	147	0.152	2	1.59	0.023	0.37	< .1	0.05	4.5	0.3	< .05	9
NHC 19	263291	919328	0.9	15.8	18.3	79	0.1	67.7	24.6	2557	4.07	4.2	4.6	0.6	16.8	108	0.2	0.1	0.1	68	1.58	0.596	95	92.6	1.11	148	0.106	1	1.83	0.033	0.51	< .1	0.02	5.8	0.4	< .05	10
NHC 20	263050	919913	1.1	18.6	33.5	91	0.1	42.2	32.4	5074	5.13	6.4	4.3	0.6	17.5	57	0.3	0.3	0.1	77	0.77	0.209	53	69.2	0.86	193	0.168	2	1.99	0.026	0.48	< .1	0.02	6.6	0.4	0.13	12
NHC 21	263938	919469	4.4	28.4	24.4	111	< .1	29.1	52.9	15697	2.96	5.5	13.4	2.7	20.1	57	0.3	1.1	0.1	48	0.77	0.161	61	35.7	0.52	436	0.13	2	1.39	0.04	0.35	< .1	0.04	4.3	0.3	< .05	9
NHC 22	263392	917564	2.3	9.4	32.1	109	< .1	16.5	26.3	12432	16.24	10.7	3.9	1.5	10.8	80	0.3	0.5	0.1	119	0.75	0.3	36	30.9	0.43	365	0.123	2	1.22	0.021	0.24	< .1	0.05	4.5	0.4	0.09	9
NHC 23	263114	920045	1.9	35	25.9	169	< .1	47.8	39	4103	6.6	5.4	6.4	2.8	26	43	0.2	0.8	0.1	97	0.67	0.245	63	88.6	1.01	221	0.238	3	2.32	0.032	0.71	< .1	0.02	8.8	0.4	< .05	15
NHC 24	263788	917937	2.2	20.1	49.9	182	< .1	25.9	60.5	29994	10.7	9.7	4.1	1.8	8.4	115	0.9	0.6	0.2	84	1.06	0.209	34	33.1	0.48	595	0.121	4	1.48	0.027	0.32	< .1	0.06	4.4	0.7	0.1	10
NHC 25	263156	920635	0.4	10.5	15.9	58	< .1	33.5	13.7	1412	2.07	3.3	2.4	1.2	9.7	36	0.1	0.2	0.1	45	0.56	0.146	29	69.3	0.79	100	0.18	1	1.31	0.026	0.3	< .1	0.01	3.4	0.3	0.07	8
NHC 27	263237	920650	0.5	4.9	23.8	56	< .1	12.9	14.4	2444	1.98	3.8	1.9	0.5	7.2	33	0.2	0.3	0.1	37	0.36	0.074	24	22.8	0.38	90	0.132	1	0.94	0.026	0.2	< .1	0.04	2.6	0.3	< .05	6
NHC 29	282346	938031	0.4	8.7	18.1	83	< .1	13.9	17	3239	4.09	8.8	7.6	11	12	23	0.2	0.5	0.1	39	0.55	0.128	42	24.7	0.37	248	0.126	3	0.97	0.026	0.25	0.2	0.04	3.1	0.2	< .05	6
NHC 30	282226	938359	0.5	6	33.4	77	0.1	13.4	23.4	8629	3.78	8.6	1.9	58.1	8.9	23	0.3	0.5	0.1	43	0.4	0.108	45	18.5	0.27	175	0.061	3	0.96	0.022	0.15	0.2	0.06	2.1	0.4	< .05	5
NHC 31	282300	939438	0.4	4	13	38	< .1	7.3	6.7	2264	2.34	7.2	2.4	1.3	11.9	18	0.1	0.4	< .1	22	0.3	0.105	42	13.2	0.22	104	0.065	2	0.59	0.03	0.16	0.1	0.02	1.9	0.2	< .05	4
NHC 32	277820	938517	1.2	54	39.9	109	0.1	14.1	11.4	2542	11.02	9.9	11.3	497.2	11	56	0.2	0.9	0.2	72	0.73	0.148	37	26.8	0.48	383	0.129	3	1.26	0.029	0.25	0.1	0.05	3.6	0.3	0.1	6
NHC 33	278707	937669	1.4	6.9	22.8	94	< .1	13.2	22	7495	6.88	6.2	4.8	1.3	11.3	34	0.3	0.4	0.1	52	0.54	0.133	35	23.9	0.41	397	0.132	2	1.11	0.029	0.26	0.1	0.03	3.2	0.3	0.14	6
NHC 34	285986	938943	1.7	4.7	20.6	55	< .1	10	10.2	2019	6.76	13	2.8	27.1	10.1	29	0.2	0.3	0.1	44	0.35	0.133	34	18.3	0.3	84	0.08	2	1.02	0.02	0.15	0.1	0.13	2.5	0.1	< .05	6
NHC 35	285272	940021	1.3	8.9	39.2	42	< .1	14.3	35.4	3102	5.92	11.3	3.4	4.3	15.2	26	0.1	0.5	0.1	73	0.22	0.106	49	28.1	0.35	107	0.107	2	1.37	0.024	0.31	0.1	0.05	3.1	0.3	< .05	6
NHC 36	285073	939495	1.6	6.3	19.6	44	< .1	12.1	20.8	3481	9.81	10.8	2.9	12.8	7	33	0.1	0.3	0.1	70	0.35	0.221	31	22.3	0.27	128	0.069	2	0.75	0.025	0.16	0.1	0.05	2.7	0.2	0.07	4
NHC 37	283117	959933	1.6	8.6	36.4	82	< .1	42.6	18.5	1335	7.69	9.8	1.9	0.6	13.4	35	0.1	0.3	0.1	108	0.36	0.18	48	65.3	1.04	183	0.26	1	1.71	0.022	0.26	0.1	0.05	6.5	0.3	0.17	12
NHC 38	283125	960980	1.2	6.4	79	80	< .1	15.5	84.4	17779	15.2	9.3	1.6	0.7	7.5	42	0.2	0.4	0.2	94	0.54	0.078	30	24.7	0.39	402	0.047	2	0.94	0.021	0.2	0.3	0.17	2.9	0.8	< .05	7
NHC 39	283439	962356	1.1	6.9	21.7	75	< .1	16	30.4	5170	4.04	1.5	1.7	1	9.4	24	0.2	0.2	0.1	53	0.38	0.081	33	27.3	0.52	158	0.127	4	1.63	0.02	0.26	0.2	0.15	3	0.3	0.07	9
NHC 40	283910	963808	1	4.9	43.1	62	< .1	12.4	55.3	11422	6.2	8.3	1.5	0.8	7.3	29	0.2	0.4	0.1	62	0.37	0.07	35	18.9	0.33	147	0.049	2	0.88	0.023	0.18	0.1	0.14	1.9	0.6	0.08	7
NHC 41	284356	964442	0.8	8.1	39.1	77	< .1	18.7	43.2	14111	3.96	62.7	2.1	1.4	6.8	32	0.3	0.5	0.1	48	0.57	0.074	34	20.9	0.32	189	0.057	2	1.01	0.024	0.2	0.1	0.11	2.2	0.8	0.08	8

NHC 42	285644	965144	0.2	11.2	18.5	72	< .1	42	23.1	1984	3.36	7.5	3.7	0.8	11.6	22	0.1	0.2	0.1	47	0.41	0.097	44	46.5	0.67	87	0.068	1	1.41	0.018	0.27	0.1	0.03	4.3	0.3	0.07	11
NHC 43	285856	964400	0.9	6.1	71.9	63	< .1	26.9	79	7380	7.88	12.8	2	1.1	6.3	41	0.3	0.3	0.2	79	0.55	0.181	39	22.4	0.36	164	0.037	4	0.81	0.032	0.16	0.2	0.09	2	0.5	0.09	8
NHC 44	286632	965202	1.4	19.9	31.7	52	< .1	20.2	12.1	1304	5.02	20.8	1.2	0.5	7.5	30	0.1	0.8	0.1	51	0.4	0.059	27	25.3	0.58	56	0.048	4	0.8	0.024	0.15	0.1	0.02	1.7	0.2	0.06	7
NHC 45	294840	962860	3.1	18.2	291.4	91	0.1	22.7	81	23512	10.38	19	1.7	2.2	9.8	52	0.5	0.6	0.3	89	0.59	0.116	38	31.6	0.52	601	0.072	2	1.26	0.034	0.16	0.3	0.48	2.2	0.8	0.1	9
NHC 47	279529	963879	2.8	56.1	116.6	166	0.1	41.2	26.1	3936	7.38	6	1.3	1.1	4.5	30	0.4	0.8	0.2	131	0.6	0.088	16	90.4	1.94	141	0.121	2	1.98	0.041	0.18	0.1	0.05	11.5	0.3	0.08	13
NHC 48	287026	965026	1.2	16.4	23.8	66	< .1	29.9	13.4	917	3.44	10.9	2	0.6	8.4	22	0.1	0.6	0.1	62	0.26	0.095	30	42	0.84	61	0.076	4	1.2	0.021	0.25	0.2	0.03	3.1	0.2	< .05	8
NHC 49	293922	964475	1.1	14.5	34.4	68	< .1	49.5	20.6	2041	4.64	9.3	1.8	2.4	15.2	23	0.1	0.4	0.1	84	0.38	0.143	48	70.7	1.18	100	0.189	1	1.29	0.026	0.39	0.3	0.02	3.1	0.3	< .05	11
NHC 50	296291	962336	0.3	19.2	114.7	46	< .1	22.4	7.3	411	4.3	2.9	4.4	3.7	15.2	26	< .1	0.3	< .1	121	0.48	0.188	55	48.3	0.59	198	0.111	3	1.05	0.026	0.4	0.7	0.07	9.8	0.2	0.06	6
NHC 51	296681	961032	0.1	11.1	12.2	36	< .1	21.3	6	229	1.26	1.6	1.8	6.5	9.5	14	0.1	0.2	0.1	29	0.28	0.123	34	25.2	0.48	52	0.039	1	0.56	0.013	0.15	0.1	0.02	2.9	0.1	< .05	3

Panned concentrate samples

Sample No	Easting	Northing	Mo ppm	Cu ppm	Pb ppm	Zn ppm	Ag ppm	Ni ppm	Co ppm	Mn ppm	Fe %	As ppm	U ppm	Au ppb	Th ppm	Sr ppm	Cd ppm	Sb ppm	Bi ppm	V ppm	Ca ppm	P %	La ppm	Cr ppm	Mg %	Ba ppm	Ti %	B ppm	Al %	Na %	K %	W ppm	Hg ppm	Sc ppm	Tl ppm	S %	Ga ppm	Au[1] ppb	Pt[1] ppb	Pd[1] ppb
NHP 1	254975	920556	0.3	42.4	7.6	30	0.1	23.2	7.6	365	2.34	0.5	1.1	21.6	3.5	27	0.1	0.1	0.5	55	0.79	0.073	12	49.4	0.59	658	0.154	< 1	0.57	0.089	0.1	0.1	< .01	3.9	< .1	< .05	3	15	< 2	< 2
NHP 2	256395	920720	0.1	4.1	2.5	15	< .1	8.7	4.2	244	1.03	0.5	0.8	1.4	2.6	16	0.1	< .1	< .1	25	0.48	0.049	9	23.9	0.34	24	0.085	< 1	0.44	0.074	0.09	< .1	< .01	2.3	< .1	< .05	2	2	< 2	< 2
NHP 3	256396	920721	0.2	3.3	2.5	14	< .1	8	3.7	217	1.03	0.6	0.8	0.9	2.5	15	< .1	< .1	< .1	25	0.46	0.061	9	21.7	0.32	22	0.085	< 1	0.42	0.066	0.09	< .1	< .01	1.9	< .1	< .05	2	2	< 2	< 2
NHP 4	257161	922783	< .1	0.6	2.8	15	< .1	3.1	2	257	0.58	0.7	1.3	1	7.1	10	< .1	< .1	< .1	11	0.15	0.03	20	6.5	0.13	24	0.051	< 1	0.34	0.053	0.07	< .1	< .01	1	< .1	< .05	2	3	< 2	< 2
NHP 5	257609	923035	0.1	0.9	2.5	11	< .1	3.1	1.6	196	0.66	< .5	0.7	17.9	4.9	7	< .1	< .1	< .1	14	0.13	0.011	13	8.6	0.13	14	0.065	< 1	0.27	0.038	0.05	0.1	< .01	1	< .1	< .05	1	5	< 2	< 2
NHP 6	258919	921792	< .1	2.1	2.9	14	< .1	3	2.1	127	0.49	0.5	1	< .5	6.5	8	< .1	< .1	< .1	11	0.09	0.025	21	6	0.13	36	0.059	< 1	0.38	0.029	0.14	< .1	0.01	1	0.1	< .05	2	< 2	< 2	< 2
NHP 7	259509	920937	0.3	1.1	2.7	8	< .1	2.3	1.6	272	0.65	0.8	1.6	< .5	8.2	10	< .1	< .1	< .1	10	0.23	0.059	30	6.4	0.11	23	0.059	< 1	0.32	0.044	0.07	< .1	< .01	1.6	< .1	< .05	1	20	< 2	< 2
NHP 8*	261880	919934	0.1	1.9	3.7	10	0.1	2.9	2.6	472	1.07	1.3	2.5	391.7	18.8	10	< .1	< .1	< .1	17	0.23	0.042	58	11.6	0.14	21	0.084	< 1	0.38	0.041	0.07	< .1	< .01	1.9	< .1	< .05	2	17	< 2	< 2
NHP 9	261622	921647	0.1	2.1	3.1	9	< .1	2.7	2.9	226	0.65	0.7	1.4	15.9	8.9	9	< .1	< .1	< .1	13	0.16	0.025	28	11.8	0.11	22	0.061	1	0.28	0.037	0.07	< .1	0.01	1	< .1	< .05	1	13	< 2	< 2
NHP 10	261904	921342	0.1	2.2	3.2	11	0.4	3	2.4	257	0.61	0.5	1.3	1739.4	7.8	13	< .1	< .1	< .1	11	0.15	0.026	28	7.7	0.11	31	0.056	1	0.39	0.05	0.1	< .1	< .01	1.3	< .1	< .05	2	747	< 2	< 2
NHP 11	261644	921688	0.1	0.7	2.5	7	< .1	2.2	1.4	190	0.35	0.9	1.8	3	13.1	10	< .1	< .1	< .1	8	0.14	0.016	44	6.6	0.09	22	0.059	1	0.29	0.046	0.08	< .1	< .01	0.9	< .1	< .05	1	5	< 2	< 2
NHP 12	261854	920776	0.1	1.5	3.1	11	< .1	3.2	2.5	416	0.74	0.8	2	3	10	15	< .1	< .1	< .1	11	0.2	0.025	33	10.9	0.15	34	0.074	1	0.48	0.065	0.11	< .1	< .01	2.2	0.1	< .05	2	3	< 2	< 2
NHP 13*	261773	921654	0.1	1.3	2.8	8	0.1	2.6	1.7	356	0.6	0.7	4.7	275.8	12.9	12	< .1	< .1	< .1	9	0.17	0.016	39	9.2	0.13	31	0.063	1	0.42	0.06	0.11	< .1	0.01	1.8	< .1	< .05	1	271	< 2	< 2
NHP 14	262966	918753	0.1	1.9	3.2	11	< .1	3.5	2.8	365	0.75	0.7	1.8	1.7	10.4	13	< .1	< .1	< .1	13	0.22	0.037	35	11.2	0.15	31	0.066	1	0.39	0.048	0.1	0.3	< .01	1.6	< .1	< .05	2	6	< 2	< 2
NHP 15	263076	918137	< .1	2	3.3	11	< .1	3.4	3.1	321	0.74	0.7	1.5	< .5	7.7	10	< .1	< .1	< .1	13	0.17	0.042	26	7.4	0.11	26	0.055	1	0.32	0.035	0.08	< .1	< .01	1.2	< .1	< .05	1	2	< 2	< 2
NHP 16	262627	919436	0.1	2.6	4.7	14	< .1	5	3.7	456	0.95	0.5	4.2	< .5	38	11	0.1	< .1	< .1	14	0.21	0.047	110	10.4	0.16	36	0.082	1	0.47	0.044	0.13	< .1	< .01	2.2	0.1	< .05	2	2	< 2	< 2
NHP 17*	263019	918758	0.1	2.6	3.4	15	< .1	8.6	3.9	495	0.86	1.2	1.8	0.9	10.8	20	< .1	< .1	< .1	14	0.35	0.084	40	15.9	0.25	36	0.089	< 1	0.51	0.048	0.13	< .1	< .01	2.2	0.1	< .05	2	4	< 2	< 2
NHP 18	263059	919453	0.3	4	6.6	17	< .1	7.6	6.6	693	1.34	< .5	8.5	0.6	60.7	10	0.1	< .1	< .1	19	0.32	0.087	174	13.8	0.24	39	0.114	1	0.59	0.037	0.14	0.1	< .01	3.1	0.1	< .05	2	2	< 2	< 2
NHP 19*	263291	919328	0.1	2.8	4.3	13	0.2	7.1	3.6	475	0.87	1.4	2.1	3144.8	13.7	18	< .1	< .1	< .1	12	0.29	0.091	46	10.5	0.2	29	0.074	1	0.44	0.028	0.11	< .1	< .01	2.2	0.1	< .05	1	11	< 2	< 2
NHP 20	263050	919913	0.1	4.4	5.7	22	< .1	10.3	6	427	1.21	1	3.5	< .5	21.6	10	< .1	< .1	< .1	23	0.24	0.066	62	17.9	0.3	53	0.11	1	0.59	0.028	0.21	0.1	< .01	2.3	0.1	< .05	3	< 2	< 2	< 2
NHP 21	263938	919469	0.1	1.7	3.9	12	0.3	4.4	3.4	442	0.64	1.8	2.3	1639.1	17.8	12	< .1	< .1	< .1	12	0.19	0.05	56	8.8	0.14	37	0.06	1	0.43	0.043	0.14	< .1	< .01	1.7	0.1	< .05	2	264	< 2	< 2
NHP 22	263392	917564	0.1	3.7	2.9	11	< .1	3.1	2.3	696	1.18	1.3	2	1	14.8	12	< .1	< .1	< .1	14	0.25	0.047	41	9	0.15	30	0.078	1	0.43	0.042	0.07	< .1	< .01	2.2	< .1	< .05	1	4	< 2	< 2
NHP 23	263114	920045	0.3	4.2	4.7	22	< .1	9.2	6	464	1.3	0.8	3.2	1.5	22.9	11	< .1	< .1	< .1	25	0.24	0.055	69	18.7	0.32	57	0.127	< 1	0.66	0.036	0.26	< .1	< .01	2.9	0.1	< .05	3	3	< 2	< 2
NHP 24*	263788	917937	0.1	2.1	4	25	0.2	5.8	4.5	1216	1.24	1.2	2.6	1447.2	18.7	13	< .1	< .1	< .1	21	0.31	0.077	62	11.5	0.23	65	0.113	1	0.58	0.038	0.21	< .1	< .01	2.2	0.1	< .05	3	2284	< 2	< 2
NHP 25	263156	920635	0.1	2.3	3.2	12	< .1	7.5	2.8	222	0.55	0.7	1.3	< .5	6.7	10	< .1	< .1	< .1	11	0.2	0.041	21	17.7	0.2	29	0.081	1	0.37	0.034	0.11	< .1	< .01	1.3	0.1	< .05	2	2	< 2	< 2
NHP 27	263237	920650	< .1	0.7	2.9	8	< .1	2.8	1.4	133	0.31	0.9	0.9	0.9	6.1	12	< .1	< .1	< .1	8	0.14	0.017	21	7.3	0.11	28	0.045	1	0.31	0.05	0.09	< .1	< .01	0.9	0.1	< .05	1	2	< 2	< 2
NHP 29	282346	938031	0.1	1.3	3.2	9	< .1	2.9	2.6	429	1.18	1.2	1.5	0.9	9.4	9	< .1	< .1	< .1	21	0.15	0.022	29	8.4	0.1	36	0.054	1	0.35	0.04	0.08	0.2	< .01	1.6	< .1	< .05	2	2	< 2	< 2
NHP 30*	282226	938359	< .1	0.8	3	7	< .1	2.1	1.6	418	0.61	0.8	1.3	9.9	8.8	9	< .1	< .1	< .1	10	0.11	0.019	29	5.5	0.09	28	0.043	1	0.33	0.038	0.07	0.1	< .01	1.6	< .1	< .05	1	10	< 2	< 2
NHP 31	282300	939438	0.1	0.7	2.9	7	< .1	1.8	1.2	287	0.46	1.1	0.9	1.8	5.1	8	< .1	< .1	< .1	6	0.07	0.018	18	4	0.08	31	0.03	1	0.29	0.04	0.08	< .1	< .01	0.9	< .1	< .05	1	2	< 2	< 2
NHP 32	277820	938517	0.1	2.5	3.3	11	< .1	2.2	1.4	220	0.69	0.9	1.1	0.6	5.5	9	< .1	< .1	< .1	9	0.13	0.022	19	5.4	0.1	40	0.04	1	0.32	0.039	0.08	0.1	< .01	1.2	< .1	< .05	1	2	< 2	< 2
NHP 33	278707	937669	0.1	0.9	2.9	10	< .1	1.9	1.9	374	0.67	0.5	0.8	< .5	3.5	9	0.1	< .1	< .1	11	0.12	0.016	12	5.4	0.09	40	0.037	1	0.29	0.037	0.07	< .1	< .01	0.9	< .1	< .05	1	3	< 2	< 2
NHP 34	285986	938943	0.2	0.6	3.2	6	< .1	1.3	0.9	72	0.66	1.1	0.5	0.9	2.1	9	< .1	< .1	< .1	4	0.04	0.015	8	2	0.04	25	0.013	< 1	0.25	0.039	0.07	< .1	< .01	0.4	< .1	< .05	1	2	< 2	< 2
NHP 35	285272	940021	0.1	1.9	5.3	11	0.1	3.6	2.8	268	1.11	1.6	2.3	221.3	18.2	9	< .1	0.1	< .1	25	0.07	0.02	54	12.1	0.12	42	0.07	1	0.43	0.037	0.15	0.1	< .01	1.7	0.1	< .05	2	446	< 2	< 2
NHP 36	285073	939495	0.1	1.1	3.2	8	< .1	3.4	1.8	177	0.56	< .5	1	26	5.7	10	< .1	< .1	< .1	12	0.11	0.02	20	6.4	0.1	31	0.034	1	0.25	0.048	0.09	< .1	0.01	0.9	< .1	< .05	1	57	< 2	< 2
NHP 37	283117	959933	0.2	1.3	5	12	< .1	7.5	5.3	210	4.33	< .5	1.4	1.7	14.9	13	< .1	0.1	< .1	119	0.2	0.07	47	40.4	0.1	31	0.09	1	0.26	0.04	0.07	0.1	0.01	1	0.1	< .05	4	2	< 2	< 2
NHP 38	283125	960980	0.1	1	4.2	6	< .1	2	3	322	1.14	< .5	0.6	1.8	5.7	7	< .1	0.1	< .1	22	0.04	0.013	18	6.7	0.05	36	0.02	1	0.17	0.028	0.09	0.1	0.01	0.4	< .1	< .05	2	3	< 2	< 2

NHP 39	283439	962356	0.8	1.1	8.1	13	< .1	5	7	337	3.9	< .5	1.8	1.8	18.5	7	0.1	0.3	0.1	94	0.08	0.023	53	26.2	0.11	32	0.072	3	0.32	0.031	0.09	0.3	0.01	1.3	< .1	< .05	4	< 2	< 2	< 2
NHP 40	283910	963808	0.2	1	3.8	8	< .1	3.1	4.5	308	1.46	0.7	0.7	0.8	7.4	6	< .1	0.1	< .1	33	0.05	0.016	24	12.4	0.06	28	0.026	1	0.2	0.025	0.1	0.1	0.01	0.6	0.1	< .05	2	2	< 2	< 2
NHP 41	284356	964442	0.4	1.2	5.7	11	< .1	5.2	5.5	410	2.31	3	1	1.5	8	7	< .1	0.2	0.1	60	0.05	0.014	26	21.9	0.07	31	0.034	2	0.22	0.031	0.1	0.3	0.01	0.8	0.1	< .05	3	< 2	< 2	< 2
NHP 42	285644	965144	0.1	1.5	3	12	< .1	5	2.8	149	0.55	0.5	1.2	9.4	7.6	9	< .1	< .1	< .1	9	0.11	0.037	28	6.1	0.12	29	0.028	< 1	0.28	0.032	0.11	< .1	< .01	0.8	0.1	< .05	1	7	< 2	< 2
NHP 43	285856	964400	0.1	1.1	5	8	< .1	3.1	4.8	338	1.12	1.4	0.6	1.7	5.4	7	< .1	0.1	< .1	17	0.06	0.022	18	6.2	0.06	30	0.018	1	0.18	0.026	0.09	0.1	< .01	0.5	0.1	< .05	1	< 2	< 2	< 2
NHP 44	286632	965202	0.2	2.6	2.7	6	< .1	5.1	2.3	86	1.14	5.4	0.4	1.7	3.7	11	< .1	0.2	< .1	10	0.05	0.011	13	5	0.06	21	0.019	1	0.18	0.046	0.07	< .1	< .01	0.4	< .1	< .05	1	2	< 2	< 2
NHP 45	294840	962860	0.1	0.6	5.7	6	< .1	1.9	1.7	230	0.49	0.7	0.4	0.7	3.6	12	< .1	< .1	< .1	7	0.04	0.008	13	3.2	0.05	43	0.012	1	0.23	0.051	0.08	< .1	< .01	0.3	0.1	< .05	1	2	< 2	< 2
NHP 46	295583	962999	0.3	0.8	4.9	9	< .1	1	0.9	244	1.68	6.1	0.4	1.6	2.1	11	< .1	< .1	< .1	10	0.08	0.02	9	2.4	0.03	51	0.009	1	0.19	0.034	0.04	< .1	< .01	0.4	0.1	< .05	1	< 2	< 2	< 2
NHP 47	279529	963879	0.4	6.7	411.1	22	< .1	9.6	8.5	371	4.67	3	0.6	0.9	3.8	6	0.1	11.2	0.2	113	0.27	0.023	11	33.6	0.36	17	0.048	< 1	0.56	0.064	0.04	0.1	0.01	3.6	< .1	< .05	5	2	< 2	< 2
NHP 48	287026	965026	0.1	2.9	4.9	12	< .1	5.8	1.8	61	0.51	0.8	0.6	< .5	3.6	13	< .1	0.1	< .1	10	0.07	0.018	15	6.7	0.13	32	0.02	2	0.3	0.05	0.12	< .1	< .01	0.8	0.1	< .05	2	< 2	< 2	< 2
NHP 49	293922	964475	0.1	1.7	4.1	9	< .1	6.8	2	75	0.64	0.5	0.6	3	5.4	15	< .1	0.3	< .1	14	0.1	0.02	20	12	0.15	41	0.042	2	0.29	0.065	0.13	0.1	< .01	0.6	0.1	< .05	2	3	< 2	< 2
NHP 50	296291	962336	< .1	1.7	5.3	6	< .1	2.6	1.1	48	0.47	< .5	0.7	32	5.6	13	< .1	< .1	< .1	11	0.06	0.022	22	3.9	0.07	40	0.018	2	0.25	0.057	0.1	0.1	< .01	0.6	< .1	< .05	1	42	< 2	< 2
NHP 51	296681	961032	< .1	1.4	4.3	20	< .1	4.3	1.5	49	0.33	< .5	0.6	1.6	4.3	10	0.1	< .1	< .1	7	0.05	0.02	18	3.7	0.08	24	0.011	2	0.2	0.04	0.07	0.1	0.01	0.5	< .1	< .05	1	2	< 2	< 2

* Visible gold grain(s) in pan
[1] Au Pt Pd 30g sample by lead fire assay

Rock samples

Sample No	Easting	Northing	Mo ppm	Cu ppm	Pb ppm	Zn ppm	Ag ppm	Ni ppm	Co ppm	Mn ppm	Fe %	As ppm	U ppm	Au ppb	Th ppm	Sr ppm	Cd ppm	Sb ppm	Bi ppm	V ppm	Ca ppm	P %	La ppm	Cr ppm	Mg %	Ba ppm	Ti %	B ppm	Al %	Na %	K %	W ppm	Hg ppm	Sc ppm	Tl ppm	S %	Ga ppm	Au[1] ppb	Pt[1] ppb	Pd[1] ppb
NHR 201	256868	923017	0.1	1.8	7.2	45	< .1	9.2	3.9	141	1.96	< .5	2.7	0.8	8.3	7	< .1	< .1	< .1	35	0.04	0.028	28	22	0.35	55	0.092	1	1.37	0.034	0.25	< .1	0.01	2.7	0.1	< .05	7	< 2	< 2	< 2
NHR 202	261780	919740	2.1	1.3	2	7	< .1	4.7	19.8	14791	2.97	< .5	1.9	0.6	2.7	28	< .1	< .1	< .1	7	0.07	0.046	10	5.4	0.07	570	0.027	1	0.32	0.042	0.09	< .1	< .01	0.9	0.1	< .05	2	< 2	< 2	< 2
NHR 203	262783	919432	0.1	3.8	7.3	11	0.1	3.5	1.5	178	0.83	< .5	0.9	1.5	7	11	< .1	< .1	< .1	11	0.05	0.023	13	10.7	0.05	30	0.01	1	0.37	0.088	0.09	0.1	< .01	0.9	< .1	< .05	1	< 2	< 2	< 2
NHR 204	262880	919430	0.2	8.3	8.6	12	< .1	7.3	4.6	302	0.59	< .5	0.5	< .5	4.6	8	< .1	< .1	< .1	6	0.04	0.009	16	7	0.12	20	0.003	1	0.5	0.004	0.14	< .1	< .01	1.4	0.1	< .05	2	< 2	< 2	< 2
NHR 205	260030	919480	0.1	2.1	4.1	9	0.2	6.4	2.1	103	0.65	< .5	0.5	1.1	5.6	6	< .1	< .1	< .1	10	0.02	0.015	18	11.5	0.06	18	0.023	< 1	0.4	0.096	0.07	< .1	< .01	0.6	< .1	< .05	1	< 2	< 2	< 2
NHR 206	263030	919480	0.3	18.8	116.9	197	4.6	12.4	3.7	100	1.54	0.6	1	55.5	0.8	36	0.2	< .1	< .1	6	0.04	0.021	3	11	0.21	340	0.002	< 1	0.75	0.004	0.09	< .1	0.01	0.6	< .1	< .05	2	55	< 2	< 2
NHR 207	263058	919872	0.1	4.5	10.3	20	0.2	6.5	2.1	52	0.49	< .5	0.3	4.2	0.9	8	0.1	< .1	< .1	3	0.04	0.02	4	10.4	0.09	17	0.004	< 1	0.28	0.004	0.06	< .1	< .01	1.8	< .1	< .05	1	4	< 2	< 2
NHR 208	263095	919986	0.9	7.1	53	91	0.1	55.1	19.8	241	4.34	< .5	1.7	1.4	5.6	11	0.2	< .1	< .1	14	0.06	0.066	24	9.9	0.89	173	0.008	2	2.52	0.014	0.26	< .1	< .01	1.4	0.1	< .05	8	2	< 2	< 2
NHR 209	263095	919986	0.2	8.9	24.1	32	0.6	9.6	4.5	93	1.07	< .5	0.7	4.3	5.8	9	0.1	< .1	< .1	7	0.08	0.043	23	5.3	0.17	73	0.004	2	0.92	0.016	0.2	< .1	< .01	1.2	0.1	< .05	2	6	< 2	< 2
NHR 210	263120	920035	0.1	7.4	9.6	10	< .1	5	3.5	67	0.51	< .5	1.7	0.6	8.1	14	< .1	< .1	< .1	15	0.05	0.009	20	13.1	0.14	52	0.073	< 1	0.55	0.082	0.18	< .1	< .01	2.3	0.1	< .05	4	2	< 2	< 2
NHR 211	263122	920043	0.2	6.4	26.6	18	< .1	14	4.3	99	2.07	< .5	4	1.5	9.4	21	< .1	< .1	< .1	40	0.07	0.013	29	32.6	0.19	73	0.151	1	0.57	0.039	0.2	< .1	< .01	4.4	0.1	< .05	5	< 2	< 2	< 2
NHR 212	263167	920192	0.1	2	12.1	18	< .1	13.1	4.4	27	1.36	< .5	1.6	0.7	15.2	18	< .1	< .1	0.1	31	0.11	0.025	37	24.8	0.11	33	0.128	< 1	0.44	0.12	0.07	0.1	< .01	3.6	< .1	< .05	3	< 2	< 2	< 2
NHR 213	284345	940820	0.1	3	6.6	13	< .1	5	2.4	81	1.1	< .5	0.9	2.2	8.9	7	< .1	0.4	0.1	15	0.05	0.042	29	11.3	0.12	35	0.02	2	0.42	0.035	0.23	0.4	< .01	1.3	0.1	< .05	4	2	< 2	< 2
NHR 214	284480	941021	0.1	3.8	3.3	17	< .1	4.9	3.7	108	1.1	< .5	1.7	2.1	8	8	< .1	0.3	0.1	14	0.05	0.03	19	8	0.21	31	0.01	2	0.52	0.047	0.18	0.6	0.01	1	0.1	< .05	5	2	< 2	< 2
NHR 215	284391	941016	0.3	1.5	6.1	17	< .1	8.7	3	148	1.23	< .5	0.7	4.4	8.6	8	0.1	0.5	0.1	15	0.05	0.031	24	18.7	0.15	37	0.021	2	0.53	0.036	0.22	0.5	< .01	1.2	0.1	< .05	4	3	< 2	< 2
NHR 216	284034	940889	0.1	5.9	13.5	31	< .1	14.9	6.5	442	1.95	< .5	0.9	3.9	8.9	5	< .1	0.3	0.1	21	0.03	0.035	47	26.6	0.27	29	0.029	2	0.68	0.037	0.2	0.5	0.01	2.1	0.1	< .05	7	4	< 2	< 2
NHR 217	283596	940952	0.1	5	8.5	19	< .1	11.3	4.2	531	0.98	< .5	0.7	1	6.5	8	0.1	0.2	0.1	10	0.03	0.027	31	18.3	0.13	36	0.011	2	0.57	0.038	0.18	0.3	0.01	1.7	0.1	< .05	4	< 2	< 2	< 2
NHR 218	283207	941116	0.1	2.7	2.9	4	< .1	3.6	1	158	0.61	1.6	0.6	0.8	7.3	6	< .1	0.1	< .1	9	< .01	0.007	26	7.5	0.02	51	0.01	1	0.26	0.006	0.16	0.2	< .01	0.8	0.1	< .05	1	< 2	< 2	< 2
NHR 219	279729	939516	0.1	2	6.8	9	< .1	5	2.8	288	0.67	< .5	0.4	0.7	8.2	6	< .1	< .1	< .1	10	0.01	0.004	18	6.4	0.3	35	0.022	4	0.88	0.01	0.2	0.2	0.01	1.3	0.1	< .05	2	< 2	< 2	< 2
NHR 220	279949	939767	0.1	1.8	24.9	24	< .1	11.6	5	203	1.07	< .5	0.6	1.8	5.9	9	< .1	0.1	0.1	13	0.16	0.023	20	17.4	0.33	37	0.082	1	0.63	0.048	0.17	0.5	0.01	1.6	0.1	< .05	4	3	< 2	< 2
NHR 221	280019	939055	0.1	0.9	10.4	11	< .1	7.8	3	199	1.08	< .5	0.4	1.6	9.9	5	< .1	0.1	0.1	13	0.01	0.004	28	11	0.21	27	0.022	5	0.9	0.016	0.26	0.1	< .01	1.6	0.1	< .05	3	3	< 2	< 2
NHR 222	280095	939020	0.1	0.8	6.8	13	< .1	6	2.1	93	0.77	< .5	0.4	2.8	3.9	5	0.1	0.1	0.1	11	0.01	0.007	18	7.9	0.19	35	0.011	5	0.89	0.013	0.3	< .1	0.01	1	0.2	< .05	2	4	< 2	< 2
NHR 223	280126	938078	< .1	14.9	3.7	17	< .1	8.5	3.7	306	0.69	< .5	0.4	0.7	6.7	40	< .1	< .1	0.1	9	0.93	0.016	32	9.7	0.59	75	0.04	3	1.23	0.011	0.26	< .1	< .01	2.1	0.2	< .05	3	3	< 2	< 2
NHR 224	280941	939079	< .1	6	2.5	9	< .1	7.2	2.5	272	0.68	< .5	0.5	1.4	6.2	12	< .1	0.1	0.1	10	0.46	0.016	26	14.2	0.09	49	0.011	1	0.32	0.014	0.15	0.1	< .01	0.9	0.1	< .05	1	< 2	< 2	< 2
NHR 225	283264	960384	0.2	5.5	7	14	< .1	3.9	3	90	1.57	< .5	0.8	3.6	10.4	9	< .1	0.1	< .1	29	0.06	0.03	32	13.3	0.11	34	0.022	3	0.46	0.046	0.21	0.6	0.01	1	0.1	< .05	3	2	< 2	< 2
NHR 226	283299	960435	0.2	1.9	6.6	10	< .1	2.6	2.1	141	0.93	< .5	0.6	1.6	10.1	8	< .1	0.1	< .1	14	0.02	0.019	27	9.6	0.08	41	0.012	1	0.39	0.038	0.22	0.3	< .01	1.3	0.1	< .05	2	3	< 2	< 2
NHR 227	283526	960272	0.1	1.9	6.3	18	< .1	9.4	5.5	161	1.69	< .5	0.8	1.6	11.1	7	< .1	0.2	< .1	27	< .01	0.014	34	14.8	0.12	41	0.029	3	0.57	0.026	0.25	0.3	0.01	1.2	0.1	< .05	4	2	< 2	< 2
NHR 228	283900	960191	0.1	3.8	5.5	9	< .1	2.7	2	26	1.2	< .5	1	5	9.1	6	< .1	0.1	< .1	22	0.02	0.018	24	9.4	0.06	25	0.016	1	0.41	0.038	0.19	0.4	< .01	0.8	0.1	< .05	4	3	< 2	< 2
NHR 229	286693	964746	0.2	5.1	2	23	< .1	9.4	7.2	149	1.92	0.5	0.8	5	13.2	8	< .1	0.1	< .1	36	0.02	0.032	61	20	0.19	41	0.034	2	0.75	0.042	0.23	0.1	< .01	1.8	0.1	< .05	6	4	< 2	< 2
NHR 230	286237	964829	< .1	5.7	2.4	22	< .1	6.4	2.9	61	1.2	< .5	0.8	1.4	8.9	8	< .1	0.1	< .1	23	0.04	0.03	31	15.1	0.21	40	0.029	1	0.61	0.022	0.27	0.2	< .01	1.8	0.1	0.06	5	< 2	< 2	< 2

NHR 231	286486	964789	0.2	1.3	2.9	22	< .1	6.4	2.9	44	1.55	< .5	1.1	2	9.4	7	< .1	0.1	< .1	27	< .01	0.02	39	18.4	0.19	38	0.037	2	0.57	0.022	0.3	0.2	0.01	1.7	0.1	0.07	6	< 2	< 2	< 2
NHR 232	294304	963638	0.4	1.4	6	28	< .1	23.8	7.8	261	2.34	< .5	0.7	2.2	7.7	15	< .1	0.2	0.2	49	0.06	0.042	35	43.9	0.41	89	0.136	4	0.76	0.024	0.45	0.3	< .01	3.2	0.2	0.06	5	< 2	< 2	< 2
NHR 233	293961	963751	< .1	2.5	1.2	20	< .1	18.1	4.8	93	1.1	< .5	0.3	0.9	3.8	4	< .1	< .1	< .1	15	0.01	0.018	17	15.7	0.25	32	0.012	< 1	0.64	0.016	0.11	< .1	< .01	1.7	< .1	< .05	3	2	< 2	< 2
NHR 234	293961	963751	< .1	3.4	3.7	43	< .1	33.1	10.4	95	2.39	1	0.6	1	6.7	7	< .1	0.1	0.2	40	0.02	0.035	29	31.3	0.53	64	0.012	1	0.98	0.019	0.16	< .1	0.01	2.5	< .1	< .05	6	< 2	< 2	< 2
NHR 235	294193	963900	< .1	2	1	10	< .1	8.9	1.8	22	0.65	< .5	0.5	< .5	4.7	3	< .1	< .1	< .1	12	0.01	0.01	22	12.1	0.12	21	0.006	< 1	0.37	0.012	0.12	0.1	< .01	1.4	< .1	< .05	3	< 2	< 2	< 2
NHR 236	294228	963892	0.1	8.1	2	38	< .1	37.2	8.5	395	2.09	< .5	0.8	1.3	8.5	19	0.1	0.1	0.1	38	0.25	0.055	37	45.4	0.67	66	0.059	2	0.85	0.032	0.27	0.3	< .01	3.4	0.1	< .05	7	< 2	< 2	< 2
NHR 237	277688	963520	< .1	12	22.4	4	< .1	< .1	0.9	3058	0.36	< .5	0.1	< .5	0.8	785	< .1	< .1	< .1	8	39.17	0.006	61	3.5	0.12	15	0.011	< 1	0.13	0.005	0.03	< .1	< .01	2.1	< .1	0.09	1	< 2	< 2	< 2
NHR 238	277670	963499	0.6	51.3	142.5	61	1.3	24.3	13.6	376	7.58	23.4	1	0.6	1.5	11	< .1	5.6	< .1	64	0.14	0.046	11	34.9	0.74	25	0.274	1	1.59	0.043	1.21	0.1	0.21	5.7	26.7	4.45	9	11	< 2	< 2
NHR 239	274280	961880	0.8	102	939.4	130	< .1	51.3	14.2	615	3.07	1	6.2	2.7	11.4	8	0.1	0.1	0.1	54	0.17	0.079	46	39.6	0.98	213	0.167	2	2.37	0.029	0.49	0.1	0.03	4.8	0.5	< .05	11	4	< 2	< 2
NHR 240	274280	961880	1.2	13.3	200.9	59	< .1	17.1	9.1	395	2.66	< .5	2.6	0.6	9.8	10	0.1	0.1	0.1	46	0.15	0.061	31	29.2	0.78	152	0.201	< 1	1.62	0.039	0.69	0.1	0.01	4	0.4	< .05	9	4	< 2	< 2

[1] Au Pt Pd 30g sample by lead fire assay