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Exploration for stratabound mineralisation in the Argyll Group (Dalradian) of north-east Scotland

Department of Trade and Industry

MRP Report 145

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SUMMARY

The Mineral Reconnaissance Programme (MRP) identified several horizons of stratabound mineralisation within the Argyll Group during investigations of the Dalradian Supergroup in Scotland between 1973 and 1987. These included the multi-million tonne Aberfeldy baryte deposits. Most of the discoveries were made in the central and south-western Scottish Highlands, where the Dalradian succession is well recognised. The Dalradian of north-east Scotland, because of its poorer exposure and greater complexity, did not receive the same level of attention.

The project reported here was set up to assess the potential of the Argyll Group in north-east Scotland for stratabound mineralisation, based on the geological models developed in the central Highlands. An initial desk study involved the digitisation (where necessary), integration and review of the following datasets: (i) geological mapping, including the results of new BGS mapping, (ii) BGS airborne aeromagnetic data, (iii) BGS geophysical ground survey results, (iv) BGS Geochemical Baseline Survey of the Environment drainage data, (v) existing MRP data, (vi) BGS traverse-based soil sampling results, and (vii) datasets collected by Exploration Ventures Ltd, principally detailed airborne and ground geophysical information. Assessment of these datasets identified three broad areas which contained geochemical, geophysical and geological features that merited examination to determine their sources and indicate the potential for economic stratabound mineralisation. These areas were Ballater–Strathdon, Upper Deveron and Huntly–Portsoy. Geochemical and geophysical ground surveys were carried out in parts of all three of these areas and followed-up locally by pitting and trenching to clarify the sources of individual anomalies.

The studies indicated that the areas with the most potential for stratabound mineralisation occur to the east of the Portsoy Lineament and/or in rocks which cannot be easily correlated with Argyll Group rocks elsewhere. These rocks tend to be lithologically different from the typical Argyll Group sequence and are generally more fractured, sheared, brecciated and altered.

The most promising area for the discovery of stratabound mineralisation is considered to be in the Upper Deveron area at Wellheads. Here, high levels of lead and zinc in overburden are probably enhanced by hydromorphic processes, but the source of the lead has been traced to quartzites and the zinc to adjacent pelites within the Corinacy Pelite Member of the Blackwater Formation. The predominantly lead-zinc mineralisation is similar to that at Glenshee and Dericambus. Detailed VLF EM and IP surveys are recommended to assist in defining trenching and drilling targets. Lead and coincident IP anomalies at Succoth–Gouls also merit follow-up investigation.

In the Ballater–Strathdon area a large EM and magnetic anomaly on Creagan Riabhach, although apparently low in base-metal content, merits further investigation on the grounds that: (1) a significant amount of sulphide mineralisation is present at shallow depth, (2) there is good evidence for stratabound mineralisation, and (3) the rocks are thought to be similar to the Ben Lawers Pyrite, where copper mineralisation occurs sporadically.

In the Upper Donside part of the Ballater–Strathdon area several lead-zinc anomalies have been identified from drainage sampling, but very little mineral-exploration work has been carried out over the c. 10 km strike length of the Argyll Group metasedimentary rocks. The Glenbuchat Graphitic Schist Formation has a volcanic component here, providing the potential for hydrothermal mineralisation. In the Glen Avon part of the area lead and zinc drainage anomalies have been identified and their potential is enhanced by proximity to the Lecht mineralisation.

INTRODUCTION

Exploration for stratabound sulphide mineralisation in the Argyll Group of the Dalradian Supergroup was a major theme of the multidisciplinary DTI-funded Mineral Reconnaissance Programme (MRP) in the 1970s. The initial stimulus for the study was the knowledge that certain Argyll Group rocks contained stratabound sulphide mineralisation and, more importantly, were recognised as being similar to those hosting the Stekenjokk Cu-Pb-Zn deposit in Sweden (Smith et al., 1977). Between 1973 and 1987 the MRP identified eight separate levels of stratabound base-metal mineralisation in the Argyll Group of the central and south-west Scottish Highlands (Figures 1 and 2). In economic terms the most significant horizons are those in the Ben Eagach Schists, which host the world-class Aberfeldy Ba-Zn-Pb deposits (Coats et al., 1980).

Following identification of the Aberfeldy deposits in 1979, systematic exploration of the Ben Eagach Schist outcrop led to further discoveries of Ba-Zn mineralisation to the north-east and south-west of Aberfeldy (e.g. Johnstone and Gallagher, 1980; Coats et al., 1984a; 1987a; Smith et al., 1988). The most northerly of these are at Corrie Loch Kander and Allt an Loch near Braemar (Gallagher et al., 1989; Fortey et al., 1993). Although significantly smaller than the Aberfeldy deposits they nevertheless confirmed the prospectivity of the formation in north-east Scotland.

The Dalradian of the central and south-west Highlands is reasonably well exposed and its stratigraphy and deformational history are comprehensively documented. By contrast, prior to the BGS mapping of the 1980's and early 1990's, the Dalradian north-east of Braemar was not well known, so the outcrop of the Argyll Group could not be readily identified. This is mainly due to poor exposure, partially the result of Tertiary deep weathering and, in the extreme north-east, a thick covering of till. Tracing the Argyll Group is further complicated by lateral facies changes and the truncation of the metasediments by major shear zones and large granitoid and basic-ultrabasic bodies.

The lack of knowledge of the Dalradian of north-east Scotland does not render it any the less prospective: rather the reverse. However, exploration has been discouraged by the lack of obvious targets. In particular, there is little visible or historical evidence of mineralisation, and drainage geochemistry, which was the most successful reconnaissance exploration tool elsewhere in the Dalradian, is far less effective in areas of deep overburden. Nevertheless, in the wake of the Aberfeldy discovery a number of exploration projects were undertaken in north-east Scotland. These included work by the MRP and Exploration Ventures Ltd (EVL).

The mineralisation sought was of the sedimentary exhalative (SEDEX) type (Large, 1983), with stratabound sulphates, silicates and sulphides occurring in small, third-order basins in the Middle Dalradian (Figure 3), especially in the Ben Eagach Schist Formation (Coats et al., 1980). Lenses of Pb-Zn sulphides with up to 10% Pb+Zn were found at several localities, and other areas of Ba-enriched sediments also occur (Coats et al., 1984a; 1984b). The mineralisation and the methods used to detect these deposits are described below.

To the north-east of Aberfeldy the most important deposits discovered so far are at Coire Loch Kander and Allt an Loch near Braemar, where geochemical and geophysical surveys carried out by the MRP in 1986 and 1987 found bedded baryte up to 5 m thick, with significant base-metal values, over a 700 m strike length in the Ben Eagach Formation (Gallagher et al., 1989).

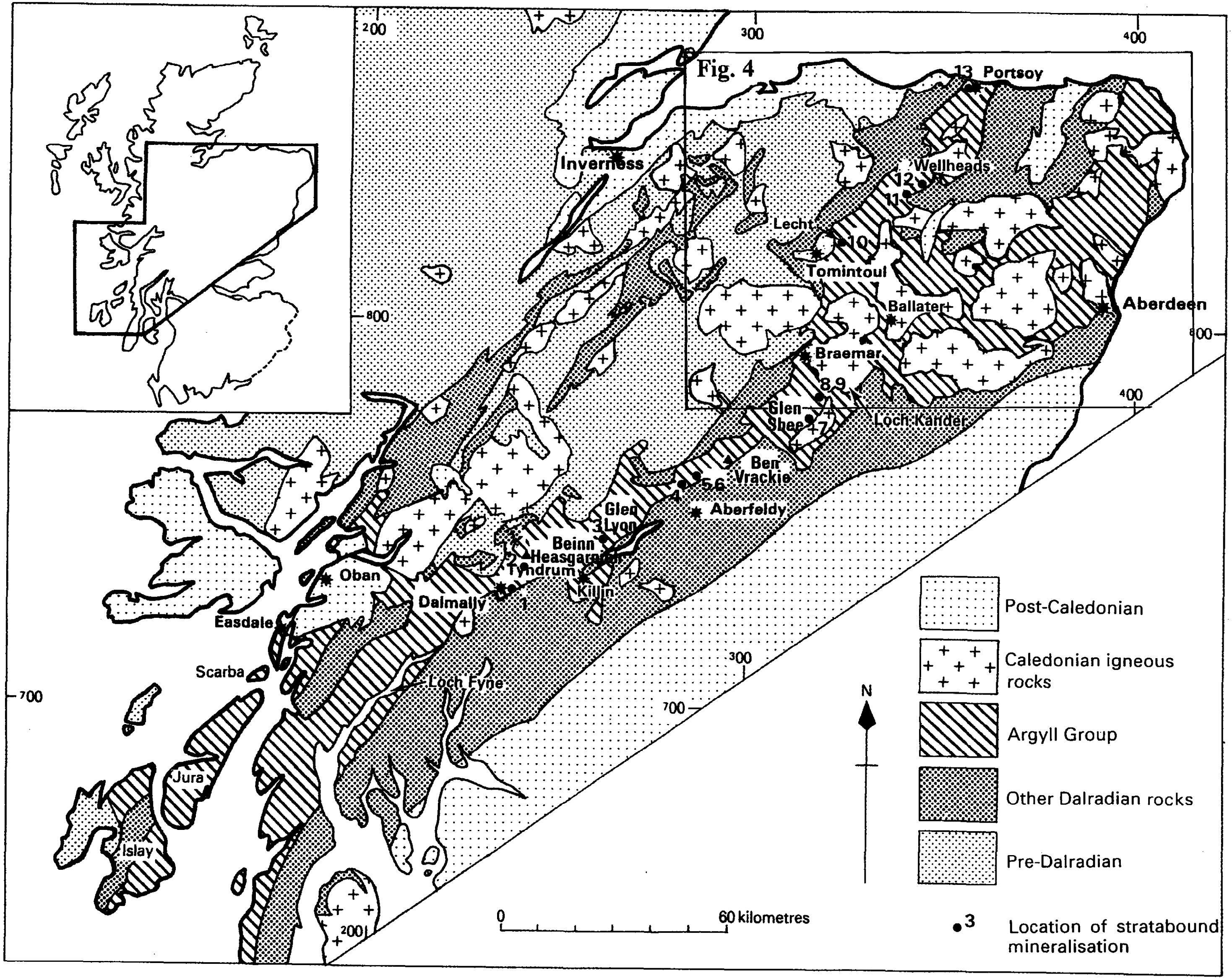


Figure 1 Generalised geological map showing the outcrop of the Argyll Group and location of stratabound mineralisation in the Grampian Highlands of Scotland. The numbers refer to deposits and occurrences listed in Table 1

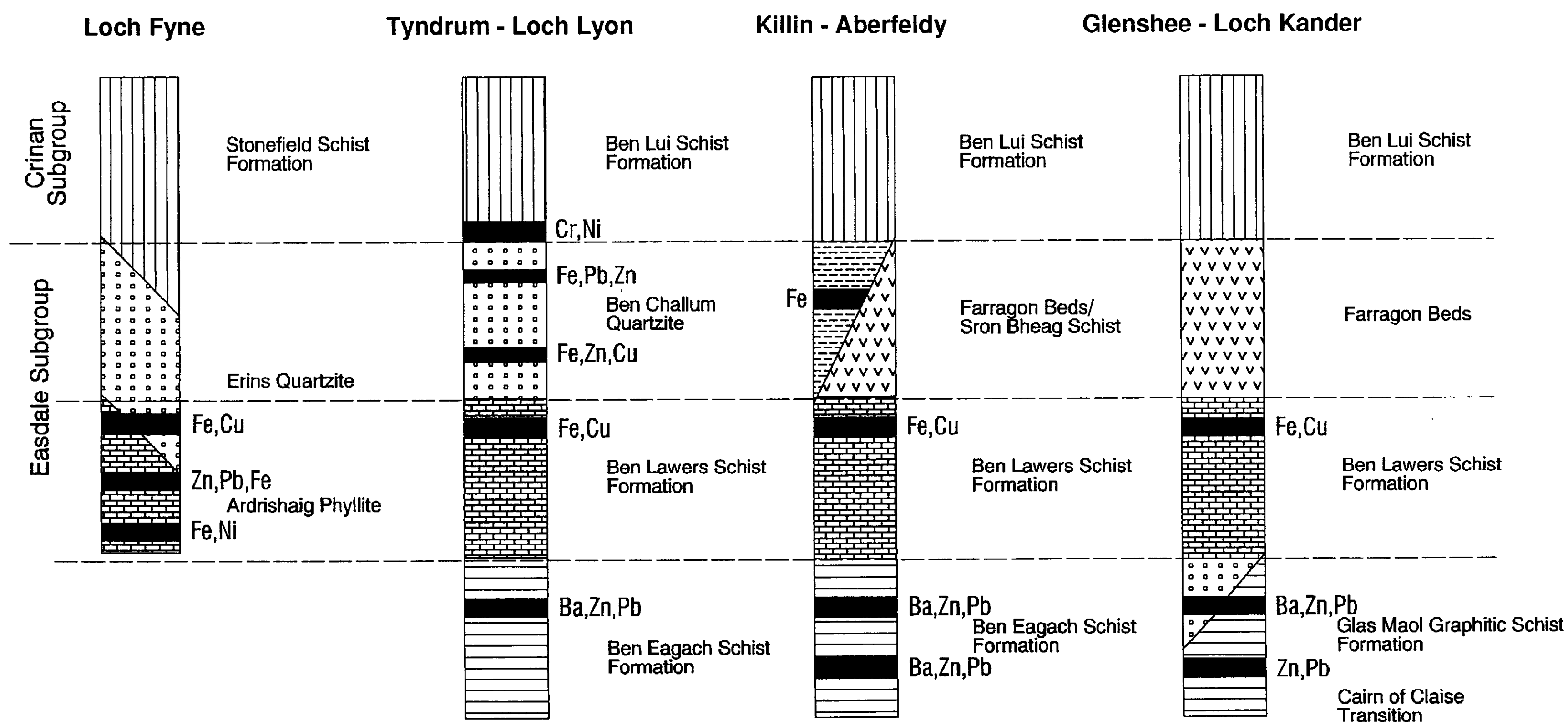


Figure 2a Stratigraphical correlation of the Argyll Group in central Scotland, showing mineralised horizons

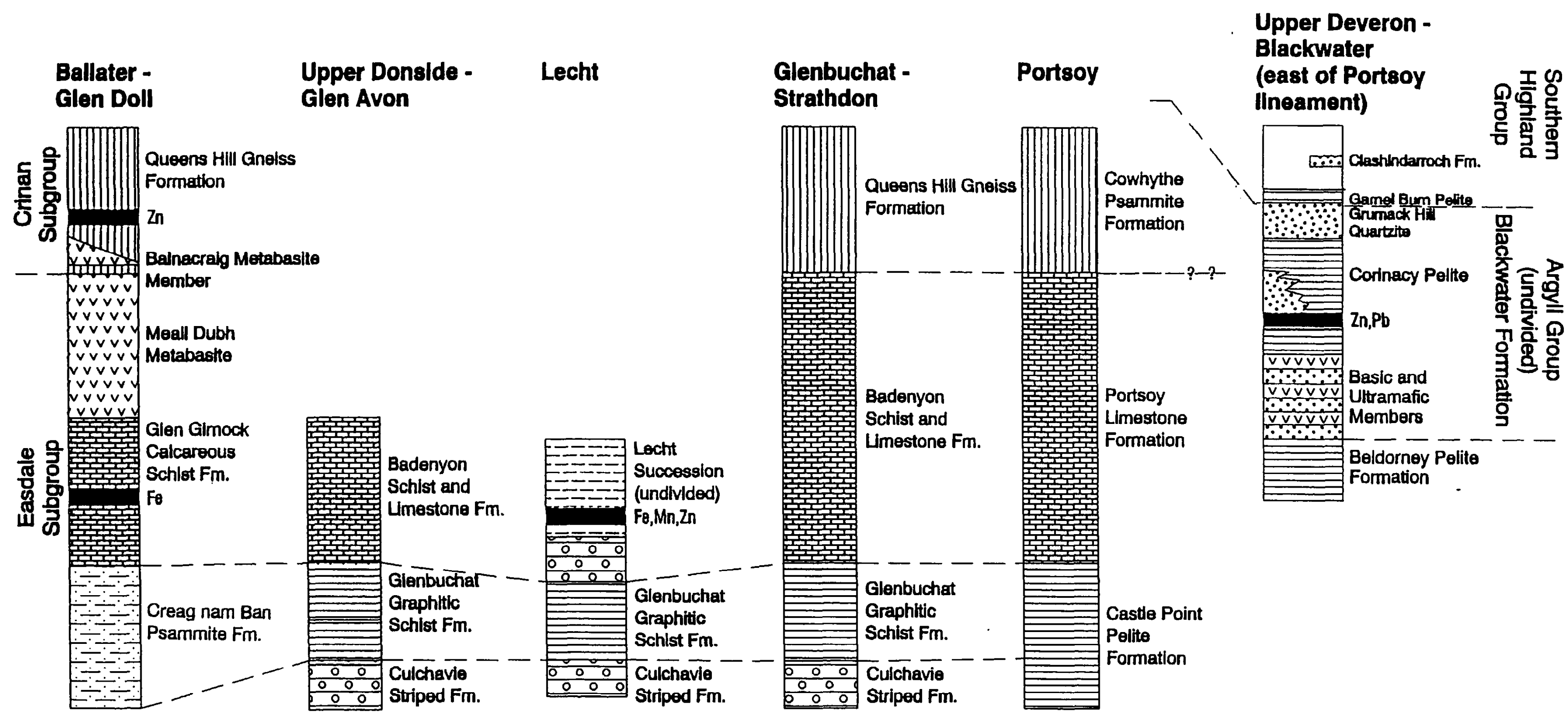


Figure 2b Stratigraphical correlation of the Argyll Group in north-east Scotland, showing mineralised horizons

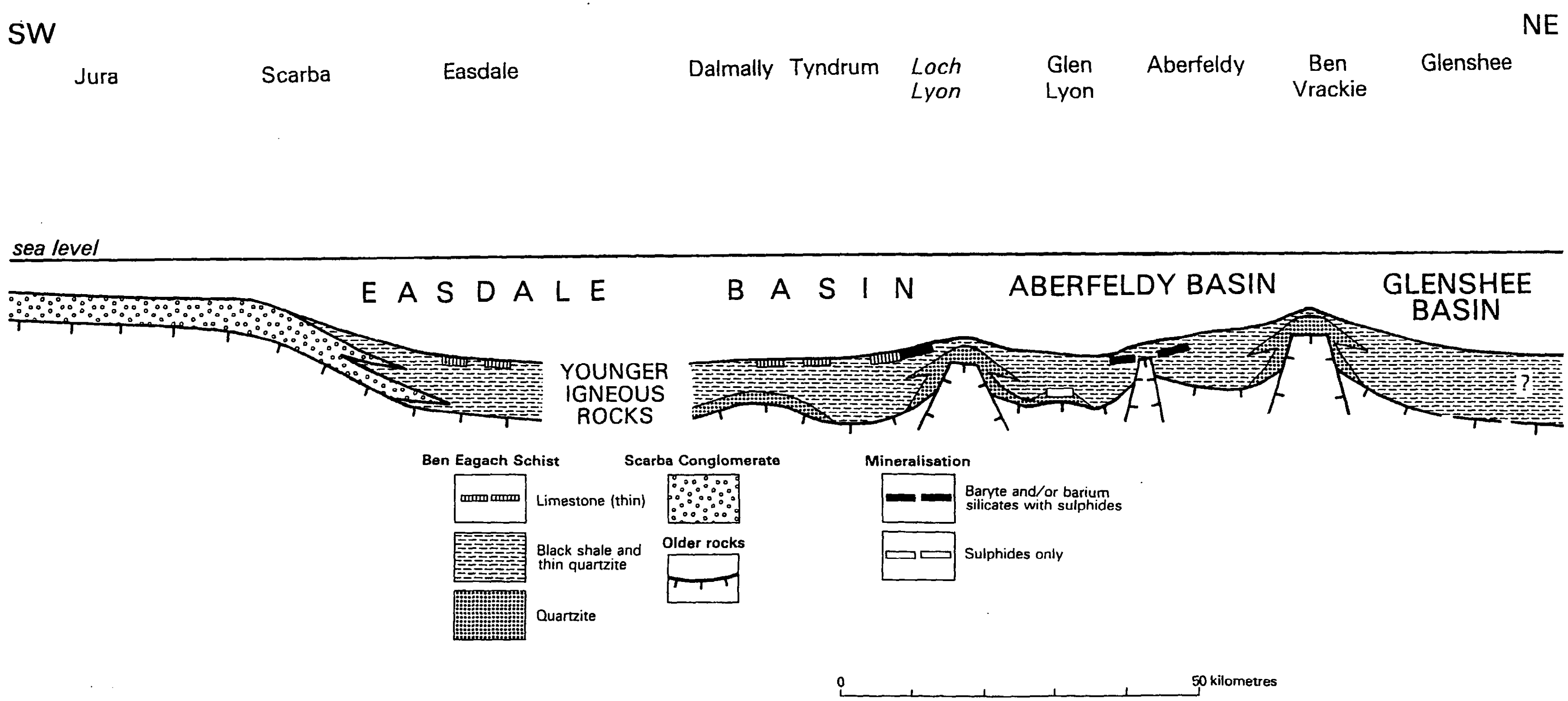


Figure 3 Schematic section of the Dalradian basin at the time of deposition of the Ben Eagach Schist, showing the location of stratabound mineralisation (from Gallagher et al., 1989)

The 100 km tract of the Dalradian belt between Coire Loch Kander and the coast at Portsoy, received less attention than elsewhere, primarily because of the poor exposure and general lack of stratigraphy of this area. The occurrence of Zn anomalies in stream sediments over the Argyll Group outcrop led to investigations at Wellheads (Coats et al., 1987b) and Gouls Burn. Other surveys were carried out over the Lecht manganese mine (Smith, 1985; Smith et al., 1991), and numerous soil megatraverses were sampled over what were regarded at the time as Argyll Group as geochemical input to the East Grampians mapping programme in the mid- to late-1980's. Exploration for base-metals in the Dalradian ended in 1987 following the completion of survey work at Allt an Loch.

In the light of recent BGS geological mapping, the release of EVL data and a general resurgence of interest in base-metals, a new MRP project was set up to assess the mineral potential of the north-east section of the Middle Dalradian. This comprised a desk study involving the evaluation of all existing datasets, detailed below under sources of information, followed by geochemical and geophysical surveys in three broad areas considered prospective for stratabound mineralisation. These three areas were: Ballater–Strathdon, Upper Deveron, and Huntly–Portsoy (Figure 4). The results of these surveys form the basis of this report.

Planning and development framework

The southern limit of the project area lies within the Deeside and Lochnagar National Scenic Area. The terrain here is mountainous with elevations up to 1000 m. The middle section is typically open moorland with moderate relief and free from designated areas except for a few small sites of special scientific interest. The northern area from Huntly to the Portsoy coast has gentle relief and is predominantly agricultural. A good road network crosses the lower ground and there are excellent communications with Aberdeen, a major port and industrial centre with an international airport. The dominant land uses are agricultural grazing and forestry on the lower ground, with moorland grazing and grouse shooting on the higher land. Access to hill areas is facilitated by the use of well-maintained vehicle tracks, which are provided for forestry and sporting purposes.

GEOLOGY

Dalradian: Argyll Group

In north-east Scotland rocks of the Argyll Group can be followed for nearly 80 km from the coast at Portsoy southwards to the Ballater area. Lying above the Appin Group and below the Southern Highland Group, the Argyll Group forms the middle part of the Dalradian Supergroup, a 25 km thick sequence of marine sedimentary and basic igneous rocks which accumulated in an ensialic basin in Neoproterozoic and possibly Cambrian times (Harris et al., 1994). At the time of deposition the Grampian area lay close to the margin of the Laurentian Shield, prior to its collision with the Baltic Shield. The Dalradian succession is considered to have been deposited during several periods of large-scale basin deepening and shallowing, with a progressive increase in tectonic instability and contemporaneous volcanicity with time.

The Argyll Group succession comprises turbidites, quartzites, shales, black shales, limestones together with basic extrusive and intrusive rocks. Sedimentation in the lower part of the group (Islay and Easdale subgroups) took place in a series of fault-bounded second- and third-order basins (Coats et al., 1984 a, b; Anderton, 1985) resulting in rapid lateral facies changes at the basin margins. This feature seriously hinders attempts to establish a regional lithostratigraphy. Correlation is also hampered by the Portsoy Lineament (Fettes et al., 1991), a north-east-trending zone of steeply inclined,

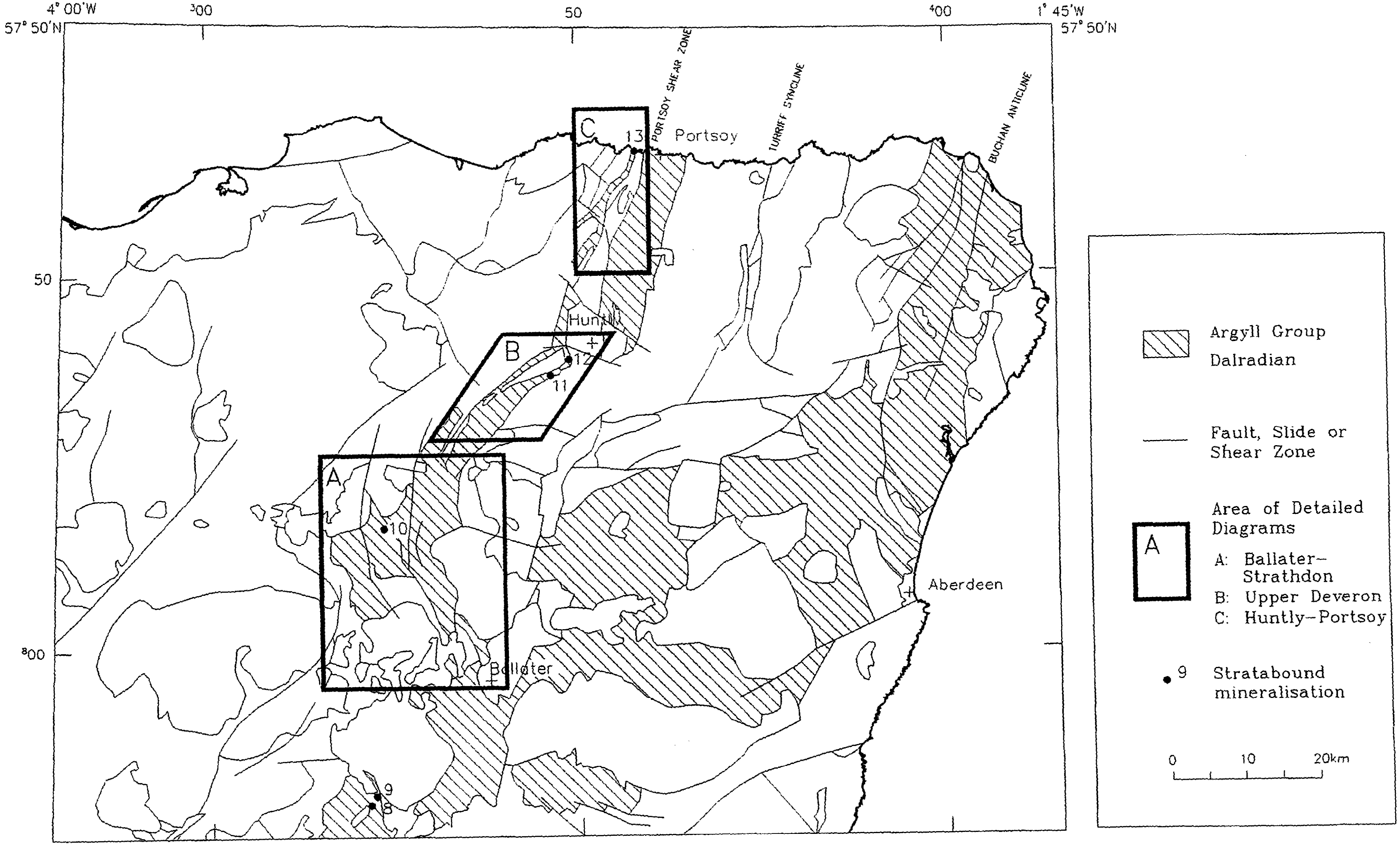


Figure 4 Geological map showing the outcrop of the Argyll Group in north-east Scotland and the location of the study areas. The numbers refer to deposits and occurrences listed in Table 1

anastomosing shears which can be traced through much of the study area. This lineament divides the Appin Group and lowest Argyll Group to the north-west from a distinctly different lithological assemblage of Argyll Group and Southern Highland Group to the south-east (Stephenson et al., 1993). The succession to the north-west of the lineament is both well established and fairly coherent on a regional scale, so that it can be correlated with the sequence in the central Highlands to the south and west and with the Banffshire coast sequence to the north (Figure 2). To the south-east of the lineament broad similarities enable approximate correlations with the Argyll and Southern Highland groups elsewhere, but units and local successions have a restricted extent, and it is difficult to assign them even to subgroups with confidence.

During the early Palaeozoic Caledonian orogenic events, the Dalradian rocks in north-east of Scotland were subjected to polyphase deformation and regional lower- to upper-amphibolite facies. metamorphism of two types: Buchan (high temperature-moderate pressure), characterised by cordierite, andalusite and sillimanite, and Barrovian (high temperature and high pressure) where the index minerals are staurolite, kyanite and sillimanite.

Magmatism

The Dalradian of north-east Scotland has a long history of magmatism. Earliest manifestations are the sheeted basic igneous rocks which were emplaced before the first deformation. Possibly associated with these are serpentinised ultramafic rocks which are largely confined to the area of the Portsoy Lineament. A second generation of basic and ultrabasic bodies, Read's (1919) 'Younger Basics', were emplaced to the east of the Portsoy Lineament during the third deformation. The final magmatic phase was the intrusion during the late Silurian of granitoid plutons in the Ballater district.

Tertiary and Quaternary

In common with other parts of north-east Scotland, the study area was subjected to deep subtropical weathering during the Miocene, with the resultant degradation of the bedrock. Although some of the unconsolidated material was removed during the Quaternary glaciation, patches extending to a depth of several metres survived where the ice was locally static. During the late Devensian glaciation most if not all of the area would have been ice-covered. The pre-existing topography was modified and the northern part of the area plastered with a thick blanket of till. In the last major ice readvance, during the Loch Lomond stadial, corrie glaciers formed on the higher slopes. Subsequent melting of the ice created a number of spectacular glacial overflow channels and, in some of the major river valleys, extensive fluvioglacial sand and gravel deposits were deposited.

MINERALISATION AND PREVIOUS EXPLORATION

Recognition of the 'Pyrite Zone' within the Easdale Subgroup of the Dalradian Supergroup was based on observations, during excavation of tunnels for hydroelectric power, of pyrite-bearing rocks in the Ben Lawers Schist Formation in Glen Lyon (Johnstone and Smith, 1965). This Pyrite Zone was one of the first targets of the MRP, which traced its outcrop from Loch Fyne to Glenshee (Smith, 1977).

As part of these early MRP investigations drainage geochemical sampling over the Argyll Group north of Aberfeldy led to the discovery of the baryte and base-metal mineralisation within the Ben Eagach Schist Formation (Coats et al., 1978; 1980; 1981). This mineralisation occurs in two principal horizons, both stratigraphically lower than the Pyrite Zone. Study of these occurrences led to the development of a mineralisation model (Figure 3) that assisted in further discoveries. Occurrences of baryte and/or base-metal mineralisation were found in the same formation at Glen Lyon (Coats et al., 1984a), Ben Heasgarnich (Coats et al., 1984b), Glenshee (Pease et al., 1986; Coats et al., 1987b) and Loch Kander (Gallagher et al., 1989 and Fortey et al., 1993). Company work at Aberfeldy identified two economic zones of baryte mineralisation and production from the upper horizon commenced at Foss in 1985. The principal occurrences of stratabound base-metal and baryte mineralisation discovered in the Dalradian are listed in Table 1.

Table 1 Main deposits and occurrences of Dalradian stratabound mineralisation

Ref. No.*	Deposit name	Grid reference	Host rock/mineralisation	Elements, commodities
1	Auchtertyre	NN 365 310	Ben Challum quartzite	Zn Cu Pb
2	Beinn Heasgarnich, Loch Lyon	NN 413 383	Barium-enriched calcareous schist near the top of the Ben Eagach schist	Ba Zn Pb
3	Dericambus, Glen Lyon	NN 675 462	Quartzite and graphitic schist with disseminated galena and sphalerite	Zn Pb
4	Foss Mine	NN 814 545	Graphitic schist, quartz-celsian rock near the top of the Ben Eagach schist	Baryte (in production) Zn Pb
5	Ben Eagach Quarry	NN 856 565	Ba-rich muscovite schist, quartz-celsian rock, graphitic schist	Baryte Zn Pb
6	Duntanlich	NN 870 568	Ba-rich quartzite, laminated quartzite, graphitic schist, massive sulphide layers	Baryte Zn Pb
7	Allt an Daimh	NN 141 717	minor amounts of galena, sphalerite, pyrite and pyrrhotite in laminated quartzites	Zn Pb Cu
8	Allt an Loch	NO 196 796	Bedded baryte-quartz rock at the top of the Ben Eagach Schist	Baryte
9	Coire Loch Kander	NO 192 807	Stratabound sulphides in a 15 m band of Ba-rich quartzite close to the top of the Ben Eagach Schist	Baryte Zn Pb
10	Lecht	NJ 238 159	Iron and manganese derived by leaching of stratabound enrichments in adjacent Dalradian metasediments	Fe Mn
11	Gouls Burn	NJ 422 349	Black schist with sphalerite	Zn
12	Wellheads	NJ 489 380	Graphitic quartzite, chert and intraformational breccias with stratabound pyrite and ?sphalerite	(?) Zn
13	Portsoy	NJ 580 670	Graphitic schist and limestone, sphalerite and pyrite coating	Zn Fe

* Shown on Figure 1.

It is now recognised that there are at least five, and possibly up to eight, horizons at which stratabound synsedimentary mineralisation is present within the Argyll Group (Figure 2) and that, whilst certain stratigraphic levels are the preferred locations, because of rapid facies changes, local synsedimentary faulting and volcanic episodes, the whole of the Argyll Group and the lower part of the Southern Highland Group are prospective for base-metal mineralisation. These horizons are located within the Ben Eagach Schist, Ben Lawers Schist, Ben Challum Quartzite and Ben Lui Schist formations in the central and south-west Highlands (Smith et al., 1984). Their stratigraphic position is indicated in Figure 2 and they change in character from being dominantly Ba, Zn and Pb-bearing in the lower part, to being dominated by Fe, Cu and Zn in the upper part. This change in chemistry is related to the increase in mafic volcanicity during continued evolution of the sedimentary basin.

Previous exploration: BGS work

Methods of exploration for stratabound deposits in the Dalradian have been outlined by Coats et al. (1984 a), but these techniques are less efficient in the lower, more drift-covered ground to the north-east. MRP drainage geochemical surveys covered most of the outcrop of the Argyll Group from Loch Fyne to Glenshee (Coats et al., 1982), and this involved detailed drainage sampling upstream of Ba and base-metal anomalies. Further to the north-east, geochemical sampling was carried out by the BGS G-BASE Programme (then the Geochemical Survey Programme) in 1980–81 at a density of about 1 sample per 1.5 km^2 and reported in the East Grampians Geochemical Atlas (British Geological Survey, 1991). This reconnaissance sampling was followed-up in 1982 and 1983 by the MRP with detailed resampling of the original sites and at about 200–400 m intervals upstream of Ba and base-metal anomalies, where they occurred on Dalradian rocks thought to be correlated with the Ben Eagach Schist and also near known mineral occurrences. The following threshold levels were used to identify anomalies in the East Grampians Geochemical Atlas area: Ba > 1000 ppm, Cu > 45 ppm, Pb > 80 ppm and Zn > 300 ppm.

At the time of the regional geochemical survey, geological remapping of the East Grampians had only just started and identification of even the major subdivisions of the Dalradian was difficult. The existing 1 inch scale geological maps were essentially lithological and no lithostratigraphy had been attempted by the compilers. Also, the extent of major shear structures such as the Huntly-Portsoy lineament (Fettes et al., 1991) which juxtapose very different parts of the Dalradian succession, was not recognised. Thus, the follow-up sampling in the period 1982–83 was driven more by the geochemical anomalies and known mineralisation than a detailed knowledge of Dalradian stratigraphy, which is only now being published by BGS in a series of 1:50 000 maps and memoirs.

The drainage sampling follow-up areas are listed in Table 2. The subgroups listed in this table are those which form the majority of the stream catchment, and other lithologies, such as meta-igneous rocks, may form some part of the catchment geology. Analytical data for the East Grampians Atlas samples and the subsequent follow-up drainage sampling are available from the BGS Geochemistry Database.

Subsequent Mineral Reconnaissance Programme investigations in north-east Scotland were concentrated in three areas, the Lecht, Succoth–Gouls and Wellheads, and each of these three areas was covered by shallow overburden (soil) sampling and geophysics (Smith, 1985; Coats et al., 1987b; Smith et al., 1991). These three areas were chosen because the anomalies were reproducible and increased upstream of the original site.

Table 2 Follow-up drainage sampling areas in north-east Scotland

Name	1 km Grid Square	Subgroup (1995)	Anomalous metals
Burn of Loinherry	NJ 24 11	Easdale	Mn, Cu, Zn, Ba, Pb
Lecht	NJ 23 15	Easdale	Mn, Zn, Ba, Pb
Scalan	NJ 24 19	Blair Atholl	Zn
Milltown Burn	NJ 26 09	Islay	Mn, Zn, Pb
Coire Riabhach	NJ 26 12	Islay	Zn, Pb
Slochd Burn	NJ 25 18	Islay	Zn
Allt Slochd Chambeil	NJ 26 16	Islay	Zn, Pb
Allt an t-Slochd Mhor	NJ 27 17	Islay	Zn
Ladder Burn	NJ 27 19	Islay	Cu
Kymah Burn	NJ 29 22	Islay	Cu
Water of Nochty	NJ 30 15	Easdale	Cu
Glenbuchat Lodge	NJ 32 18	Easdale	Cu
Leadensider Burn	NJ 33 20	Easdale	Cu
River Livet, Suie	NJ 26 23	Glenlivet granite	Zn, Pb
Gouls	NJ 42 34	Easdale	Mn, Cu, Zn
Succoth	NJ 42 35	Easdale	Mn, Cu
Markie Water	NJ 37 35	?Ballachulish	Mn, Zn, Ba, Pb
Wellheads	NJ 48 39	Easdale	Mn, Zn, Pb
Cairnborrow	NJ 45 41	Blair Atholl	Mn, Cu
Meikle Balloch Hill	NJ 48 50	Ballachulish	Pb
Mains of Edingight	NJ 51 55	Blair Atholl	Pb

The Lecht

The Lecht area was of interest because of the known Fe-Mn mineralisation and Mn, Zn, Ba and Pb anomalies in drainage samples. It was the subject of a high-cost data package released in 1983 and has been briefly reported by Smith (1985). Six boreholes were drilled adjacent to the old workings and on a previously unknown, anomalous Mn zone identified by the shallow overburden sampling. This 58 m thick, Fe-Mn -rich zone was shown to be stratabound and mainly due to the presence of spessartine garnet in the metasediments. The stratigraphic position of the host formation was unclear at the time, but it is now considered to form part of the Argyll Group and may be part of the Easdale Subgroup. The stratabound Mn mineralisation was the first to be identified in the Dalradian of the East Grampians and may be correlated with the lower mineralised horizon at Aberfeldy, which shows Mn enrichment at Ben Eagach (Coats et al., 1980). The origin of the breccia ore worked at the Lecht is controversial, and various theories have been put forward by Nicholson (1987) and Smith (1985; 1989). Limited work in 1983, not contained in an MRP report, involved further shallow overburden sampling and geophysics south of the Lecht.

Succoth–Gouls

This area was sampled in 1982 and again in 1985 as part of the BGS East Grampians mapping project. No subsequent follow-up was conducted, except for limited lithogeochemical sampling for the platinum-group elements (PGE), on the Succoth–Brown Hill serpentinite body (Gunn et al., 1990). The intervening ground between this area and Wellheads is poorly exposed, and geochemical sampling of the stream sediment is unlikely to produce a good representation of the underlying geology and mineralisation. In the course of the present study, therefore, further shallow overburden traverses were run across the ground between Succoth and Wellheads in order to test the continuity of Zn and Pb anomalies between the two areas (see below).

Wellheads

The Wellheads area was the subject of MRP follow-up work in 1983–86. The original G-BASE anomalies of 1152 ppm Zn and 104 ppm Pb in the lower part of the Wellheads stream were confirmed, and detailed sampling upstream showed increased anomalies to 1880 ppm Zn and 180 ppm Pb. Four shallow overburden lines (0, 250, 500 and 750 m S) were laid out across the valley at approximately right angles to the strike and, when these returned maximum values of 7838 ppm Zn and 725 ppm Pb, the deep overburden was sampled with a power auger. It was recognised during the shallow overburden work that the base-metal anomalies were probably hydromorphic in origin, and this influenced the decision to proceed with geophysical surveying and deep overburden sampling. The results confirmed those from the shallow overburden survey (Zn reached 1.06% in one sample of the deep overburden), and six diamond drillholes were bored in 1986 on the deep overburden and geophysical anomalies. The drilling results indicated the presence of deep till infill in the Wellheads valley, reaching 30 m in places, and the deep overburden sampling mainly proved anomalies perched in the top 5–10 m of the till. The results of the Wellheads work were issued as a high-cost package and brief report (Coats et al., 1987a). Geological mapping at the 1:10 000 scale of Sheet NJ 43 NE was completed in 1994 and published in 1996. The rocks intersected in the drilling were dominantly pelites and semipelites of the Corinacy Pelite Member of the Blackwater Formation, but the third borehole (BH3) proved andalusite schist at the base of the Clashindarroch Formation. The final borehole (BH7) intersected a sequence of dark pelites with intraformational breccias and limestone units within the Corinacy Pelite Member.

Traverse-based overburden sampling

With a developing understanding of the role of basin sedimentation in the genesis of stratabound mineral deposits, a further exploration technique of long, across strike, geophysical and geochemical megatraverses was employed in 1983 (Coats et al., 1984a) and this method helped to identify the Allt an Loch mineralisation. In the East Grampians area, four megatraverses were surveyed: the Lecht, Blackwater Forest, Chapeltown and Portsoy. A few shorter lines were also sampled to the south of Portsoy (see below) because the stratigraphic position of the coastal section was fairly well known in 1983. This approach of long, across-strike geochemical and geophysical traverses was also employed by the East Grampians project mapping and a large number of ground magnetic and geochemical traverses were used to aid mapping in drift-covered areas. The results are incorporated in this report where relevant.

Previous exploration: private-sector surveys

Exploration Ventures Limited (EVL), a consortium of Consolidated Goldfields and Rio Tinto Zinc, carried out extensive mineral exploration surveys between 1968 and 1973 over the basic and ultrabasic rocks of north-east Scotland in the search for nickel, chrome and copper deposits.

Stratabound mineralisation within the Dalradian was not considered a primary target at that time. However, the western margin of the survey area (Figure 5b) includes surveys over part of the Argyll Group outcrop, notably between Huntly and Portsoy, where basic and ultrabasic rocks are intruded into metasedimentary rocks, and at Strathdon, where metasedimentary rocks occur adjacent to the western margin of the Morven-Cabrach intrusion.

The work carried out included geochemical and both ground and airborne geophysical surveys. Summary information of the airborne geophysical surveys is contained in MRP Report 136 (Cornwell et al., 1995). An account of the exploration programme can be found in Wilks (1974), and further information on data arising from this work is given below.

SOURCES OF INFORMATION

For the desk study, all relevant information available was collected and, where necessary, converted to digital form to allow merging and plotting of multiple datasets using computer software. The datasets compiled and reviewed are described below.

Geological mapping

The outcrop of the Dalradian in north-east Scotland is currently being mapped at 1:10 000 scale as part of the BGS East Grampians Mapping Project. Of the maps available at this scale, almost half of the sheets to the north of Ballater have been completed and approved for publication during the last three years.

Digital geological linework obtained from the East Grampians Geochemical Atlas (British Geological Survey, 1991) provided the only complete generalised digital geological dataset covering the entire Argyll Group outcrop in north-east Scotland. This 1:250 000 scale geological linework requires some revision in the light of recent mapping, but provides a useful general guide for mineral exploration. Where available, linework from recent geological compilations covering the Huntly-Portsoy area has been digitised and shows the location of the major faults, intrusions and shear zones.

The Ballater–Strathdon area, which includes the Lecht manganese deposit, is covered by the recently published (June 1995) 1:50 000 map sheets 75W (Glenlivet) and 75E (Glenbuchat). The area south of the Dee lies within sheet 65E (Ballater), which is in press. These three maps are available in digital form and provide the most recent stratigraphic correlation of the Argyll Group sequence in this region.

Over poorly exposed ground within the Deveron belt, basic and ultramafic volcanic rocks and intrusions, and some pelitic rocks within the Blackwater sequence have been mapped using ground magnetic surveys (Fettes et al., 1991) and traced in places for several kilometres. Much of the geological information at 1:10 000 scale in this area has therefore been derived from magnetic contour maps.

Between Huntly and Portsoy geological information is sparse, due to the poor exposure in this area. Here, Argyll Group metasedimentary rocks are highly sheared and frequently displaced, and the cover of thick glacially derived till further hinders correlation. Only 1 inch to the mile maps, supplemented by a few 1:10 560 and new 1:10 000 scale maps, were available.

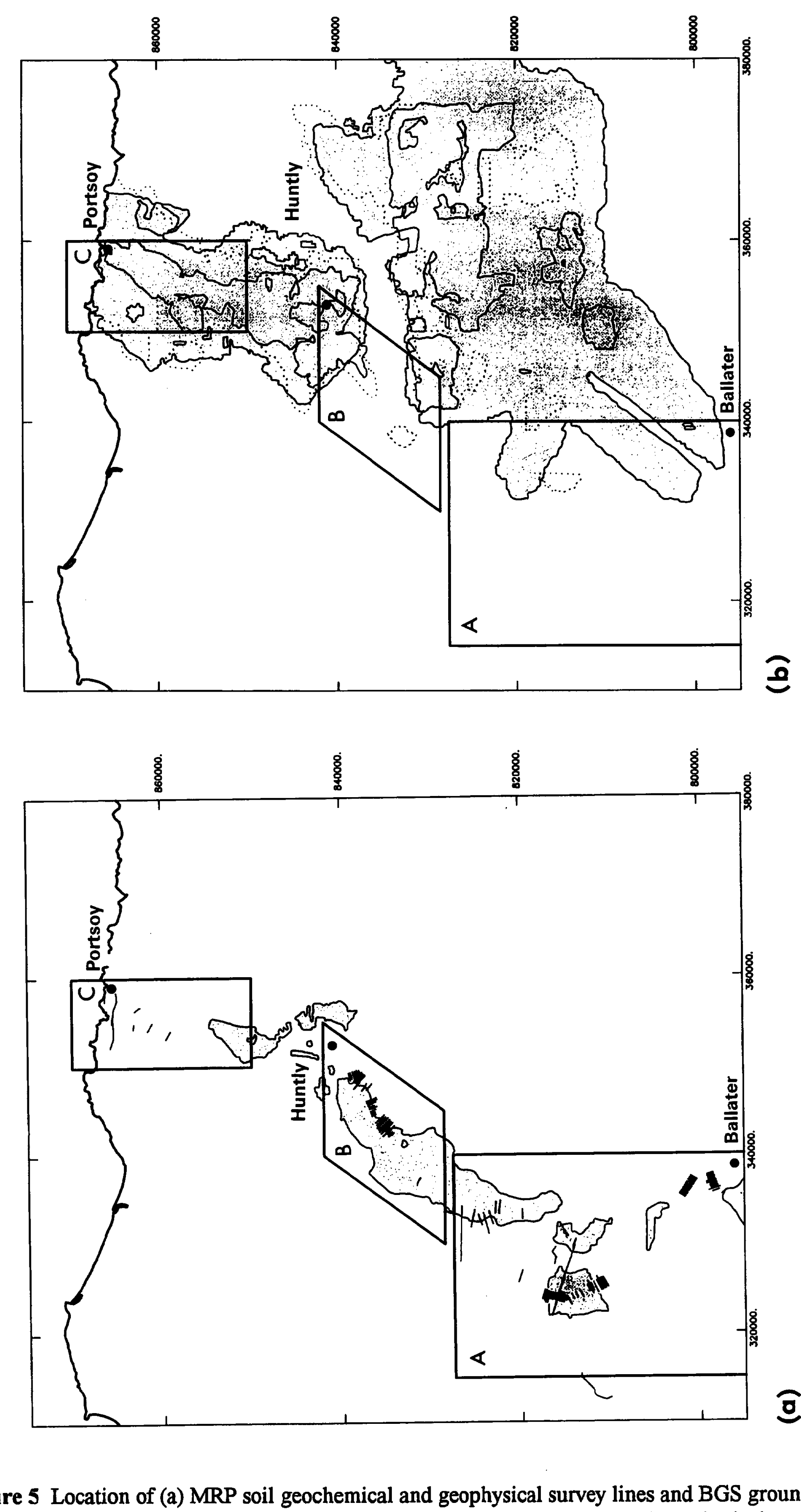


Figure 5 Location of (a) MRP soil geochemical and geophysical survey lines and BGS ground magnetic data (shaded area), and (b) EVL airborne (shaded area) and ground geophysical surveys (solid lines within shaded area), and geochemical surveys (dotted lines) in north-east Scotland

Geochemical Baseline Survey of the Environment (G-BASE)

This Programme, formerly known as the BGS Geochemical Survey Programme, has collected and analysed stream sediment and water samples from surface drainage over all of Scotland, Wales and Northern England, at an average density of one sample per 1.5 km^2. The results are available in digital form from the Geochemistry Database, and the data are published as contoured element maps in the East Grampians Geochemical Atlas (British Geological Survey, 1991).

Mineral Reconnaissance Programme

Drainage, soil (overburden) and lithogeochemical data collected under the Mineral Reconnaissance Programme (Figure 5) is available in digital form from the BGS Geochemistry Database. Megatraverse data is also held on this database.

Geophysical megatraverse data and detailed surveys are listed in the MRP Geophysical Local Surveys Database. Most of the surveys from 1986 to date were surveyed using digital equipment and are thus in digital form. Most of the older megatraverse data covering this study area have been digitised but some data for the Lecht area remain in analogue form.

BGS aeromagnetic and gravity data

The aeromagnetic survey of the United Kingdom was flown for the Geological Survey of Great Britain between 1955 and 1965, and analogue records have been subsequently digitised (Smith and Royles, 1989). Digital data are available for the whole of the UK land mass and adjacent sea areas. Data coverage for north-east Scotland consists of east–west flight lines 2 km apart with north–south tie lines at 10 km intervals. The mean terrain clearance is 305 m (1000 feet). This dataset provides a uniform coverage suitable for regional assessment but in most cases lacks the detail required for mineral exploration.

There are currently over 150 000 regional gravity stations on land in the BGS database. Data coverage for Scotland is approximately 1 station per 2 km^2 in upland areas and roughly 1 station per km^2 in lowland areas. The data are available as maps in the BGS 1:250 000 UTM series, and grids and images of the data can be provided to customer requirements.

High-resolution airborne surveys

High-resolution airborne magnetic, EM and radiometric surveys were carried out for the MRP between 1972 and 1978. In addition, various exploration companies also undertook surveys over large areas of the Grampian region of Scotland, some of which are available in digital form from the BGS. Details of these surveys and the availability of data are contained in MRP Report No 136 (Cornwell et al., 1995). Surveys relevant to the Argyll Group include an MRP survey between Blair Atholl and Glenshee (Burley and Howard, 1976), and commercial surveys by Exxon Minerals Company (ten separate areas from Loch Awe to Glenshee in 1983) and Exploration Ventures Limited (EVL) flown over much of Aberdeenshire in 1970 (see below).

Ground magnetic data

BGS holds digital ground magnetic traverse data surveyed for the East Grampians mapping project to assist geological mapping in areas of poor exposure (Figure 5). These cover most of the Argyll Group volcanic and metasedimentary sequence within the Upper Deveron belt. The surveys were carried out by the BGS, Aberdeen University and Queens University Belfast. Magnetic measurements were made at 20 m intervals along east–west or north-west–south-east oriented survey lines, spaced roughly 200 m apart.

Exploration Ventures Limited (EVL) data

The EVL surveys (see above) were part-funded by the Department of Trade and Industry under the Mineral Exploration and Investment Grants Act (MEIGA) scheme and are on open file at the BGS. A considerable quantity of data, maps and reports are stored and indexed at BGS Edinburgh, and in the National Geological Records Centre (NGRC) at BGS, Keyworth. An account of the EVL exploration programme in north-east Scotland is contained in EVL report No R01/1 (Wilks, 1974) and an index to EVL geophysical data and other exploration surveys carried out under the MEIGA scheme is held by the BGS. The most useful EVL surveys across the Middle Dalradian are listed below. Asterisks denote data digitised from contoured maps.

Geochemical surveys

- (i) Reconnaissance and detailed soil sample surveys

Airborne geophysical surveys

- (i) Fairey Surveys Ltd - aeromagnetic survey
- (ii) Barringer Research Ltd - Combined helicopter EM/magnetic survey *

Ground geophysical surveys

- (i) Reconnaissance Induced Polarisation (IP) surveys *
- (ii) Detailed Dipole - Dipole and Gradient array IP surveys
- (iii) Ground follow-up of helicopter EM survey

Extensive geochemical drainage sampling was also carried out over the Dalradian of north-east Scotland, but the range of elements analysed was limited to Cu, Ni, Pb and Zn and these were determined by an acid attack and atomic absorption spectrometry (AAS). The drainage sampling covered much of the Argyll Group but, because it was not available in a digital form and was essentially duplicated by the G-BASE work, it was not used to identify geochemical anomalies in this assessment.

Data evaluation and selection of field survey areas

Integrated geophysical, geochemical and geological linework assembled for this study are stored in a variety of formats including GEOSOFT. Following compilation, digitisation, processing and integration of these datasets, plots of selected variables were examined for features favourable for the occurrence of stratabound mineralisation, based on the geological models developed in the Aberfeldy and other areas of similar geology and mineralisation (e.g. Coats et al., 1984 a, b). This work resulted in the identification of three general areas (Figure 5) containing geochemical and geophysical anomalies and geological features which merited field investigation to determine whether there was any evidence for potentially economic concentrations of stratabound mineralisation in the vicinity. The work carried out in these three areas, Ballater–Strathdon, Upper Deveron and Huntly–Portsoy, is described below.

BALLATER–STRATHDON

This is the largest of the three designated study areas. Regional correlation of the lithostratigraphy of the Argyll Group in this area has only recently been made possible after the completion of mapping by the BGS East Grampians Project, which resulted in the publication of three 1:50 000 geological maps, 75W (Glenlivet), 75E (Glenbuchat) and 65E (Ballater), in 1995/96.

General geology and lithostratigraphy

A correlation of the stratigraphy of the Dalradian rocks of the East Grampians Project area is described in Stephenson et al. (1993), and the most recent correlations are summarised on the 1:50 000 scale geological maps. A more detailed account of the geology of the area can be found in the Memoirs accompanying these maps.

Within the study area the Argyll Group can be simplified into five main lithostratigraphic sequences. These are correlated where possible with equivalent rocks in the central Perthshire succession (Figure 2).

In the Ballater area (A in Figure 6) the Argyll Group lies to the east of the Portsoy Lineament. The overall sense of younging in the Dalradian rocks, as deduced from the gross lithostratigraphy, is to the south-east or east, so the strata form a right-way-up succession. Throughout much of the Ballater district the regional strike of the Dalradian rocks is north-east, although more variation is evident close to Ballater, where certain sections show a more east-north-east oriented alignment. The regional dip is to the south-east at moderate angles. Further to the north of Ballater the regional strike displays a marked change to a north-north-west direction.

The Glen Girnock Calcareous Formation (Figure 2) is predominantly a mixed sequence of calc-silicate rocks, locally pyrrhotite-rich, with quartzites, pelites and limestones. This formation overlies the Creag nam Ban Formation which is a fairly monotonous sequence of psammite and semipelite. Despite the very obvious lithological differences, the Creag nam Ban Formation is equated with the metalliferously fertile Ben Eagach Schist Formation in the Perthshire succession. The succession above the Glen Girnock Calcareous Formation mirrors than in Perthshire with the succeeding volcanogenic Meall Dubh Metabasite Formation being the lateral equivalent of the Farragon Beds.

The complete Glen Girnock succession and its relationship with other Dalradian rocks is only seen south of the river Dee. To the north of the Dee, the formation overlies a predominantly amphibolitic block and the upper part is progressively cut out by the Ballater Granite. Above the Glen Girnock Calcareous Formation the Queens Hill Gneiss Formation consists of migmatites, and semipelitic gneiss and is assigned to the Crinan Subgroup.

In the Glenbuchat district (B in Figure 6) west of the Portsoy Lineament, rocks of the Culchavie Striped Formation, Glenbuchat Graphitic Schist Formation and Badenyon Schist Formation represent a continuous stratigraphic sequence of micaceous psammite and semipelites, graphitic pelites, and schists and limestones respectively. The Glenbuchat Graphitic Schist Formation is thought to be the lateral equivalent of the Ben Eagach Schist Formation which hosts the mineralisation at Aberfeldy.

Further to the west, in the upper Donside-Glen Avon district (area C, Figure 6) the rocks are regarded as equivalent to those of the Glenbuchat area although the Glenbuchat graphitic schist here has an amphibolite unit in its upper part.

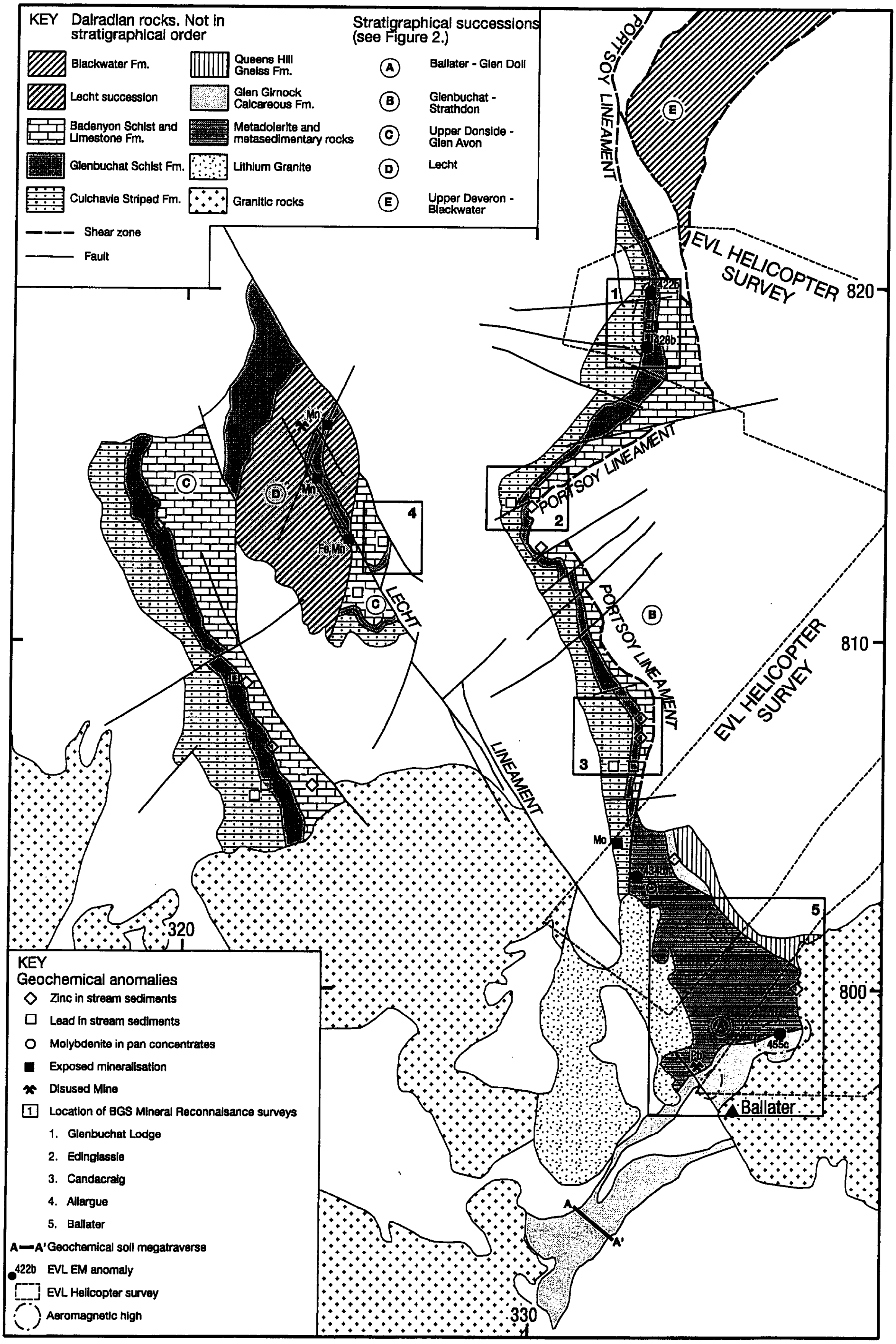


Figure 6 Geological map of the Ballater–Strathdon area showing the location of MRP surveys, mineral occurrences, Pb and Zn drainage anomalies, and EVL airborne geophysical anomalies

At the Lecht (area D, Figure 6), and in the Upper Deveron Blackwater belt (area E, Figure 6), it is difficult to assign the rocks to a particular lithostratigraphical unit or even subgroup within the Dalradian succession. The Lecht block is largely fault-bounded, so correlation with the adjacent Dalradian cannot be easily established. However, the rocks are assigned to the Argyll Group on the basis of limited exposures of Boulder Bed and/or the passage to Appin Group rocks through poorly exposed ground on the south-east side of the block. The lithological units which make up the Lecht succession are not directly comparable with formations in the adjoining areas and were probably deposited in a half-graben bounded on the north-east side by the Lecht Lineament. Way-up evidence from surface and boreholes indicates a general easterly sense of younging.

Lithologies within the Lecht succession range from quartzose, gritty psammites to micaceous psammites, semipelites and graphitic pelites and are of a lower metamorphic grade than the surrounding rocks. Manganese and iron are both abundant in the sequence, and micaceous psammites and semipelites containing fine-grained magnetite produce conspicuous aeromagnetic and ground magnetic anomalies. The sequence is bounded to the north-east by a north-west-trending major fault, part of the Lecht Lineament, and to the south-east by a major fault trending 005°.

In the Glenbuchat-Blackwater area (area E, Figure 6) lithologically distinctive rocks, similar in character to Argyll Group rocks elsewhere in Scotland, are bounded by major shear zones and faults relating to the Portsoy Lineament. Because of the intense shearing and faulting it is not possible to relate them to the Argyll Group rocks immediately west of the Portsoy Lineament, or to establish a lithostratigraphic succession within the shear zones. They are termed here the Scors Burn Schist Formation and the Blackwater Formation (Fettes et al., 1991). It is not possible at the present state of knowledge to allocate these formations to the recognised subgroups of the Argyll Group.

The Blackwater Formation, which hosts the Gouls and Wellheads mineralisation, is thought to comprise a continuous south-east-younging stratigraphical sequence, with marked along-strike facies changes in the upper part. The formation is characterised by gritty psammites, dark grey pelites and semipelitic andalusite-schists, all of a general turbiditic nature.

Metavolcanic rocks within the Blackwater Formation produce high-amplitude magnetic anomalies and have been mapped across most of the Upper Deveron belt using ground magnetic data. However, some of the pelitic and semipelitic rocks which contain magnetite thought to be of igneous origin (Fettes et al., 1991), also produce magnetic anomalies.

Mineralisation and previous work

The principal mineral occurrences are shown on Figure 6. At Abergairn [NJ 3550 9735] lead was mined on a small scale in the nineteenth century, although the exact date of the working is uncertain. The mineralisation lies within a north-north-west-trending fault-controlled vein in pyritic schists of the Glen Girnock Calcareous Formation, and is thought to be due to a late-stage process related to the emplacement of the Ballater or Coilacriech granite.

To the north and west of Ballater (area 5), stratabound pyrite and pyrrhotite mineralisation has been identified in rocks of the Glen Girnock Calcareous Formation. This formation, which is up to 1300 m thick, is part of the Easdale Subgroup and is equated with the lithologically comparable Ben Lawers Schist in the Perthshire succession. It can be followed for just over 13 km in the ground between the

Lochnagar and Ballater granites. To the north of this area anomalies of Mo in pan concentrates, centred on Morven Lodge [NJ 339 030] are associated with skarn mineralisation related to granite at depth. The till is particularly thick in this area and the anomaly occurs over (Argyll Group) metasedimentary rocks. On sheet NJ 30 SW molybdenite has been mapped in quartz veins at Sron Gharbh [NJ 3260 0440].

On Lary Hill at [NJ 3352 0050] a north-east-trending quartz-fluorite vein is reported in the Coilacreich Granite. Fluorite is also reported in the marginal parts of the Ballater Granite farther south in the Ballater district, suggesting that minor mineralisation may be present related to these leucogranites. Baryte is recorded in a quartz vein on Lary Hill at [NJ 3326 0111].

Numerous faults in the district have acted as channelways for fluids, ranging from juvenile fluids to supergene and meteoric water. These have typically resulted in silicification of the adjacent rocks, notably in crystalline limestones. However, only in rare instances is pyrite noted in such silicified material. Thick quartz veins are seen along some of the larger fault traces, e.g. from near The Luib [NJ 268 088] on Upper Donside to the Delavine Burn at [NT 283 071], but again few instances of mineralisation have been reported.

Mineral Reconnaissance Programme surveys in the Ballater–Strathdon district in the 1980s, described above, concentrated on detailed geochemical and geophysical surveys over the Lecht manganese mine (Figure 6). This was followed by megatraverses at the Lecht, Chapeltown and Blackwater Forest carried out primarily to identify geochemical anomalies and geophysical signatures of the metasedimentary rocks. At this time the stratigraphy was less well known, and only the far western and eastern ends of the Lecht megatraverse cross rocks recognised as Easdale Subgroup metasedimentary rocks. These megatraverse data did not find any significant anomalies and are not considered further in this report. No MRP exploration surveys for stratabound mineralisation were carried out elsewhere in the area, except for some limited soil geochemical work south of the Lecht in 1984.

Recent geophysical surveys and geological mapping for the East Grampians Project suggests that the mineralisation at the Lecht may be related both to an early lineament (Lecht Lineament) that controls the distribution and nature of the lithologies and to later structures that focused fluid flow (supergene and meteoric waters mainly) in Silurian-Devonian times.

Exploration Ventures Limited (EVL) surveys

Barringer Research Limited carried out a helicopter-borne multi-sensor survey on contract to EVL in what they referred to as the Strathdon Area. The western margin of the survey crosses Argyll Group metasedimentary rocks in two areas (Figure 6). Instrumentation included an AM-104 airborne magnetometer, a helicopter EM system, and a RADIOPHASE and E-PHASE system. Surveys were flown at a minimum height of 25 m above ground level. Flight lines were flown at approximately 600 m spacing and oriented at 291° and 220° grid north.

The magnetic data were presented as contour maps which have subsequently been digitised by the BGS. The EM data, however, were too noisy to contour and were plotted only as various symbols. Fourteen EM anomalies were chosen for ground follow-up by EVL, of which four occur over Argyll Group rocks (Table 3).

Table 3 Ground follow-up results of EVL helicopter EM anomalies over the Argyll Group in the Strathdon area

Anomaly No.	Grid Ref.	Geology and mineralisation	Geophysical signature	Soil geochemistry
455C	NJ 374 984	6–9% pyrrhotite in calc-silicate rocks	600 m x 90 m EM conductor with coincident 90–5000 nT magnetic anomaly	Cu 20–60 ppm Ni 5–20 ppm Pb 15–105 ppm Zn 50–245 ppm
434B	NJ 335 040	Margin of lenticular black schist body within uralitised gabbroic rocks	Double peaked in-phase EM with no quadrature. 300 nT coincident magnetic anomaly	Cu 20–2200 ppm Ni 5–45 ppm Zn 10–850 ppm
428B	NJ 332 200	Glenbuchat Graphitic Schist Formation	200 nT magnetic anomaly	Pb up to 40 ppm Zn up to 50 ppm
422B	NJ 332 180	Glenbuchat Graphitic Schist Formation	200 nT magnetic anomaly	Pb 50 ppm Zn 65 ppm

Anomaly 455C, located over Creagan Riabhach immediately north of Ballater, was regarded by EVL as a target worthy of more extensive investigation for Cu, Pb and Zn because of the quantity of sulphide mineralisation present and the similarity of this area with the geological environment and magnetic anomaly over the nearby disused Abergairn lead workings.

Anomaly 434B, located over metasedimentary rocks in an area of thick drift-covered ground, midway between Morven Lodge (where BGS found high Mo in panned concentrates, and elevated Pb and Zn values in G-BASE data), and the molybdenum occurrence at Sron Gharb. Here, EVL soil geochemistry revealed enhanced Cu, Ni and Zn near a magnetic/ground EM anomaly, and elevated Cu and Zn downslope of the anomaly. At the time of the present work, this ground was being investigated by a commercial company and was not therefore followed-up by the MRP.

Reconnaissance geochemical survey

For the current study a reconnaissance geochemical survey was carried out in five areas within the Ballater–Strathdon region (areas 1–5 in Figure 6) to follow-up anomalous levels of Zn or Pb in stream sediment, EVL airborne EM anomalies, and mineral sightings in the most easily recognisable Easdale Subgroup lithologies. The survey involved the collection of 12 drainage (panned concentrate and stream sediment) and 41 rock samples, the preferred geochemical medium in this area.

Drainage sampling

The highest Zn values in panned concentrates are from the Lecht area on the Allargue Estate (Area 4). Values of 250–280 ppm are similar to those reported from a previous study in the area.

Four panned concentrate samples from the Morven area on the Candacraig Estate (area 3 in Figure 6) contained Zn in the range 115–197 ppm. These values appear to reflect the slight enhancement in Zn due to the upgrading of silicate minerals from the Morven metabasic body to the south.

One sample from Glenbuchat (area 1) also showed slight enrichment in Zn, which can be attributed to the pelitic Glenbuchat schists in the catchment area.

In the Ballater area (area 5 in Figure 6) three stream-sediment samples collected from Peter's Hill contained slightly elevated levels of Ag (11–19 ppm) but were not significantly enriched in base-metals. One panned concentrate sample was also slightly enriched in As (16 ppm) and Au (26 ppb). Due to the low density of streams in this area, and the preponderance of exotic, glacially-transported drift in the main stream valleys, drainage sampling was deemed unsuitable as a detailed exploration technique.

Rock sampling

A wide variety of rocks containing visible iron sulphide (usually pyrite) were sampled. On the southern flank of Creagan Riabhach (area 5), sulphide-bearing calc-silicate rocks of the Glen Girnock Formation are exposed sporadically over a wide area, between the track leading to the communications mast [NO 370 980] to c. 250 m south of the summit [NO 360 990]. Due to the width of the sulphide-bearing outcrop over a strike length of 2.5 km in the Creagan Riabhach area alone, with along strike extension to the south-west of the area at Creag Phiobaidh [NO 320 940] and to the north at Peter's Hill [NJ 360 010], this formation was considered suitable for more detailed investigation.

Data and observations from the remaining four areas did not prove sufficiently promising to justify further study. However, minor sulphide occurrences of note are described below.

At Edinglassie in the Ernan Water catchment [NJ 30395 12415] a float sample of brecciated pelite with hematitised cavities was collected. The sample was slightly enriched in Cu (217 ppm), Zn (119 ppm) and Ag (19 ppm). The brecciation and open texture suggests that mineralisation is probably epigenetic.

At Glenbuchat, in the Corriemore roadside quarry [NJ 33620 17700], a 30 cm wide clay alteration zone occurs on the roadside flank of the main limestone unit. Low Ca levels suggest that this represents a separate, altered unit marginal to the limestone. Minor enrichment in Cu (314 ppm) and Ag (12 ppm) was noted. North of this locality a riverside exposure of semipelite south-east of Badenyon [NJ 34220 18810], heavily stained with Fe and Mn hydroxides over c. 1 m width, contained 56 ppm As but showed no base-metal enrichment.

Follow-up surveys north of Ballater

More detailed geochemical and geophysical investigations were carried out in the Creagan Riabhach and Peter's Hill areas because of (i) the widespread presence of stratiform pyrite, (ii) similarity to the pyrite belt in Perthshire, (iii) the presence of a large EVL EM and magnetic anomaly (455C) and (iv) the close proximity of the abandoned Abergairn lead mine.

Geology

A simplified lithostratigraphic succession for rocks in the Ballater area is shown in Table 4 and a simplified geological map of the follow-up survey area forms the base to Figure 7.

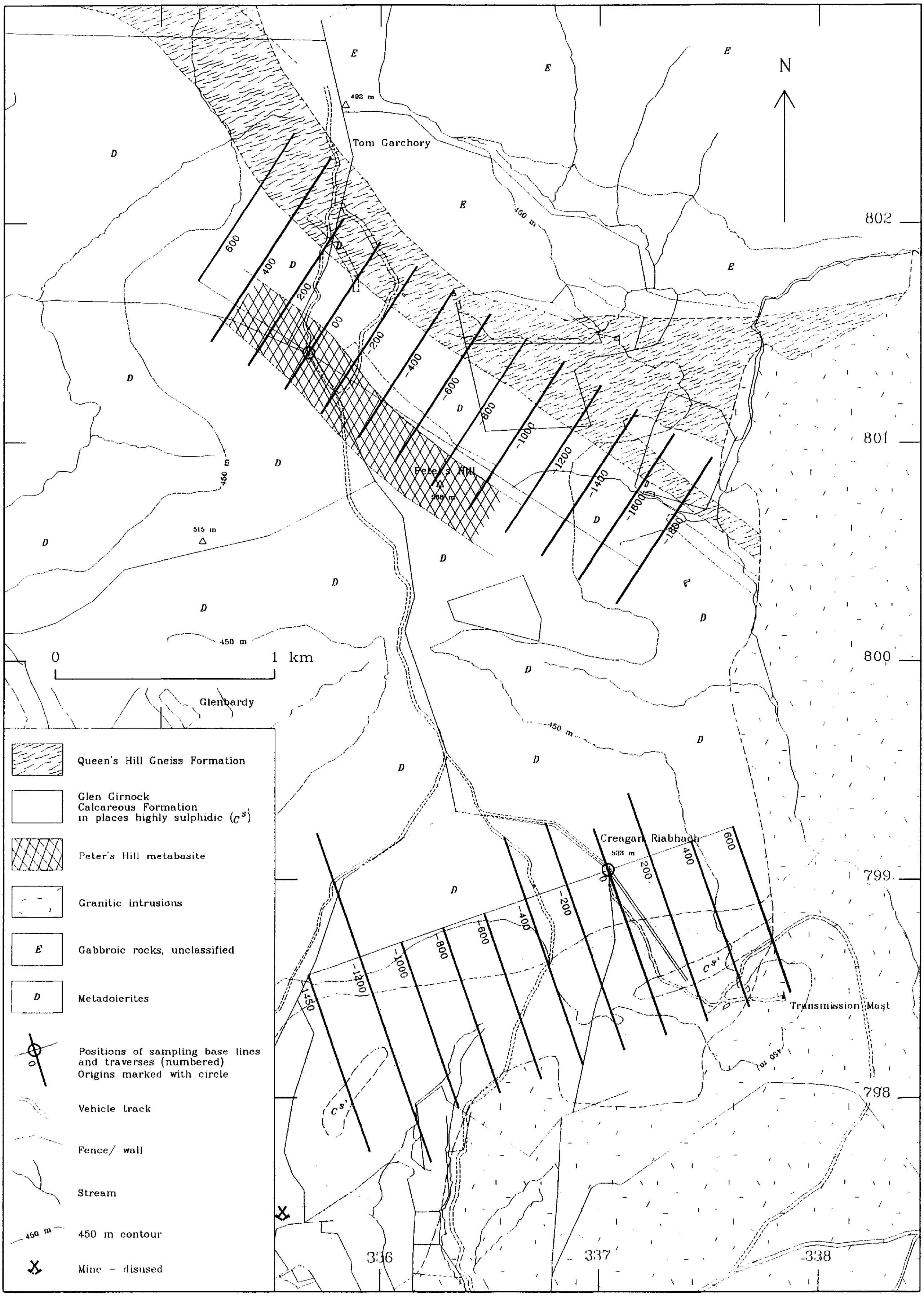


Figure 7 Geological map showing the location of new geochemical and geophysical traverses in the area north of Ballater

Table 4 Main lithological units in the Ballater area

Formation/Member	Main lithology	Group
Queens Hill Formation	Semipelitic migmatitic gneiss containing garnet, sillimanite, and cordierite	Crinan Subgroup
Glen Girnock Calcareous Formation ——— Basal Mixed Member	Calc-silicate rocks, abundant sheets of amphibolite Forsterite limestone (where differentiated) Rusty weathered pyrite-pyrrhotite-rich calc-silicate rocks Calc-silicate rocks, laminated micaceous psammite, hornblende schist, semipelite and quartzite	Easdale Subgroup
Creagh nam Ban Formation	Striped semipelites, quartzites, and psammites	Easdale Subgroup
Metamorphosed igneous rocks	Amphibolite, hornblende schist, and metagabbro	

The Glen Girnock Calcareous Formation, which hosts the pyrite mineralisation, is dominated by calc-silicate and semipelite interbanded with amphibolite sheets. Overall it is a very diverse assemblage including, in addition, limestone, psammite, quartzite and notably muscovitic pelite and semipelite. The lithological diversity is particularly apparent in the Basal Mixed Member which also hosts the sulphidic mineralisation. The lower part of the member is dominated by laminated micaceous psammite but includes interbanded hornblende schist, semipelite and quartzite. However, between 40 and 50 m above the base the succession becomes distinctly more calcareous, being dominated by flaggy, fine-grained, pale to dark grey calc-silicate rock with interbedded tremolite schist, actinolite schist and rare quartzite. At about 150 m from the base, and just above the mineralised horizon, more massive hornblende schist or amphibolite units make their appearance within the calcareous rocks, marking the passage to the overlying dominantly metabasic assemblage.

These metabasic sheets consist largely of coarse-grained amphibolite and hornblende schist. There seems little doubt that the bulk of them are metadolerites which were intruded into the sedimentary rocks during or prior to deformation. Although the majority of these are strongly deformed and hence belong to the 'older' suite of basic rocks, which was emplaced before the second and possibly even the first deformation, a few are thought to be 'younger' basics intruded during the third deformation. There is also the possibility that, like parts of the Ben Lawers Schist in Perthshire, the Glen Girnock Calcareous Formation has a volcanogenic component. For instance, the hornblende schists in the Polhollick area [NO 344 965] are closely cleaved and locally epidotic, features which are also common in the Meall Dubh Metabasite Formation.

The metasediments also have several unusual features, for example their fine grain size and occasional relict larger grains, which might be explained by considering them as ashfall-sediment admixtures. Probably the most convincing evidence is to be found on the south-facing slopes of Hill of

Candacraig where fine-grained, schistose metabasic bodies are interlayered on a centimetre scale with plagioclase-tremolite schists. Taken together with apparent transitions between the two lithologies and a similar recognisable structural history, there seems little doubt that the metabasic rocks formed at about the same time as the synsedimentary volcanic or pyroclastic protoliths.

Mineralisation

Stratabound sulphide mineralisation near the top of the Basal Mixed Member of the Glen Girnock Calcareous Formation can be followed intermittently along strike for 7 to 8 km in the Ballater area between Tullich Burn and Glen Girnock. The most extensive exposures lie to the north of Ballater, most notably on the southerly slopes of Creagan Riabhach (Figure 7), where the horizon is 60 m thick and can be traced along strike for at least 700 m. The mineralisation cannot be readily followed across the largely till-covered depression around the headwaters of the Loin Burn, but is visible in a trackside borrow pit at [NO 3367 8947]. To the south-west of this outcrop the horizon crops out at Craggans and at Abergairn, where the exposure level has been enhanced by pitting in the area of the Abergairn lead mine. The outcrop width in the Craggans–Abergairn area is 70–100 m, which corresponds to a true thickness of 45–65 m.

The horizon reappears 3 km to the south-west, beyond the alluvial flats of the Dee valley, on the crags at Littlemill [NO 328 954], where it can be followed along strike for 400 m between areas of poor exposure. The outcrop width there is well constrained by good exposure and is reduced to about 50 m. The only other exposure is in a 5 m deep section on the east bank of the Girnock Burn [NO 3212 4170]. The occurrence is in an area of poor exposure but it appears to occur within calc-schist which underlies massive amphibolite.

The mineralisation consists of pyrite and pyrrhotite, with no other visually identifiable sulphides. The sulphides occur in a variety of forms including disseminated, thin, discontinuous cleavage-parallel trails and as joint coatings. The principal hosts for the mineralisation are flaggy, bluish grey calc-silicate rocks, which include tremolite and actinolite schist. In the Girnock Burn occurrence the greatest concentration of sulphides is in dark grey to black, possibly graphitic schist which forms a band up to 1.8 m thick in the calc-silicate succession. The sulphidic rocks are readily identified in the field by their distinctive weathered crust, which is typically deep brown but also includes black and yellow. The sulphidic rocks show a range of magnetic susceptibilities from 0.38 to 7.17 x 10^{-3} SI units, largely reflecting variations in pyrrhotite content.

Sulphidic rocks occur in other parts of the Basal Mixed Member but not in the same concentration. For instance disseminated pyrrhotite occurs in actinolitic and tremolitic schist in the Littlemill section and in calc-silicate rocks to the west of Creagan Riabhach. Pyrrhotite may also be present in rocks at the base of the formation since they can be magnetically distinguished from both underlying and overlying rocks.

With the exception of the presence of pyrrhotite, the Glen Girnock sulphidic horizon closely resembles the Pyritic Zone in the Ben Lawers Schist Formation (Smith et al., 1984) in character and lithostratigraphic position. The Pyritic Zone has extreme lateral persistence, being traceable for over 250 km from Glenshee to Loch Fyne, but with the exception of some very localised low-level Cu enrichment, it is largely devoid of base-metals. This type of mineralisation, which strongly resembles the Norwegian Fahlbands (Gammon, 1966), possibly resulted from sea-floor hydrothermal activity in relatively shallow water.

The quartz-fluorite vein-hosted lead deposit at Abergairn (Wilson, 1921) is epigenetic and almost certainly relates to late-stage processes in the emplacement of either the Ballater or Coilacriech granites. Its close association with the Glen Girnock sulphidic horizon may therefore be largely coincidental, although it is possible that the stratabound sulphides may have been a source of sulphur for the galena.

Soil (shallow overburden) sampling

Throughout this report soil sampling is a broad term applied to the sampling from less than 1 m depth of unconsolidated materials of glacial and recent origin from which soil profiles are in the process of being developed.

Sampling was undertaken to the north of Ballater in the vicinity of Creagan Riabhach and Peter's Hill to elucidate the distribution of base-metals over the Glen Girnock Calcareous Formation. Due to the change in strike, traverse-based sampling was divided into two areas: Peter's Hill (northern area) and Creagan Riabhach (southern area). Traverses spanned the width of the Glen Girnock Calcareous Formation, and at Creagan Riabhach were extended in a northerly direction over the Creagan Riabhach metadolerite, both of which are locally pyritic and contain traces of chalcopyrite mineralisation. The locations of soil sampling traverses, relative to bedrock geology are shown in Figure 7.

Due to the presence of magnetic pyrrhotite in the calc-silicates, compass deviations in excess of 5° are locally present. In consequence surveying of the base and traverse lines was carried out by theodolite using bearings relative to mapped fence lines. Traverse lines were spaced at 200 m over the Creagan Riabhach area and 200 to 400 m over the Peter's Hill area. Samples were collected at 20 m intervals along traverses mainly by hand auger, with two or three augers full taken from each site to reduce sub-sampling error and to collect sufficient material. In the thinner soil profiles, where rock fragments below surface inhibited successful penetration or removal of the hand auger, samples were collected from hand-dug shallow pits. Following oven drying, the samples were disaggregated using a pestle and mortar and then sieved through 180 µm nylon mesh. Representative 12 g splits of the −180 µm material were analysed for Fe, Cu, Zn, Pb and Ba, by the Analytical Geochemistry Group of BGS using X-Ray Fluorescence Spectrometry.

In addition, a single traverse was sampled over the Glen Girnock Calcareous Formation near the abandoned Loinveg Farm (line A-A' in Figure 6). The start point was [NJ 31225 93630] and the end [NJ 32375 92900]. Sixty-nine samples were collected at 20 m intervals and prepared and analysed as described above.

Creagan Riabhach. The soils of this area are mostly free draining and thin (generally <1 m), with patchy exposure of outcrop along a series of low strike-parallel ridges. On the lower ground in the south-west of the area the drift thickness increases markedly. This can be demonstrated in the upper section of Loin Burn [NO 364 982] where the stream is incised 4 m into superficial material. No bedrock is exposed along the stream course, indicating that the drift is significantly thicker than this figure.

The chemical analyses are summarised in Table 5, from which it is evident that 10% of the samples may contain significant base-metal enrichment. Levels of base-metals in soils are generally consistent with the range of lithologies present, which include pelitic and metavolcanic rocks.

Table 5 Summary statistics for chemical analyses of soils, Creagan Riabhach

	Fe	Cu	Zn	Ba	Pb
Minimum	7064	<2	24	65	9
10%	36621	13	83	248	24
25%	46475	19	108	323	32
Median	58470	28	150	400	42
75%	73262	41	205	454	57
90%	92041	61	334	507	79
Maximum	209330	350	2074	1412	460

587 samples. All values in ppm.

Most of the higher Pb values occur on or near the margins of the Ballater Granite in the south-eastern corner of the sampling area (Figure 8), with minor enrichment occurring on traverses –600 and –800, again at the granite margin. On line +200 the second highest Pb value (367 ppm) occurs over unexposed microgranite. The majority of other values above the 75 percentile are single site anomalies which occur sporadically across the sampled area.

Copper shows an erratic distribution pattern over the area, with three small clusters of values in excess of 100 ppm occurring over the calc-silicates in the eastern half of the sampling grid on traverse lines +200, +400 and –200 (Figure 8). In the western half of the area levels are generally below 50 ppm. The highest value (350 ppm) occurs in shallow, well-drained soil on traverse line –1200. This site is flanked by samples with low Cu values of 12 and 29 ppm respectively. Other base-metal levels at this site are not significantly enriched. The second highest Cu value (271 ppm) occurs on the same traverse line in a sample containing the highest value of Zn (2074 ppm) and slightly elevated Pb (161 ppm) relative to adjacent samples.

The highest values of Ba occur at the northern end of traverse line –1450, coincident with a quartzitic unit within amphibolite (Figure 9). Elevated Ba values occur over the Glen Girnock Calcareous Formation on follow-up traverses A–C (see below), and on line +600 where they fall generally in the region of 500 ppm, within the upper quartile of determinations.

Most Zn values in excess of 500 ppm occur in the north-eastern part of the sampling area, between traverse lines +200 and –400 (Figure 9). In this area the ground is mostly free-draining with relatively thin soils over metadolerite bedrock. The two highest values (2074 ppm and 1696 ppm respectively) occur close to fences on traverse lines –1200 and –200 and the samples are also enriched in Cu. Both of these sites are close to vein quartz outcrop and float. Zinc levels more typical of metadolerite bedrock occur at the northern end of traverse 00, where all values exceed 240 ppm, with maxima of 610 ppm and 525 ppm. In this area the metadolerites are intercalated with semipelitic and psammitic lithologies. These are not exposed and were not investigated to ascertain if they contain base-metal mineralisation. On traverse line –400 a broad band of values exceeding 200 ppm also occurs over metadolerite bedrock. Here the drift is thicker, frequently exceeding 1.5 m. Three pits were dug to investigate the source of these high Zn values (see below).

Over the calc-silicates there are only two Zn values in excess of 200 ppm. One of these occurs on traverse line +200 and was subsequently investigated by detailed pitting (see below).

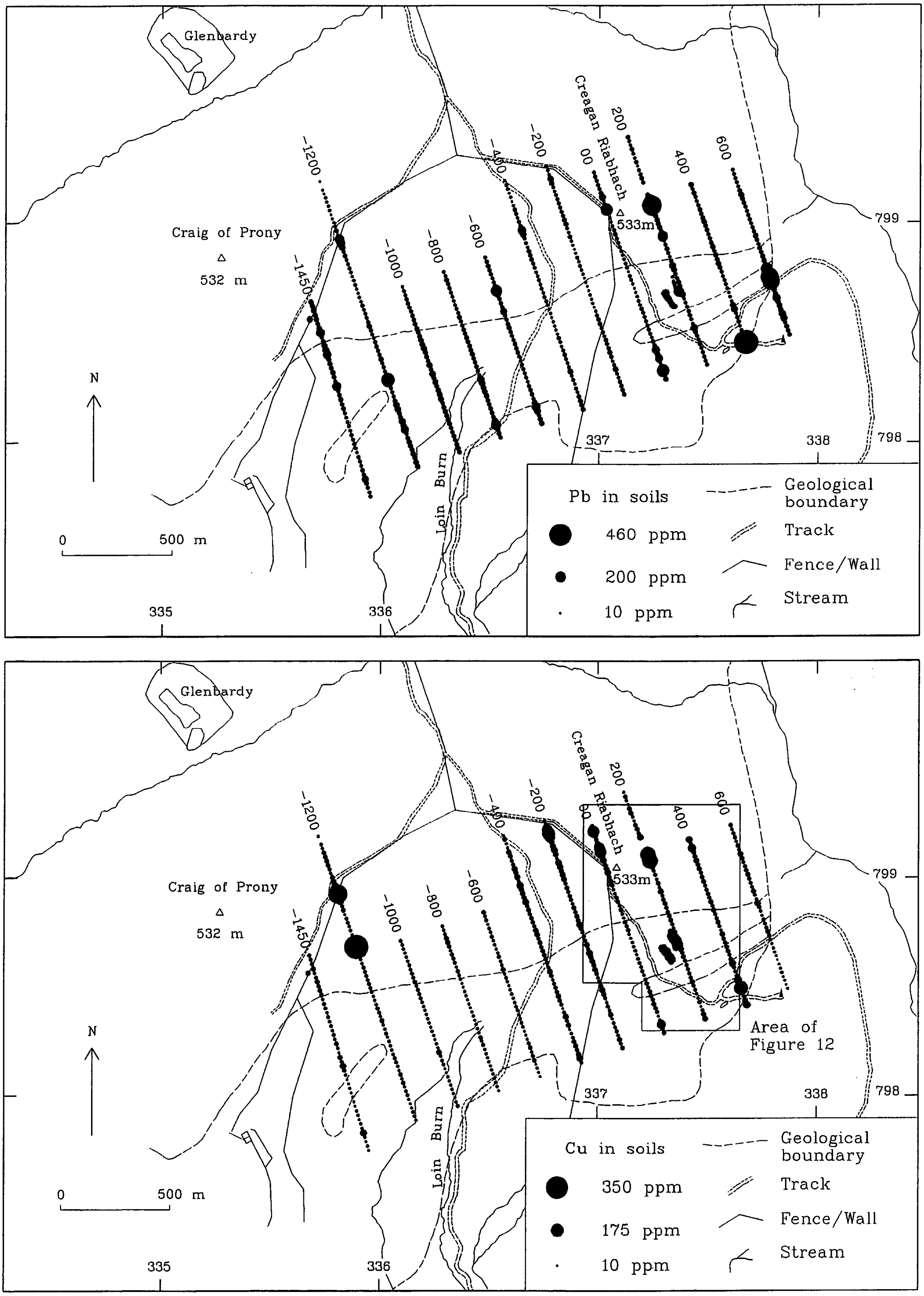


Figure 8 Plot of Pb and Cu in the −180 μm fraction of soil samples, Creagan Riabhach

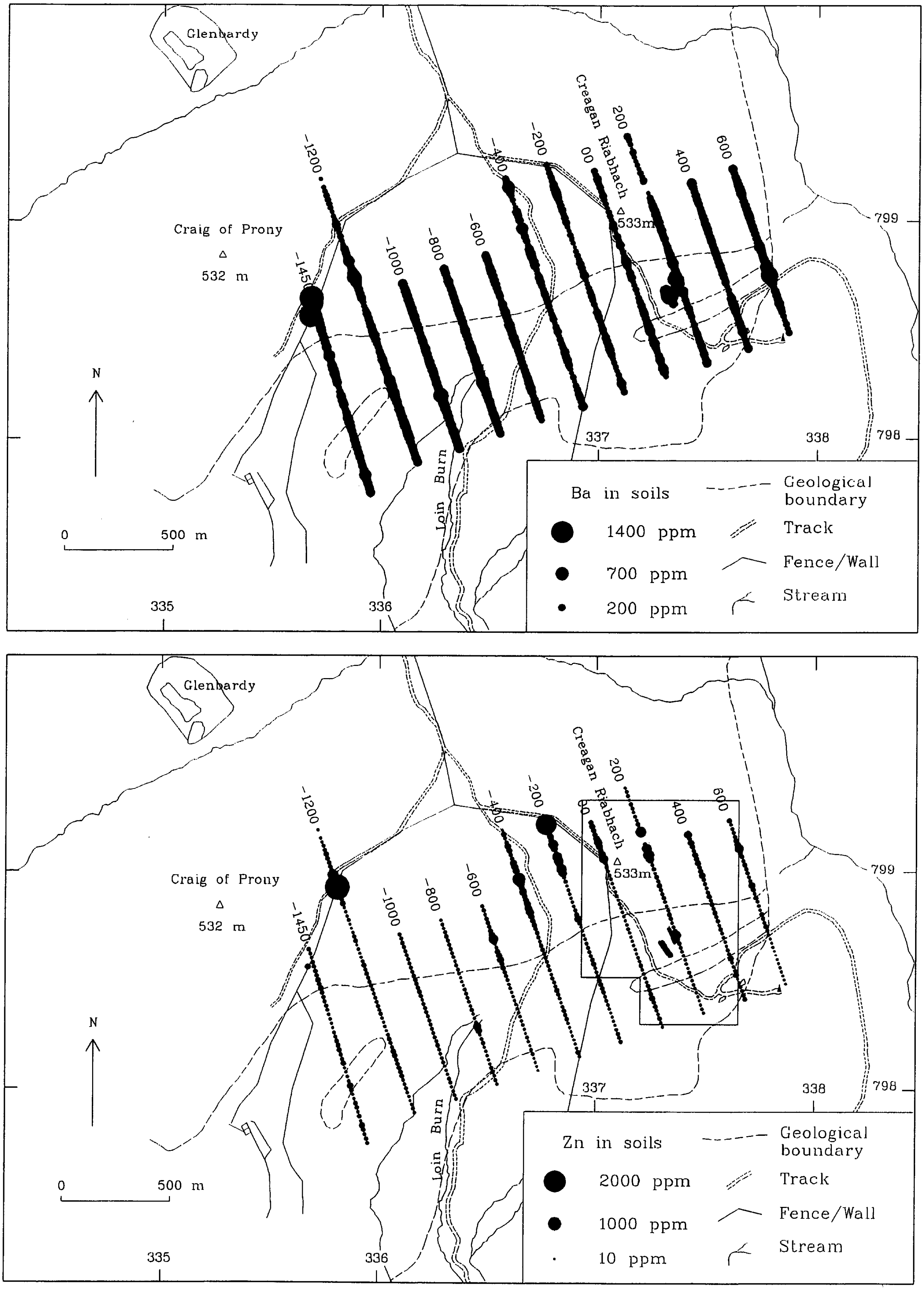


Figure 9 Plot of Ba and Zn in the −180 μm fraction of soil samples, Creagan Riabhach

The distribution pattern for Zn indicates enrichment in the Creagan Riabhach metadolerites, relative to the Glen Girnock calc-silicates to the south. Enrichment over the Glen Girnock Formation is highly localised and, in some places, appears to be associated with intercalations of semipelite. Over the metadolerites on traverses –400 to +200 a distinct contrast in Zn and Cu levels is observed between sites north and south of approximately the base line. This is coincident with the transition from exclusively metadolerites in the south to a mixed metavolcanic/psammitic assemblage to the north of the base line.

Peter's Hill. The Peter's Hill area can be divided into two topographically distinct components. In the west of the area most of the ground is elevated, forming an irregular, nobbly ridge around and to the north of Peter's Hill. In this area most of the mineral soil is locally derived, although glacially-transported material is present in the lower ground to the west of this ridge and, patchily, on the ridge itself. In contrast, the lower, eastern part of the survey area is pervasively covered with glacially-transported material of substantial thickness. This superficial covering gives rise to a smoother, gently undulating and sloping landscape within which there is no bedrock exposure.

In terms of source material and resultant texture, the samples from the Peter's Hill traverse lines are highly variable. Over most of Peter's Hill the soils are thin, well-drained and readily excavated down to bedrock. Although not extensive, granite-dominated glacially derived material forms narrow ribbons within linear strike-parallel depressions across the ridge. In contrast, on the lower ground, the suite of clast lithologies in the drift is dominated by granite, with smaller numbers of metagabbro. These clasts indicate that the principal directions of glacial transport are from the west and north.

Table 6 Summary statistics for chemical analyses of soils, Peter's Hill

	Fe	Cu	Zn	Ba	Pb
Minimum	11610	3	18	76	6
10%	34515	8	50	244	17
25%	42366	12	64	306	23
Median	49657	18	88	386	30
75%	57666	27	119	457	40
90%	70031	39	161	553	50
Maximum	103651	308	424	1319	1310

300 samples. All values in ppm.

The pattern of Pb concentration (Figure 10) shows little contrast over the sampled area, with a median value of 30 ppm and narrow 90–10 percentile range of only 33 ppm (Table 6). Only three samples were enriched in excess of 150 ppm and their positions are widely spread. Two of these occur in the lower drift-filled ground on traverse line –400. The highest Pb value (1310 ppm) is from line +400, in a sample also containing elevated Ba (1319 ppm). Baryte vein float can be found upslope between this site and the track, suggesting the presence of a baryte and galena vein.

The majority of Cu values fall within a narrow interquartile range of 12–27 ppm. Higher values on the northern parts of traverse lines –400 and –800 (Figure 10), reflect a localised minor enrichment in the underlying bedrock. The highest Cu values (308 and 215 ppm from adjacent sites) occur in peaty soils on traverse line –400 and were subsequently investigated by pitting (see below).

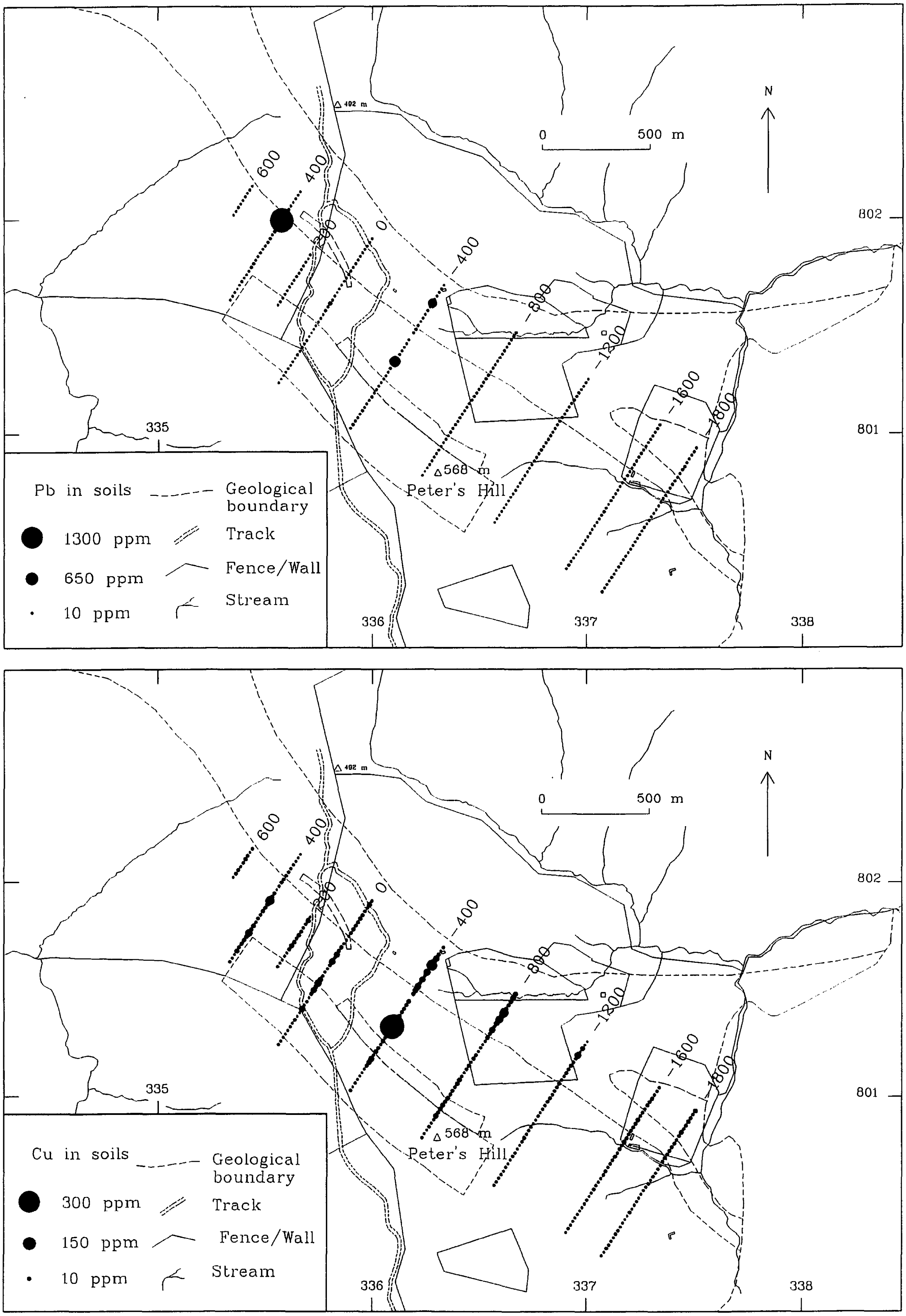


Figure 10 Plot of Pb and Cu in the -180 µm fraction of soil samples, Peter's Hill

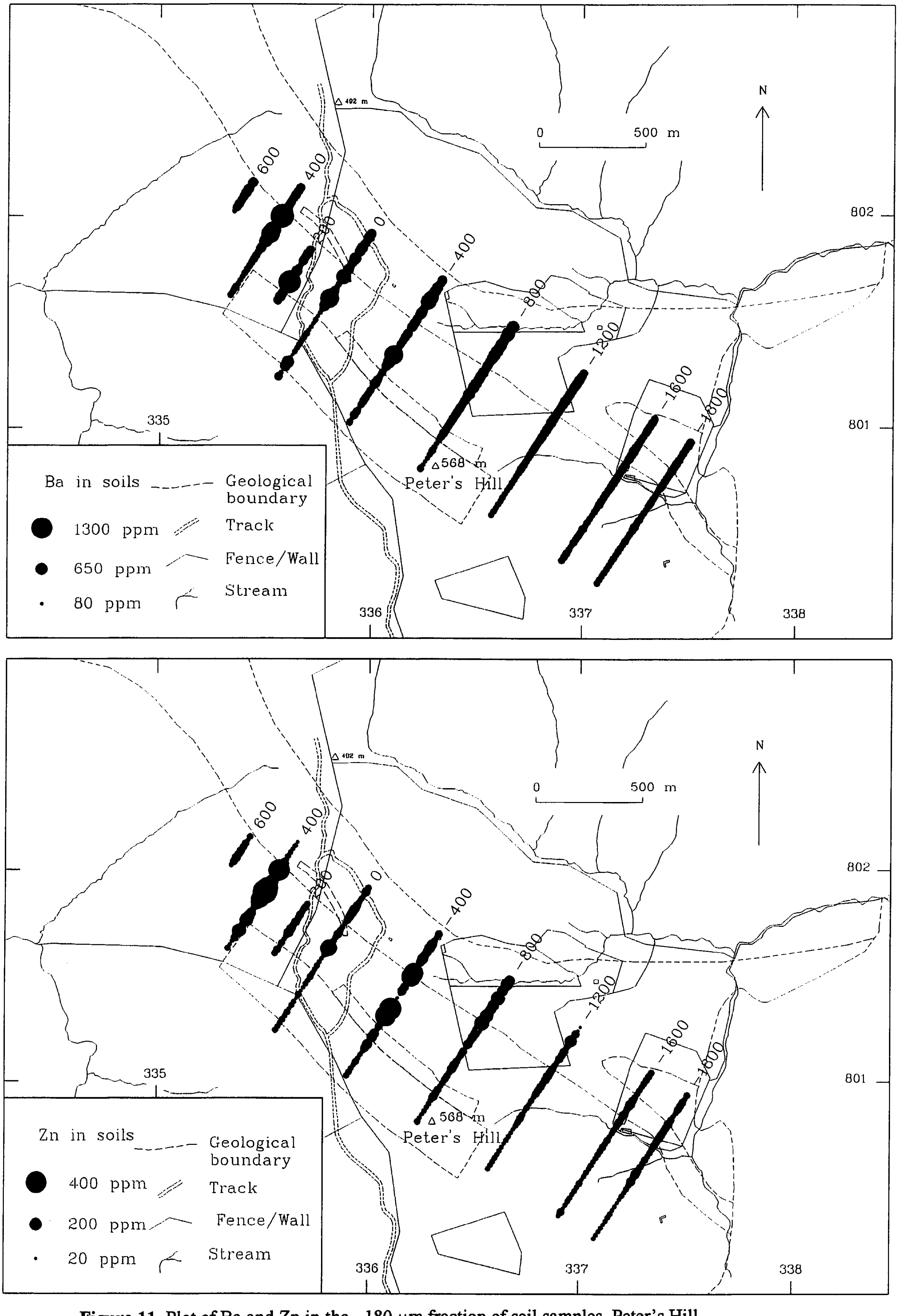


Figure 11 Plot of Ba and Zn in the −180 μm fraction of soil samples, Peter's Hill

In common with the other trace elements Ba levels show less variation over the eastern part of the area than the western part (Figure 11). A general pattern of increase in a northerly direction along the traverses reflects lower Ba levels in the Peter's Hill metabasite than in the Glen Girnock Calcareous and Queen's Hill Gneiss formations to the north. Marked variations in Ba levels are confined to the Glen Girnock Calcareous Formation over the more elevated north-western part of the sampled area. The highest Ba value (1319 ppm) is from a site downslope of an occurrence of vein baryte float and coincident with the highest Pb value (see above).

The distribution pattern of Zn indicates generally higher levels over the Queen's Hill Gneiss Formation (northern ends of lines 00, –400 and –800) than over the Peter's Hill metabasite along the southern flank of the sampled area (Figure 11). Most high Zn values reflect the presence of underlying metadolerite bedrock between these two formations from traverse lines +400 to –400 and generally occur in poorly-drained peaty soils. Pits were dug at two sites on line –400 to investigate the source of coincident high Zn and Cu results (see below).

Loinveg traverse line (A–A') Minor enrichment in Zn (395 ppm) occurs near the north-western end of the traverse at [NO 31377 93533]. This sample was also enriched in Pb (246 ppm). Rock outcrop 500 m south-west of the soil traverse comprises interbedded pelitic and psammitic lithologies. One sample of pelite contained 146 ppm Zn. It seems unlikely that such rocks could be the source of the high Pb and Zn as the soils are well drained, and it is considered more probable that the enrichment is due to minor sulphide mineralisation. However, no further investigations were carried out in the area to prove the source of the soil anomaly.

In the Girnock Burn, c. 5 km west-south-west of Ballater, two streamside exposures of possibly graphitic calc schist [NJ 32120 94170] and amphibolite (KJR 1919 and 1920) contained elevated Ba levels of 2232 and 1833 ppm respectively. However, base-metal levels were not high although the rocks are rich in pyrite and pyrrhotite.

Pitting and rock sampling

In order to investigate the source of the locally high Zn levels in soil several sites were selected for detailed investigation by profiling or hand pitting down to bedrock on Creagan Riabhach and Peter's Hill. In order to compare base-metal values between soils and the underlying bedrock, samples of each were collected.

Three short traverses (traverses A, B and C, Figure 12) were surveyed close to traverse line +200 on Creagan Riabhach to investigate the geophysical and geochemical anomalies at this location. Detailed sampling was also carried out near the baseline of traverse +200 and on traverse –400. In addition, single-site Zn anomalies in low, poorly-drained ground on traverse lines –800 and –1000 were investigated by manual pitting. The presence of thick, heavily gleyed till profiles suggested that Zn levels at these locations are enhanced due to hydromorphic processes. On Peter's Hill pits were dug at two anomalous sites on traverse line –400.

Creagan Riabhach: traverse lines A, B and C. These are located on a gently-sloping ridge c. 500 m south-east of Creagan Riabhach summit, with traverse orientations approximately orthogonal to strike. In order to investigate any small-scale variations in base-metal concentrations, site spacings were at 5 m intervals (Figure 12). All the sites in this area are free-draining, with little potential for hydromorphic dispersion or concentration. The soils are mostly shallow (<50 cm), but somewhat

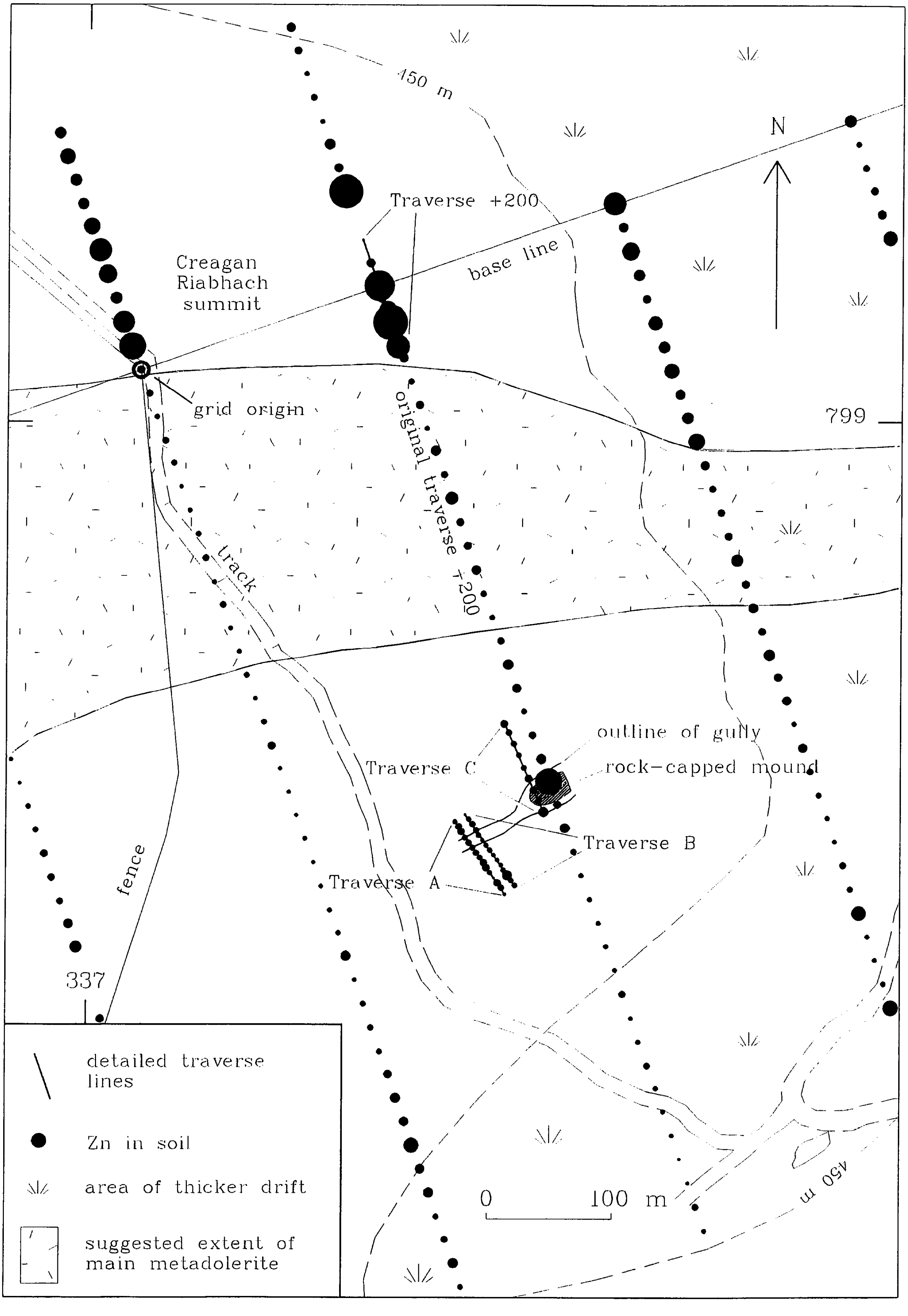


Figure 12 Location of detailed traverses and Zn in soil results, Creagan Riabhach

deeper along the line of a small depression near the northern ends of traverse lines A and B. This depression deepens to form a gully transecting Traverse C. At the shallow sites pale to dark grey calc-silicate bedrock was encountered. Within the depression no bedrock was encountered and the micaceous soils suggest the presence of semipelite.

Soil samples were prepared and analysed for Cu, Zn, Ba and Pb in the same way as those from the reconnaissance traverses. Results indicate there is little between site variation in base-metals, with maximum Zn values of 153 ppm on traverse line A, 123 ppm on traverse line B and 214 ppm on line C. The slightly higher values on line C occur in deeper soils within the depression where no bedrock was encountered. It is believed that these values reflect higher Zn concentrations in the underlying semipelitic bedrock. However, the original anomaly on traverse +200 (Figure 12) could not be traced along strike.

The rocks are pale to mid-grey calc-silicates possessing a weak, shallow-dipping strike-parallel fabric. Visible sulphide, in the form of very fine-grained disseminated pyrrhotite was present in all samples, in concentrations ranging from <1% to >5%. Magnetic susceptibility readings on bedrock exposed during pitting indicated the more sulphide-rich variants have magnetic susceptibilities sometimes in excess of 3.0×10^{-3} SI units.

Samples of bedrock were analysed for Ca, Mn, Fe, Co, Ba, Cu, Zn and Pb by XRF. Summary statistics for the 22 calc-silicate samples collected from traverses A, B and C (Table 7) indicate that there are only minor enrichments in the base-metals, the maximum value of Zn being 394 ppm. The maximum Zn value occurs on traverse A and coincides with a transition from lower Cu values over the southern part of the traverse (26–84 ppm), to slightly elevated levels in the range 122–154 ppm to the north. It should be noted that Pb and Ca show similar trends between these two traverse sections. It is likely that these element variations are of a primary character and reflect variations in the original sediment composition.

Table 7 Summary statistics for chemical analyses of calc-silicate samples from pits on traverse lines A, B and C, Creagan Riabhach

	Ca	Mn	Fe	Co	Ba	Cu	Zn	Pb
Minimum	38094	728	42315	14	131	26	53	10
10%	42296	895.3	43447	28	143	52	80	11
25%	51030	1144	49360	33	202	64	97	13
Median	64573	1355	51476	38	255	75	111	15
75%	76205	1590	59344	44	408	96	137	18
90%	88394	1722	67849	50	560	122	157	29
Maximum	100129	2525	68821	61	888	154	394	36

23 samples. All values in ppm.

Copper and Co show a positive correlation (straight line association), with the exception of two outliers which contain the highest levels of Cu. This association is consistent with the presence Cu in the form of trace chalcopyrite mineralisation and traces of Co within the pyrrhotite mineralisation. A scatterplot of Zn and Fe shows a linear trend (with the exception of two outliers) with a Zn/Fe ratio of approximately 1:10. As the most abundant iron mineral in the calc-silicates is pyrrhotite it is likely that Zn is present within that mineral as part of the ternary system Fe-Zn-S.

Creagan Riabhach: traverse line +200. Detailed sampling on line +200 between 00 and +50 (Figure 12) was carried out in order to investigate a marked Zn enrichment in soil at three adjacent sites from the original survey. Two of these sites were enriched in Zn (695 and 383 ppm) and Cu (177 ppm and 142 ppm) respectively, with the former also containing slightly elevated Pb (154 ppm).

Zinc levels in soils are markedly higher than over the calc-silicates on traverses A–C and reproduce the elevated levels from the original soil survey over this area. In addition to pitting and soil sampling, an extension of soil sampling was carried out in a northerly direction (Figure 12).

Anomalous Zn values extend from 60 m north of the baseline to 80 m south, although a break in sampling occurred at sites –40 and –60 due to the absence of any mineral soil over a small offshoot of previously unmapped granite. Zn values ranged from 87 ppm to 803 ppm. The samples containing the most Zn (803 ppm and 782 ppm) also show slight enrichment in Cu (213 ppm and 73 ppm respectively). Where granite float is present base-metal levels are substantially lower than over metadolerite. This suggests that the slightly elevated base-metal values at the former sites are the result of entrainment of material derived from the weathering of the metadolerites.

Pitting to bedrock along this section was facilitated by shallow soil profiles (<1 m) over metadolerite and granitic bedrock. One sample of metadolerite was submitted for analysis and revealed enrichment in Zn (1212 ppm) and Cu (552 ppm). Samples of granite were collected from five adjacent sites but these were low in both Cu (5–15 ppm) and Zn (52–132 ppm). Observations of the previously unmapped narrow granite intrusion show no evidence of sulphide-bearing veins or disseminations. Slightly higher Pb levels in the granite samples relative to the metadolerite reflect the presence of this element in feldspars rather than as sulphide mineralisation.

Creagan Riabhach: traverse line –400. Three pits were dug to investigate Zn in soil anomalies on reconnaissance traverse line –400. The positions of these were +80, –60 and –140. Table 8 lists trace-element data for these samples, with the original soil sample listed first, followed by the corresponding pit sample. In all pits a mineral soil profile was sampled containing little organic matter, and abundant metadolerite clasts were noted at all three sites. Only at the southernmost site (+80) was the mineral soil waterlogged and gleyed, the other two mineral soils being brown in colour and well drained.

Table 8 Comparison between Cu, Pb, Zn and Ba in augered (a) and pitted (p) soil samples from traverse line –400, Creagan Riabhach

Sample No.	Location (m)	Depth (m)	Cu	Zn	Ba	Pb
1446 (a)	–400, +80	1.0	26	469	452	45
6573 (p)	–400, +80	1.0	31	441	467	50
1820 (a)	–400, –60	0.3	42	447	283	44
6574 (p)	–400, –60	0.9	82	975	660	132
1824 (a)	–400, –140	0.3	55	450	415	28
6575 (p)	–400, –140	0.5	61	452	445	34

All values in ppm.

Levels of Zn and the other elements analysed from sites +80 and −140 were comparable to the values from the reconnaissance soil samples. At site −60, where a deeper mineral soil horizon was intercepted, levels of all elements were higher, with a maximum Zn level of 975 ppm. The results suggest that the elevated levels of Zn in soil are due to weathering of the underlying metadolerite bedrock. The relatively uniform levels of Zn in the samples collected, together with the well-drained character of the soil, indicate there is no evidence of hydromorphic upgrading in this area.

Peter's Hill. In order to evaluate the potential for hydromorphic upgrading of Zn in this area, two sites on traverse line −400 were pitted to compare values in the upper soil profile with those in the underlying mineral soil. The original samples were highly organic (c. 99% by volume), with the underlying mineral soil lying at or below the maximum augering depth of 1.3 m. Subsequent pitting to 1.5 m depth enabled samples of the underlying gleyed sandy loam mineral soil to be collected. The abundances of Cu, Zn, Ba and Pb in the original samples and the pitted mineral soils are given in Table 9.

Table 9 Comparison between Cu, Pb, Zn and Ba in augered (a) and pitted (p) soil samples from traverse line −400, Peter's Hill

Sample No.	Location (m)	Depth (m)	Cu	Zn	Ba	Pb
1060 (a)	−390, +160	1.3	308	239	546	33
6555 (p)	−400, +160	1.3	25	124	500	31
1061 (a)	−390, +180	1.0	215	375	1042	566
6556 (p)	−400, +180	1.5	53	160	594	43

All values in ppm.

The results demonstrate that Zn levels in the original organic A horizon are enriched relative to the underlying mineral soil. This pattern is true also for Cu, which typically displays a propensity for complexing and accumulating in organic-rich soils. Nevertheless, Cu levels were markedly higher at these sites than at other waterlogged, organic-rich sites sampled in the area.

Lithogeochemistry

Bedrock sampling was carried out in the Creagan Riabhach and Peter's Hill areas in order to establish the base-metal levels in the Glen Girnock Calcareous Formation. In addition, other locations in the Ballater area containing rocks enriched in sulphides were sampled. Representative rock samples weighing around 2 kg were washed and cleaned to remove entrained superficial material. Following drying, these were milled in a tungsten-carbide Tema mill to −150 μm size. Sub-samples were analysed for major and trace elements by XRF.

Creagan Riabhach. A group of seven calc-silicate rocks were collected from surface outcrop close to the southern mapped margin of the Glen Girnock Calcareous Formation. Base-metal levels ranged from 49 to 92 ppm Cu and 38 to 208 ppm Zn. Mineralisation in the form of fine-grained pyrite and pyrrhotite was observed in varying amounts in all these samples, but no other sulphide minerals were seen in hand specimen. Locally pyrrhotite forms c. 10% of the rock (e.g. KJR 621), but trace element data indicate that there is no enrichment in base-metals in these samples. Two calc-silicate samples from the Craig of Prony area contained similar base-metal levels.

Five samples of metadolerite from Creagan Riabhach summit contained Zn levels within the range 116 to 383 ppm and Cu levels more variable than the calc-silicate lithologies (Table 7). In contrast, the two metadolerites from the Craig of Prony area contained lower levels of Zn and Cu. It is probable that these samples are analogous to the southern (low Zn) metadolerites of Creagan Riabhach rather than the slightly Zn-enriched rocks of similar type around the summit area.

Peter's Hill. Bedrock sampling in the Peter's Hill area was confined to the higher ground where various metasedimentary and metavolcanic rocks were sampled. Slight Zn enrichment occurs in both metasediments and metavolcanic lithologies. However, due to the limited spatial extent of good exposure in the area, insufficient samples could be collected to ascribe median base-metal levels to each individual unit. A vein baryte sample (KJR 630), contained 48% Ba, 59 ppm Ag, 11 ppm Bi, and 97 ppm Pb.

Geophysical surveys

A reconnaissance geophysical survey was carried out over the sulphidic calc-silicate rocks within the Glen Girnock Calcareous Formation at Creagan Riabhach and Peter's Hill north of Ballater (Figure 7) in conjunction with the soil sampling survey. The aim was to map the stratigraphy, to trace possible extensions of the pyrrhotite-rich horizon through ground where bedrock is concealed by thick drift, and to further investigate EVL anomaly 455C (Table 3).

Survey methods. Magnetic and Very Low Frequency Electromagnetic (VLF-EM) techniques were employed over all survey lines, and supplementary Horizontal Loop Electromagnetic (HLEM) and Self Potential (SP) methods used over the EVL EM anomaly on Creagan Riabhach (traverse lines 00 to +400). Measurements of the magnetic total field were made at 10 m intervals simultaneously with the VLF-EM measurements using a Scintrex IGS-2 combined magnetometer/VLF receiver. A base station recorded the diurnal variation of the earth's magnetic field and the variation was subsequently removed from the data.

The VLF-EM receiver measured the electric field component, and the in-phase and out-of-phase components of the magnetic field. The source of the VLF primary field was the transmitter at Rugby (GBR, frequency 16.0, or 16.8 kHz) for the Peter's Hill survey, and Annapolis, Maryland USA (frequency 21.4 kHz) and/or GBR Rugby for the Creagan Riabhach area.

HLEM measurements were made using a Scintrex IGS2/EM4 Genie/Horizontal Loop Electromagnetic receiver and a portable TM-2 transmitter. The equipment was operated in the Genie mode as opposed to the more conventional time-consuming HLEM slingram mode, which requires an interconnecting cable. In the Genie mode of operation the sensor measured the vertical magnetic field amplitudes at two well-separated frequencies, the higher frequency being the signal frequency and the lower one the reference frequency. The ratio between the two is expressed as a percentage, or the Genie ratio. Measurements were made at 10 m intervals using a receiver-transmitter separation of 50 m, giving a theoretical depth of exploration of about 75 m. The EM Genie method was chosen as it is specifically designed to detect massive sulphide bodies, and similar EM methods had proven successful during previous EVL ground follow-up work.

SP measurements were made at 10 m intervals using one static and one moving electrode. The SP method was chosen to detect chemical weathering which sometimes occurs above a buried mineralised orebody giving a negative anomaly. The magnetic method was employed to map out the magnetic pyrrhotite-rich unit (which exhibits magnetic susceptibility measurements within the range 1 to

10 x 10 $^{-3}$ SI units) and basic intrusive rocks. The VLF-EM electric-field component was used to measure lateral conductivity changes over thin to moderate drift cover in order to distinguish resistive granite and basic rocks from the more conductive calc-silicate rocks, and to identify conductive sulphide bodies. The VLF-EM magnetic field component is effective in detecting abrupt changes in conductivity, such as at a geological contact between a conductive pelite and resistive psammite, and detecting vertical conductors, such as sulphide mineralisation, faults and shear zones.

Creagan Riabhach. Magnetic total field and VLF E field data are plotted as stacked profiles in Figure 13, and SP, HLEM, VLF E field and magnetic total field profiles for traverse line +200 in Figure 14. Positive magnetic anomalies between 500 and 2000 nT in amplitude are broadly coincident with the mapped pyrite and pyrrhotite-bearing calc-silicate unit. These form a magnetic zone approximately 200 m wide comparable in width to the sulphidic calc-silicate unit. Within this unit several individual high-amplitude short-wavelength anomalies 20 to 50 m wide form persistent features, which can be correlated across lines –600 to +400 in the eastern half of the area, over Creagan Riabhach hill, suggesting persistent magnetic horizons at a shallow depth. On lines –800 and –1000, which are located in a valley where the overburden is thicker, the anomalous zone is still present but amplitudes are smaller, and the profiles smoother, indicating that the source is more deeply buried here.

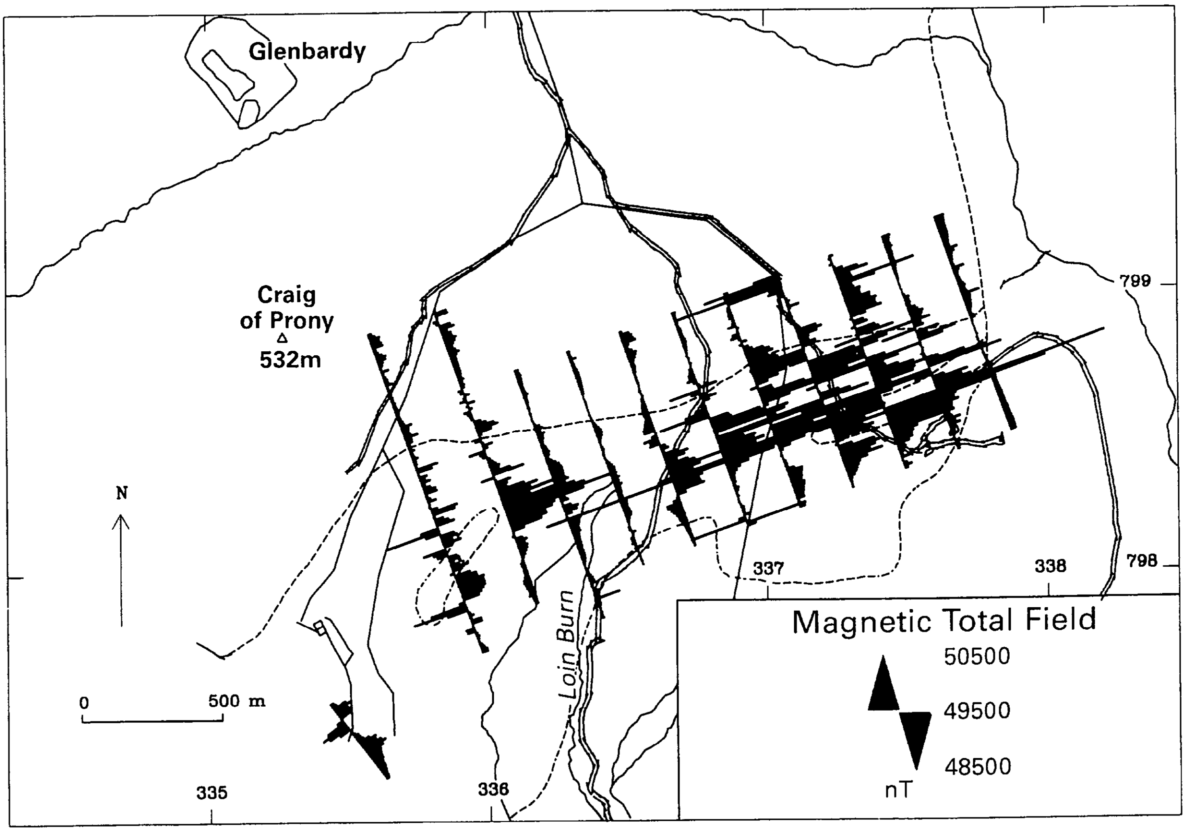
On lines –1200 and –1450 the anomaly profiles are similar to those observed over Creagan Riabhach hill and show a change in strike of the calc-silicate unit to a more north-easterly trend consistent with the mapped geology. The ground magnetic anomaly pattern is also consistent with the EVL aeromagnetic data whereby the anomalies are highest over the hilltops. Both aeromagnetic anomalies are therefore thought to be caused by magnetic calc-silicate rocks.

On Creagan Riabhach, magnetic anomalies are not confined to the calc-silicate unit, but continue uphill across the whole of the basal part of the Glen Girnock Calcareous Formation onto the metadolerite. This suggests a more widespread distribution of pyrrhotite throughout all the rocks within this area. The discovery of sporadic sulphide mineralisation in metadolerite float and at outcrop supports this conclusion.

The large 5000 nT negative anomaly on line +200 and a smaller negative anomaly on line +400 are probably caused by a pyrrhotite-rich lens, as it is also very conductive (see below). Pyrrhotite bodies, such as those over the northern margin of the Dartmoor granite, retain a strong remanent magnetisation and can produce very large negative anomalies.

The VLF electric field shows a zone of low resistivity values in the range 50–100 ohm m over most of the Glen Girnock Calcareous Formation calc-silicate rocks. On line +200 extraordinarily low resistivity values ranging from 10 ohm m down to 3 ohm m occur over a 80 m wide zone within the anomalous magnetic zone, thus providing strong evidence for a significant amount of magnetic pyrrhotite-rich sulphide at this locality. The strong negative magnetic anomaly is located on the south-east margin of the conductive zone, providing further evidence for pyrrhotite mineralisation.

The combination of high magnetic values and high conductivity is characteristic of most of the sulphidic calc-silicate unit across the area, and the main magnetic/conductive zone and the mapped sulphidic calc-silicate unit are of a similar width. This suggests that the true position of the calc-silicate unit on line +200 is probably located about 50 m to 100 m further uphill towards Creagan Riabhach.



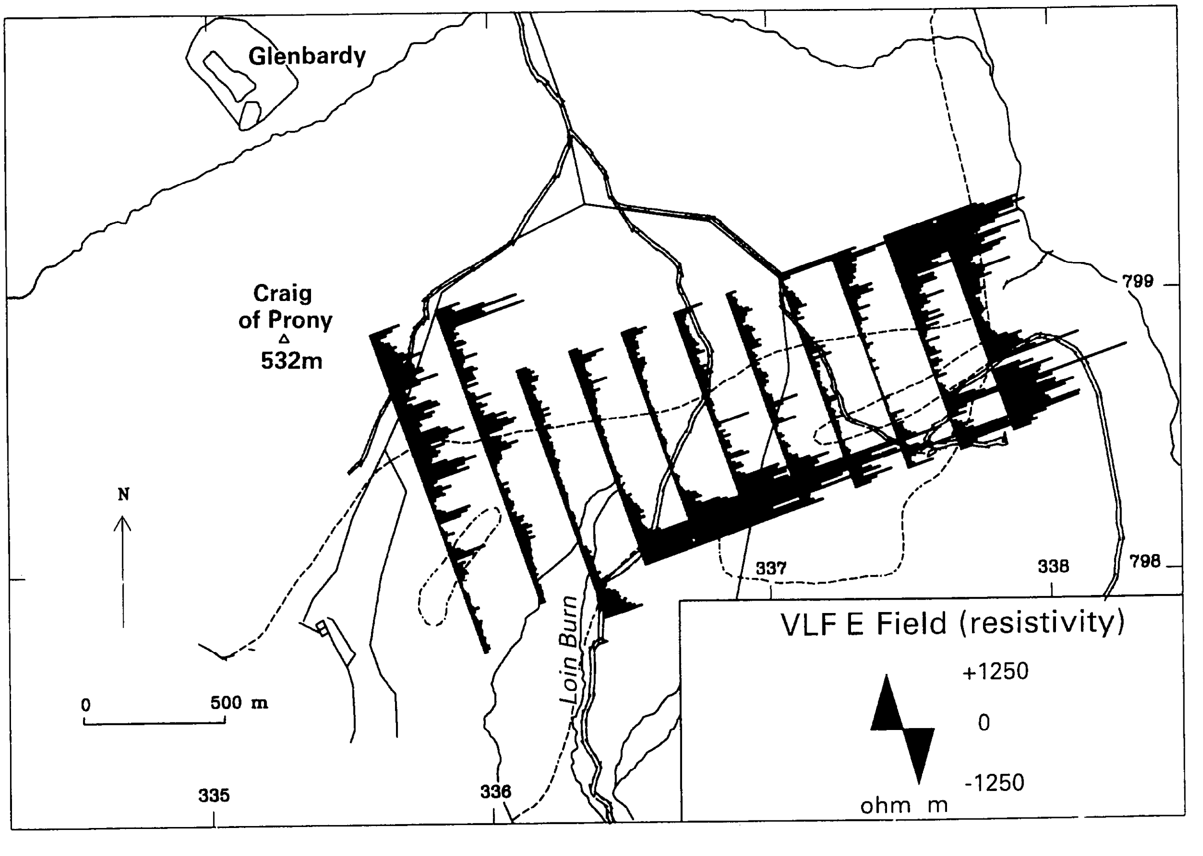


Figure 13 Magnetic total field data (above) and VLF-EM electric field data (below), Creagan Riabhach.

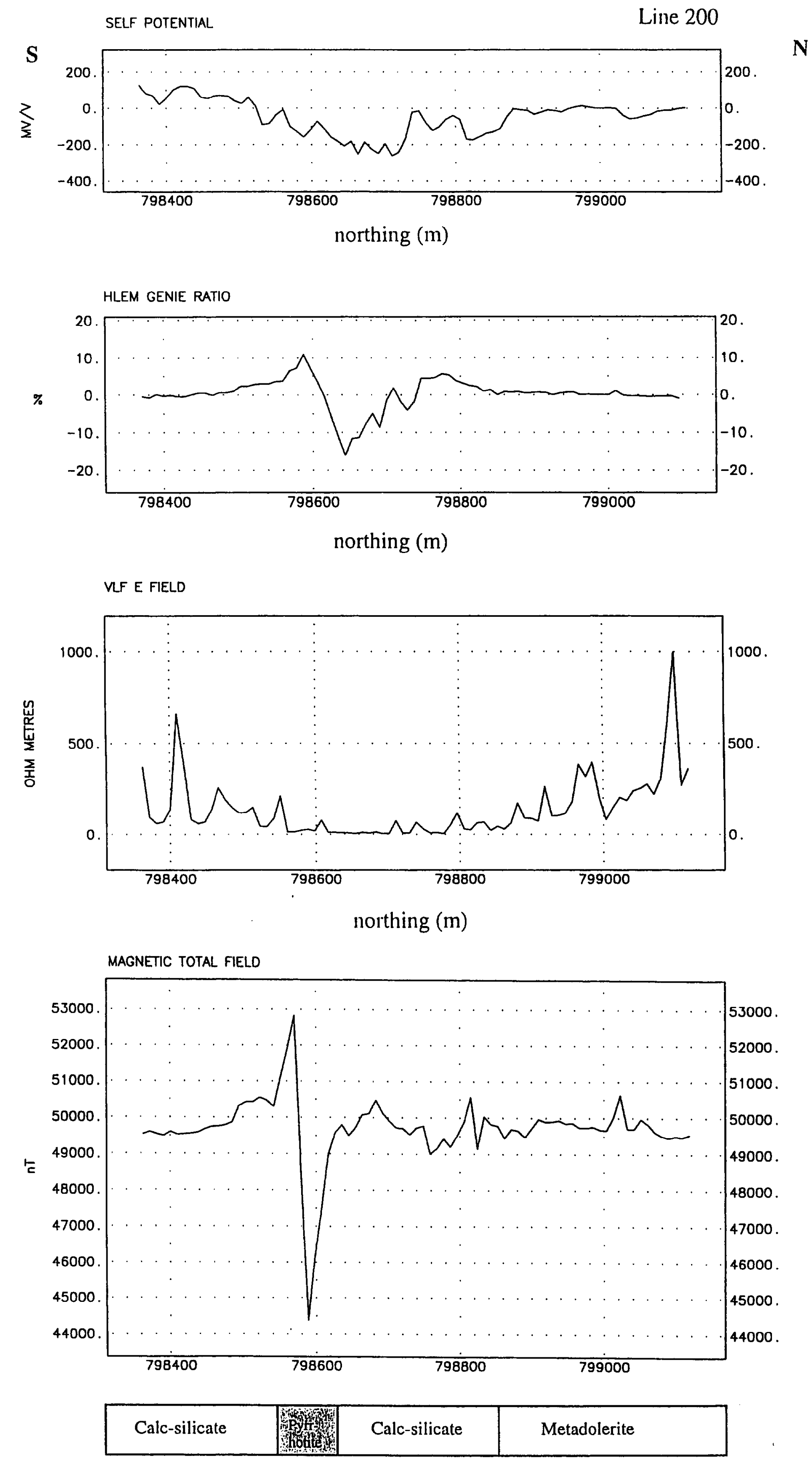


Figure 14 Geophysical profiles for traverse line +200, Creagan Riabhach. See Figure 7 for the location of the traverse line

The granitic rocks are markedly more electrically resistive (500–1000 ohm m) than the metasedimentary rocks and are non-magnetic. The strong correlation between the mapped position of the granite contact on traverse lines –600 and –800 suggests that the contact continues in a straight line towards the east and that the granite embayment shown to the south on the geological map does not exist. High resistivity along all of traverse line +600 indicates that this line probably lies entirely over the granite. Resistivity highs at the northern ends of the traverse lines (500 to 2000 ohm m) are related to resistive metadolerite which is locally magnetic.

No meaningful results were obtained from the VLF magnetic field, as the local topography distorted the primary signal and there was no suitably oriented transmitter with a sufficiently strong signal operating at the time of the survey.

The HLEM profile (Figure 14) shows a large negative EM anomaly coincident with a small negative SP anomaly. The EM anomaly is approximately 100 m wide and is asymmetrical with a larger positive anomaly on its southern flank indicating a tabular massive sulphide body with a dip towards the south-east. The inferred dip of the EM anomaly is consistent with the general geological dip, indicating that the mineralisation is stratabound. The anomaly appears to a lesser extent on line +400 but it is almost absent on line 00.

Peter's Hill. The magnetic and VLF-EM results of the Peter's Hill survey are shown as stacked profiles of magnetic total field and VLF-EM electric field in Figure 15.

On traverse lines –800 to –1600 positive magnetic anomalies of amplitude 500–1000 nT occur over an approximately 100 m wide zone within the Glen Girnock Calcareous Formation, adjacent to the contact with the Queens Hill Gneiss Formation, and are coincident with low conductivity values (50 to 100 ohm m). The width of the anomaly and the geophysical signatures are similar to those in the southern part of the area, at Creagan Riabhach, and are therefore thought to be a continuation of the calc-schist rocks beyond the area shown on the map. A second, narrower magnetic and conductive calc-silicate unit occurs adjacent to the Peter's Hill metabasite on traverse lines –200 to –600, where rusty weathered calc-silicate is seen in float adjacent to the track.

Magnetic anomalies on traverse lines 00 to +400 occur over the Peter's Hill metabasite and are accompanied by high resistivity (1000–10000 ohm m). Thus there is a clear geophysical distinction between magnetic/resistive metabasite and magnetic/conductive pyrrhotite rich calc-silicate. Other very short-wavelength anomalies are caused by wire fences. There are no strong correlations between geochemical and geophysical anomalies, but a magnetic low on lines +400 to –400 is coincident with a narrow zone of high Zn and Ba values.

Conclusions

Trace-element variations in overburden samples from the Creagan Riabhach and Peter's Hill areas are more marked in the shallower overburden in the north-east and north-west of these areas respectively. In the Peter's Hill area enhanced levels of Zn, locally in excess of 400 ppm occur in poorly drained ground on the flanks of the Peter's Hill–Tom Garchory ridge. On the ridge itself, Zn levels show little variation. Overall trends of the base-metals broadly match the three principal lithological formations within the area, and some high metal values in soil are principally the result of secondary accumulation from background sources.

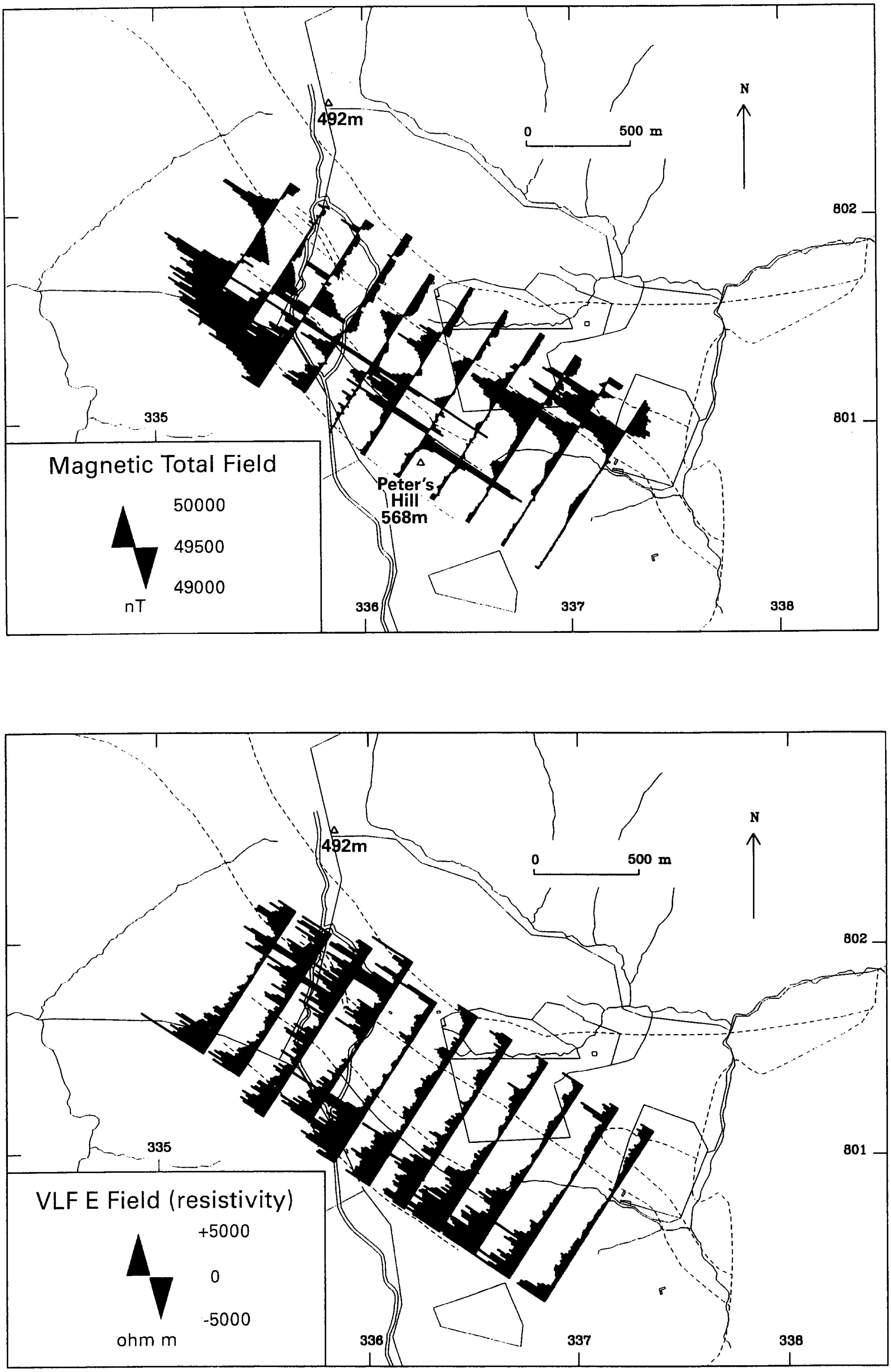


Figure 15 Magnetic total field data (above) and VLF-EM electric field data (below), Peter's Hill

In the southern Creagan Riabhach area the majority of medium tenor Zn and Cu values occur to the north of the prospective Glen Girnock Calcareous Formation, over amphibolitised metadolerites. The distribution of elevated Pb and Ba is more sporadic, and may reflect the presence of vein-style mineralisation. In the north-west of the sampling area elevated levels of Ba, Cu and Zn are found between quartz veins occurring on both sides of the main fence.

Detailed follow-up of enhanced Zn and sporadic enrichment of Cu and Pb in overburden in the Creagan Riabhach and Peter's Hill areas failed to reveal stratiform base-metal mineralisation in the metasedimentary succession, in spite of the ubiquitous presence of pyrrhotite. Minor base-metal enrichment in soils over the Creagan Riabhach metadolerite/metasediment succession was not considered of sufficient magnitude to warrant further investigation.

The presence of baryte vein float in the Peter's Hill area, and the coincidence of minor Zn and Cu enrichment in soils with quartz veining at two localities in the Creagan Riabhach area, suggests that there may have been localised epigenetic remobilisation and mineralisation associated with granite emplacement.

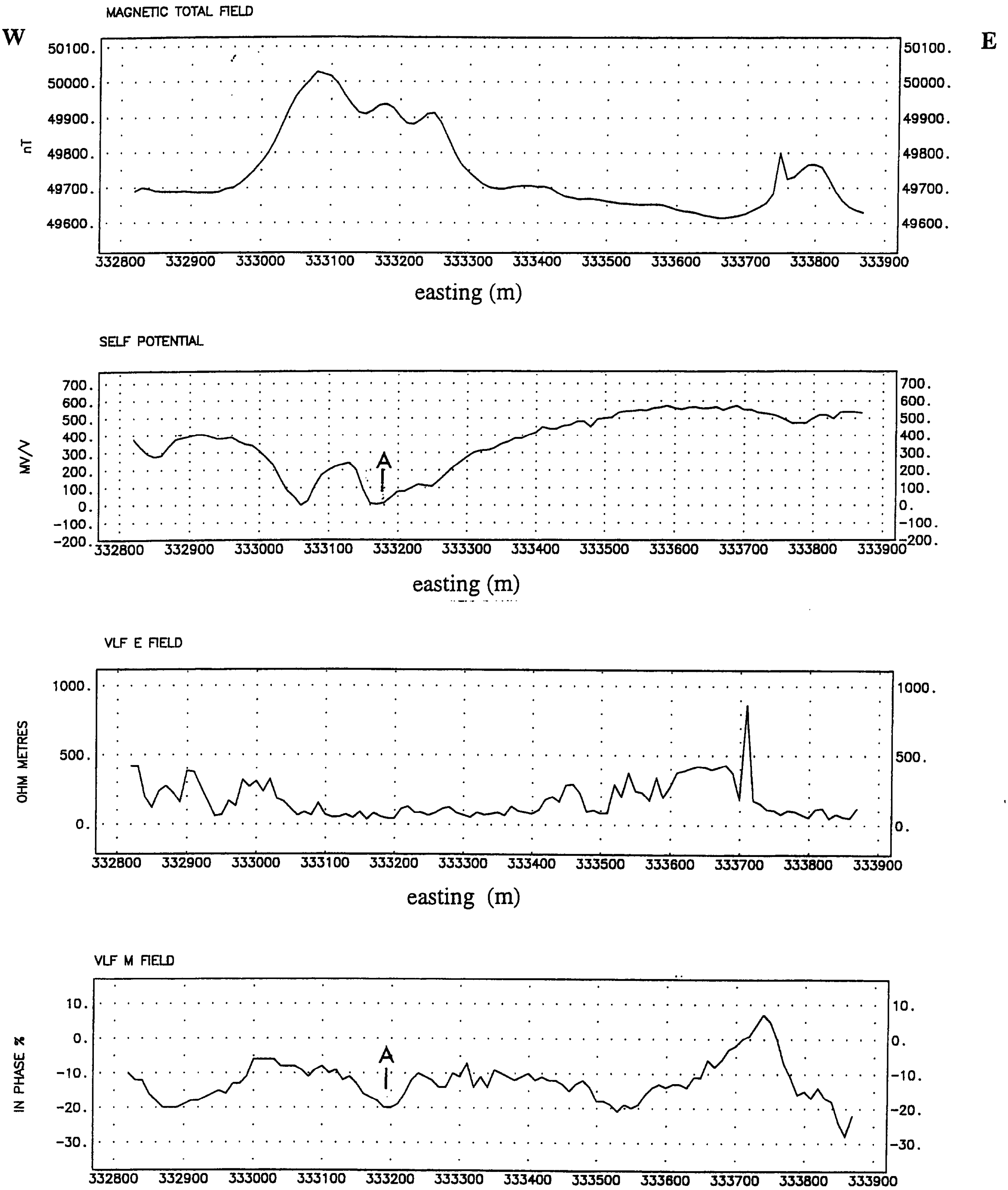
The ground magnetic survey showed that disseminated pyrrhotite is the most likely cause of the ground and EVL aeromagnetic anomaly at Creagan Riabhach. Here, the pyrrhotite-rich rocks generally occur within the sulphidic calc-silicate unit of the Glen Girnock Calcareous Formation, but in the eastern part of the area the distribution of pyrrhotite is more widespread and it is found in abundance throughout the lower part of the formation and in the adjacent metadolerite rocks. There is a clear association between high magnetic field and low resistivity (high conductivity) over the mineralised calc-silicate rocks throughout the area. This is well illustrated on traverse line +200 at Creagan Riabhach where resistivity values as low as 3 ohm metres are accompanied by a large negative EM genie anomaly and a small negative SP anomaly. The EM genie anomaly indicates a massive pyrrhotite-rich sulphide body c. 80 m wide at very shallow depth, with a moderate to steep south-easterly dip consistent with the regional geological dip. This strongly suggests stratabound mineralisation. Its strike length is probably less than 500 m and may represent a sulphide-rich lens.

In the Peter's Hill area there is no obvious correlation between geophysical and geochemical anomalies although soil anomalies on traverse lines +400 to 00 lie within a zone of low magnetic values. Two linear high magnetic/conductive zones run parallel to the geological strike and are probably a continuation of the pyrrhotite calc-silicate rocks at Creagan Riabhach.

Geochemical and geophysical surveys at Glenbuchat

A trial soil geochemical and geophysical survey was carried out in reconnaissance area 1 (Figure 6) along a single line across the Easdale Subgroup rocks near Glenbuchat, to investigate the EVL aeromagnetic high, and EM anomalies 422B and 428B (Table 3) located within the Glenbuchat Schist Formation; and to determine the geophysical signatures of this stratigraphic sequence. The geophysical results are shown in Figure 16.

The Glenbuchat Graphitic Schist Formation is readily distinguishable from the other metasedimentary rocks because of its higher conductivity (50–100 ohm m). There is also an SP low of approximately 400 millivolts, presumably over the most graphitic part. Anomaly 'A' on the SP profile (Figure 16) also has a negative in-phase VLF EM magnetic response indicating a conductor c. 80 m wide. This anomaly is in the same stratigraphic position as the EVL anomalies, and graphitic schist is therefore thought to be their most likely cause.



Culchavie Striped Fm	Glenbuchat Graphitic Schist Fm	Calc-silicate	Badenyon Schist and Limestone Fm

Figure 16 Geophysical profiles, Glenbuchat

The linear aeromagnetic high (Figure 6) is resolved on the ground into three magnetic highs with amplitudes of between 200 and 300 nT which occur over the margin of, and within, the Glenbuchat graphitic schist. The wavelength suggests a magnetic body(s) at an estimated depth of 50 to 100 m below the surface. The source of the magnetic anomaly is not known, but metadolerite in float suggests a possible igneous origin although, because of its stratigraphic position within the Glenbuchat graphitic schist, pyrrhotite mineralisation cannot be ruled out.

A total of 43 soil samples collected at sites spaced at 25 m intervals along the traverse lines showed no enhanced base-metal enrichment. The highest values recorded were Cu 65 ppm, Pb 38 ppm, Zn 132 ppm, Ba 860 ppm and Mn 1010 ppm. Soil anomalies are similar in magnitude to those obtained from the EVL EM follow-up survey a few kilometres to the north and south of this survey.

UPPER DEVERON

Geology

To the north-west of the Portsoy Lineament (Fettes et al., 1991), rocks of the Ballachulish, Blair Atholl and Islay subgroups form part of a coherent stratigraphical succession which is traceable throughout the Grampian Highlands. Lowest Easdale Subgroup rocks may be present in the core of a major syncline in the Chapel Burn area, but exposures are few. Lithologies are typically of marine, shallow-water shelf facies, comprising mainly quartzite and semipelite with some psammite, pelite and metalimestone (Figure 17). The Ballachulish and Blair Atholl subgroup rocks of this area are much intruded by sheets of metadolerite (see below) and exposures of the metasedimentary rocks are rare away from the stream sections.

Within and to the south-east of the Portsoy Shear-Zone, lithologies are typical of the higher parts of the Argyll Group elsewhere and consist of deep-water basinal sediments characterised by turbidites. The lowest unit, the Beldorney Pelite Formation, crops out between the north-western limit of the Portsoy Shear-Zone and the Succouth–Brown Hill intrusion. It consists predominantly of pelites and semipelites, some fine-grained and phyllitic, but mostly biotite-schists. Some impure quartzites and gritty psammites occur in the lower part (Table 10).

To the south-east of the Succoth–Brown Hill intrusion and south of the Succoth Fault the succession consists of alternations of greywacke-grits, pelites and metavolcanic rocks. This lower part of the Blackwater Formation is divided into three members on the basis of compositional variations in the metavolcanic rocks (Fettes et al., 1991; Gunn et al., 1990). The lowest, Lynebain Member and the highest, Ardwell Bridge Member are characterised by a predominance of metabasaltic rocks. The middle, Kelman Hill Member is dominated by fragmental, fine-grained ultramafic rocks, but includes some metabasalts. Vesiculation is common in all of the metavolcanic rocks and fragmented basaltic pillow lavas occur in places (e.g. in the River Deveron at Lynebain [NJ 412 351]). There is little doubt that these rocks are of volcanic origin although some of the more massive units may have been shallow, subvolcanic sills.

Above a particularly thick gritty psammite, the lithology changes quite abruptly to dominantly pelitic rocks in the Corinacy Pelite Member. Sheets of metabasalt are abundant in the lower part of this member, but die out upwards. Beds of gritty psammite are present throughout the member and become thick and persistent towards the top. The pelites are graphitic in parts and a dark phosphatic nodule

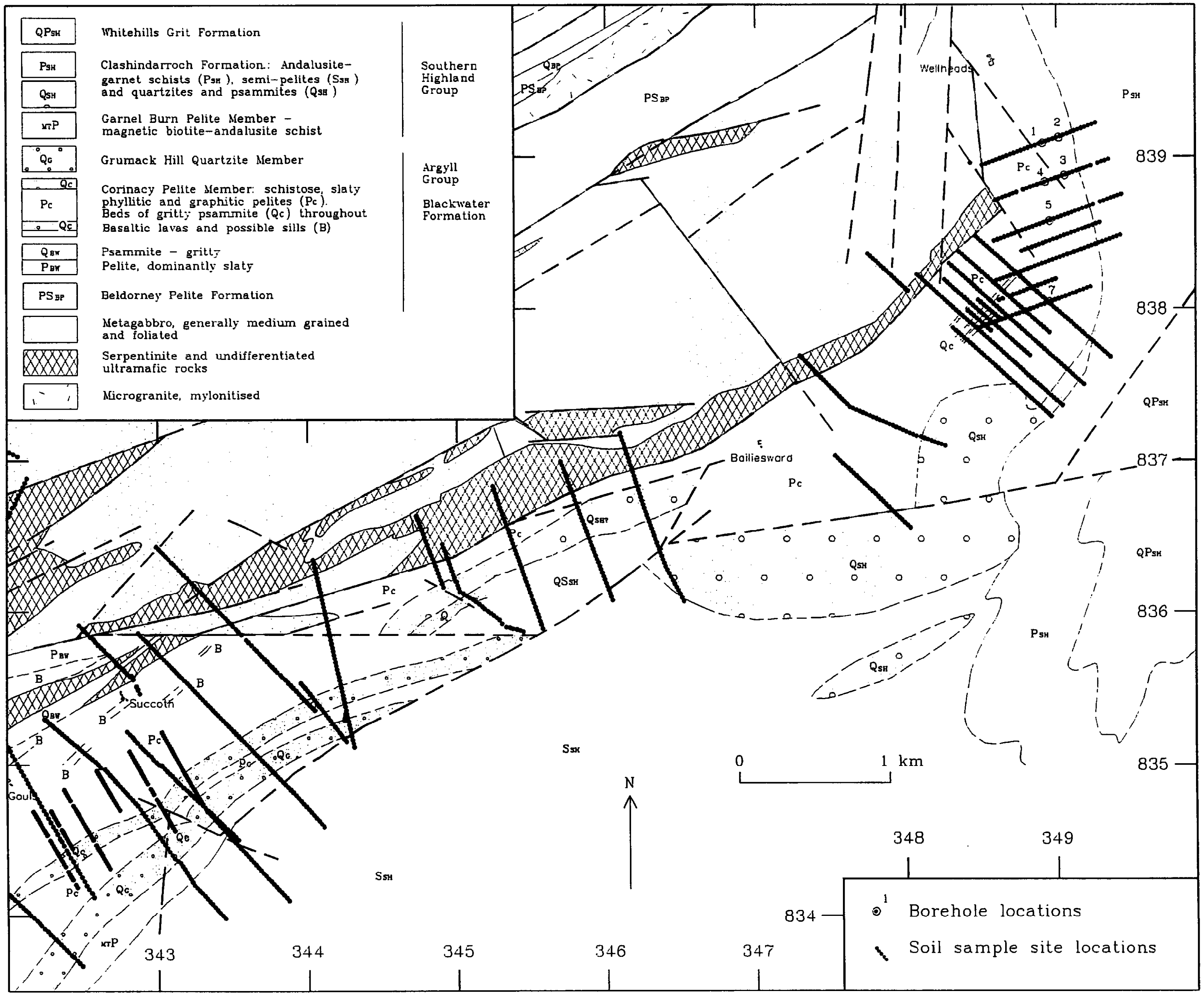


Figure 17 Geological map of the Succoth–Gouls to Wellheads area showing the location of soil geochemical survey lines from current and previous surveys

with impurities of amorphous Fe and Mn was found in the Dry Burn [436 358]. The texture of the pelites is phyllitic to slaty and parts are andalusite rich.

Table 10 Generalised succession for the Dalradian Supergroup in the area around Glass, Wellheads, Succoth and Clashindarroch Forest

Metasedimentary rocks		
Formation	*Lithology*	*Group*
Macduff Formation	Psammite and semipelite with prominent beds of pebbly grit and conglomerate.	Southern Highland Group
Clashindarroch Formation	Semipelite and pelite with rare psammite. Mostly phyllitic with andalusite schists, locally garnet-bearing. Gritty psammite, quartzite and pebble conglomerate. Garnel Burn Pelite Member: magnetic biotite-andalusite-schist.	Southern Highland Group
Blackwater Formation	Grumack Hill Quartzite Member: massive, buff-grey quartzite, gritty in part. Corinacy Pelite Member: schistose, slaty, phyllitic, and graphitic pelites. Beds of gritty psammite throughout become abundant, thick and persistent near top. Mixed sequence, gritty psammites, mica schist, locally black graphitic schist. Abundant metavolcanic rocks define three volcanic members.	Argyll Group, Subgroup unknown
Beldorney Pelite Formation	Pelite and semipelite, phyllitic to schistose. Some beds of gritty psammite and quartzite.	Argyll Group, Subgroup unknown
Meta-igneous rocks		
Serpentinised ultramafic rocks	Serpentinite and undifferentiated ultramafic rocks (dunite, peridotite and clinopyroxinite) delineated in part by magnetic surveys.	
Metagabbro	Orthoamphibolite generally foliated, locally schistose. Some highly magnetic varieties often with sulphide mineralisation.	

The Corinacy Pelite Member crops out extensively on the hill slopes south-east of the River Deveron, which is the type area. However, farther to the north-east, poor exposures in the Collonach Burn (Read, 1923) and borehole sections around Wellheads (Coats et al., 1987a) seem to be of similar lithologies. This area, previously mapped as part of the Portsoy 'group' (Read, 1923), can now be regarded as an extension of the Corinacy Pelite Member. In addition to the lithologies already described, the boreholes intersected graphitic quartzite, chert, intraformational breccias and, in Borehole 7, a 5 m-thick metalimestone. The persistent units of gritty psammite at the top of the member in the type area are probably represented in this north-eastern continuation by pebbly grits and gritty quartzites which form the long ridge of Muckle Long Hill and the high ground of Kye Hill.

Note that the lower members of the Blackwater Formation are not present to the north of the Succoth Fault; they have probably been cut out by shears which bound the Succoth–Brown Hill intrusion.

At the top of the Blackwater Formation the rocks of the Grumack Hill Quartzite Member form persistent features on the north-west side of the watershed ridge on the south-east side of the Deveron valley. It is cut out by the Long Slough Fault, but may be represented by quartzites exposed in burns on the south side of Muckle Long Hill.

The base of the Southern Highland Group is marked on the ridge of Grumack Hill by the highly magnetic Garnel Burn Pelite Member. This can be traced by distinctive tombstone-like outcrops of coarse-grained biotite-andalusite schists with little fabric, and by magnetometer, to around [441 351] where it is cut out by the Long Slough Fault. Reconnaissance magnetometer traverses to the north-east have failed to detect a continuation. Above this basal marker to the south-east is a sequence of semipelites, often flaggy and banded, with thin intercalated quartzites, pebbly psammites and schistose micaceous psammites. Andalusite and staurolite porphyroblasts are widespread and beds of andalusite schist occur locally. This unit, the Clashindarroch Formation, is coincident in this area with the Boyndie Bay 'group' of Read (1923). Farther to the north-east, over Clashmach Hill, exposure is non-existent, but coarse-grained andalusite-garnet schist is present as debris and, since Read (1923) shows this as Boyndie Bay 'group', this too is taken as Clashindarroch Formation.

Farther to the south-east the rocks are more psammitic with intercalations of slaty semipelite and pebbly grit. These constitute the Macduff 'group' of Read (1923) and are now termed the Macduff Formation. Their relationship with the Clashindarroch Formation is not entirely clear. In this area there seems to be an upward stratigraphical succession, but the relationships are probably complicated by diachronous facies changes. Immediately to the south the Macduff Formation appears to occupy a major, south-west-closing, synclinal fold hinge within the Clashindarroch Formation. Elsewhere, outwith the area, the change from Macduff 'group' to Boyndie Bay 'group' as mapped by Read (1923) appears to be a metamorphic change from lower-grade to higher grade andalusite-bearing rocks, with no sedimentological facies change. The area of Whitehills 'group' psammites shown in the north-east of the area is almost exactly as shown by Read (1923), based largely on outcrops to the east. Exposures are few and no significant remapping has been possible. This is an anomalous stratigraphical and structural position for the Whitehills 'group' and it may be that this area will be reclassed as an infold of Macduff Formation when the remapping and interpretation of Sheet 86W is completed.

Major shearing along the Portsoy Lineament post-dates the regional folding and the major intrusions, although movement commenced much earlier (Beddoe-Stephens, 1990; Fettes et al., 1991) and several episodes of shearing are recognised from the mineralogy and fabrics of the igneous rocks (Gunn et al., 1990). Several major anastomasing shears and numerous minor shears occur in a zone between 1 km and 3 km wide, which swings from north-east to north-trending in the north-eastern part of the area. Later brittle faults occur in several directions, but cross-strike north-west trends are common. A major north-east-trending fault, the Long Slough Fault, forms the boundary between the Argyll and Southern Highland groups for a distance of at least 4 km to the north-east of Grumack Hill. East-north-east-trending dextral faults, such as the Succoth Fault which has a 1.5 km displacement, seem to be the latest set in the area. Elsewhere they contain quartz-dolerite dykes of the late-Carboniferous swarm and they are therefore thought to be of about this age.

Most of the meta-igneous rocks of the area have been described in some detail and assessed for their mineralisation potential by Gunn et al., (1990; 1992). Contemporaneous metavolcanic rocks within the Blackwater Formation were considered to have potential for PGE-bearing Cu-Ni mineralisation and, in altered sections for Au, but drilling results were not encouraging (Gunn et al., 1990).

The Succoth–Brown Hill intrusion (Gunn et al., 1996) crops out over some 14 km^2, with the shape of an elongate pod trending generally north-east, but swinging northwards with the regional strike at its north-eastern end. It consists of amphibolites, serpentinites, partially amphibolitised pyroxenites and a range of peridotitic rocks. It is bounded on both sides by sinuous major shears which are splays of the Portsoy Shear-Zone. Where present, strong foliations and joints strike parallel to the margins and dip steeply to the south-east or east. Trails of quartzite debris suggest the presence of screens of country rock. About 70% of the intrusion is composed of metabasic amphibolite derived from gabbroic rocks. Original textures are commonly preserved but amphibolitisation of mafic minerals is always total. The ultramafic rocks occur in elongate masses on both margins, converging towards the south-west. Other smaller pods occur, probably elongated along shears within the intrusion.

The serpentinites rarely have small cores of olivine, but the pyroxenites commonly have well-preserved relics of clinopyroxene and retain an igneous texture. Chrome-spinel is a common accessory. Enhanced PGE contents have been found in some of the clinopyroxene-bearing ultramafic rocks (max. 270 ppb Pt + Pd) with some elevated Au values, and a possible hydrothermal origin for this localised upgrading has been suggested (Gunn et al., 1990). A long and complex history of recrystallisation and alteration and a lack of lithological, mineralogical and structural similarities with nearby 'Younger' basic intrusions (M T Styles, pers. comm.), suggests that this intrusion may be one of the 'Older' intrusions of Read (1919) which predate the main phases of regional deformation and metamorphism.

Geochemical surveys

Soil (shallow overburden) sampling

A brief account of soil sampling carried out previously in the Succoth–Gouls and Wellheads areas has been given above in the section on previous exploration.

Additional soil sampling and geophysical surveys were carried out along traverses linking the Succoth–Gouls and Wellheads areas (Figure 17). In total 1377 samples were collected, prepared and analysed by XRF. Summary statistics of the analytical data are presented in Table 11.

<u>Lead.</u> Lead values in soils from the Succoth–Gouls to Wellheads area are shown as filled contours in Figure 18. Lead shows a strongly bimodal distribution with a background population (mode at 25 ppm) and higher population extending to 200 ppm Pb. A few outliers are present from 200 ppm up to the maximum of 725 ppm. Very low values of less than 10 ppm are found over the serpentinite and gabbro on the northern ends of the traverse lines and over the Southern Highland Group rocks in the south of the area. Most of the high values occur in the Wellheads area, and 10% of the samples collected from this area in 1985 exceed 200 ppm Pb. The high values are reproduced in the resampling to the south-west of the Wellheads grid by this project, giving values up to 467 ppm at [NJ 48384 37805]. Subsequent pitting (see below) revealed the presence of quartzite and pelites enriched in Pb, for example samples KJR 4020 (quartzite) with 1423 ppm Pb and KJR 4023 (pelite) with 1459 ppm Pb. A >200 ppm Pb soil anomaly from the Succoth–Gouls area also seems to be associated with a quartzite band in the Corinacy pelite.

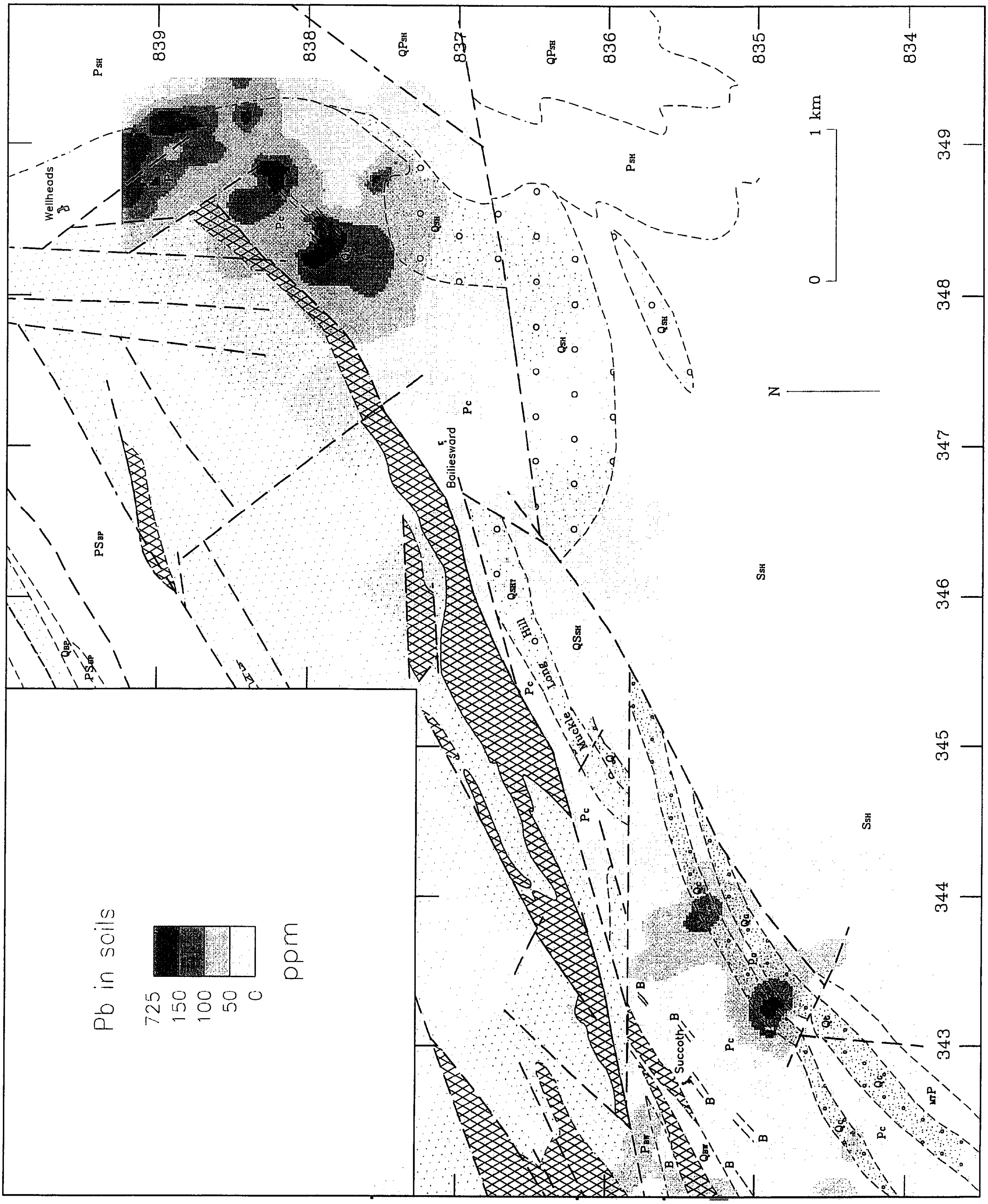


Figure 18 Contour map of Pb in soils, Succoth–Gouls to Wellheads. The key to the geology is shown on Figure 17

Table 11 Summary statistics for the chemical analyses of soil samples from the Succoth–Gouls to Wellheads area

Element	N	Median	25th percentile	75th percentile	Mean	Standard Deviation	Minimum	Maximum
Mn	780	705	470	1111	897	816	100	11526
Fe	1161	43995	32662	53600	43231	20281	1700	336800
Cu	1377	19	11	29	21	16	0	194
Zn	1377	99	65	158	156	291	7	7838
Ba	1377	594	490	701	592	204	0	1840
Pb	1377	36	26	70	56	54	3	725

All values in ppm.

Zinc. Zinc values in soil samples from the Succoth–Gouls to Wellheads area are shown as filled contours in Figure 19. Zinc is the most highly skewed element with a skewness value of 16.85 and the maximum value of 7838 ppm Zn is eighty times the median of 99 ppm. Examination of the cumulative frequency plot reveals a background population dominated by values 0–150 ppm and then a rapid rise through one or more higher populations. The highest outlying values are 1228, 1318, 1418, 1423, 1975, 2174, 4563 and 7838 ppm Zn. These nearly all come from around [NJ 48750 38300] on traverse line +750S at Wellheads (see Figure 21 for location), except for the 1318 ppm Zn value, which is found further north at 200W on traverse line +250S, also at Wellheads. Above background values are also recorded in samples from Succoth–Gouls in both the recent and earlier surveys.

The anomalies at Wellheads on traverse lines +250S and +750S are probably displaced from their source by hydromorphic transport and there is some indication that a source is present in the area to the north-west of Kye Hill where the pitting was undertaken in 1994. Quartzites and pelites from the pits contain up to 1813 ppm Zn (sample KJR 4040) and similar levels of Pb. Sources in the quartzites or pelites to the south-east of Meikle Gouls are also likely. Low values are found in samples from over the Muckle Long Hill ridge and similar low levels are found over the Clashindarroch Formation (Southern Highland Group) greywackes further south, supporting the geological mapping that correlates these two areas.

Barium. Barium in shallow overburden samples is normally distributed, with the median of 594 ppm being very similar to the mean 592 ppm and with skewness of –0.03. The higher, with values (>1000 ppm) are found over the quartzite on Muckle Long Hill and on the southern part of the traverses near Gouls. Low values <200 ppm Ba occur over the serpentinite and gabbro. One sample (KKS 8075), from a black, Mn-rich seepage deposit near Wellheads, contains 1201 ppm Ba and this Ba enrichment is a commonly observed feature of hydromorphic Mn-oxide deposits.

Manganese. Only half the samples were analysed for Mn, so conclusions are based on the earlier work at Wellheads and Succoth–Gouls. Manganese is positively correlated with Fe (Spearman Rank correlation coefficient +0.62) and in normal soil-forming processes both elements are concentrated within the B-horizon. Low values are usually the result of leaching in the A-horizon or an increase in organic content reducing the mineral and oxide components. The positive correlation between Fe and

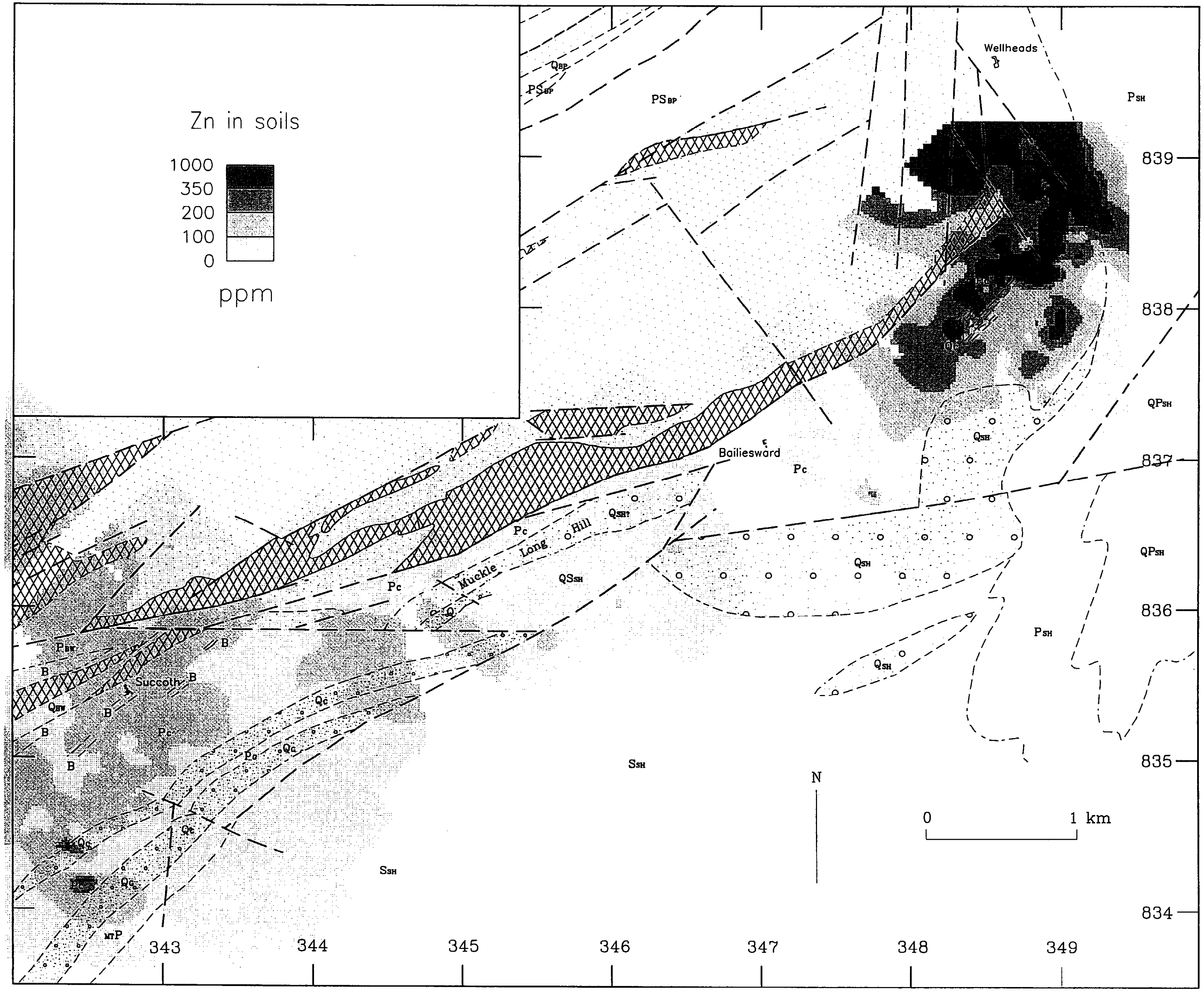


Figure 19 Contour map of Zn in soils, Succoth–Gouls to Wellheads. The key to the geology is shown on Figure 17

Mn in these samples is due mainly to this dilution effect. The areal distribution of Mn shows low values (0–500 ppm) over the Corinacy pelites in both the Wellheads and Succoth–Gouls areas. Isolated high values with between 2000 ppm and 8000 ppm Mn in the Wellheads valley are probably the result of hydromorphic seepage, and typically have lower Fe contents (1–5%) than the samples from over the serpentinite and gabbro, which have high Mn and Fe (5–7% Fe). The soil on the steeper slopes of the valley sides at Wellheads has a moderate Mn content (between 1000 ppm and 2000 ppm), which is typical of mineral soils over impure greywackes.

Iron. As discussed above, low values of Fe in soils are often the result of leaching or dilution by organic matter. This is illustrated by the Wellheads area where samples from the steeper valley sides contain around 5% Fe and those from the valley floor around 1% Fe. In the western part of the Deveron area low Fe contents are found over some of the Corinacy pelite and quartzite units but consistently higher values occur over the serpentinite and gabbro.

Copper. Copper shows a slightly skewed distribution (skewness = 2.14), with the mean of 21 ppm close to the median of 19 ppm. Levels are generally low (Table 11). Samples above the threshold value of 50 ppm Cu, calculated from the cumulative frequency distribution are generally only found over the serpentinite and gabbro. There are two exceptions. One sample, containing 135 ppm Cu, was collected from a Mn-rich seep at Wellheads (KKS 8075), and the highest value (194 ppm Cu) was found in a sample from [NJ 43731 35674] within the Corinacy pelite. The two adjacent samples have very low values, indicating a very local source for the Cu. Copper levels over the pelites are generally low.

Pitting and trenching at Wellheads

In order to investigate the Pb anomaly to the south-west of Wellheads a programme of pitting and trenching was carried out using a mechanical excavator. A total of 54 pits and short trenches were excavated over the Corinacy Pelite Member (Figure 20). A variety of metasediments, including psammite, laminated and schistose semipelite, pelite and graphitic schist were encountered.

In common with other project areas in north-east Scotland (Gunn et al., 1990; Gunn and Shaw, 1992), trenching revealed marked variations in drift thickness over the sampling area. Overburden depths in the trenches ranged from c. 2.5 m in the central part of the sampling area to more than 5 m. The deeper overburden profiles were of heavy but generally well-drained micaceous clay, varying in colour from pale grey to orange brown. Rare clasts of locally-derived quartzite or psammite were encountered in these profiles. Sampling was constrained in a south-easterly direction as a consequence of the rapid increase in overburden depth.

A total of 78 largely bedrock samples were collected representing the range of lithologies present in each pit or trench. From these samples a representative suite of 46 rocks was selected and submitted for multi-element analysis on pressed powder pellets by XRF.

Lead. The element distribution plot for Pb shows a similar spatial distribution pattern in rocks and soils (Figure 20, B and C). Higher values occur within a north-east-trending zone, coincident with the pattern of elevated values shown in the more extensive soil sample coverage. The highest values recorded occur in pelites which are intercalated with the thicker quartzites, with a maximum value of 1759 ppm (Pit No. 3). The majority of Pb levels in psammitic/quartzitic rocks were lower (c. 300 ppm to 400 ppm) although still high, and one sample contained 1423 ppm Pb.

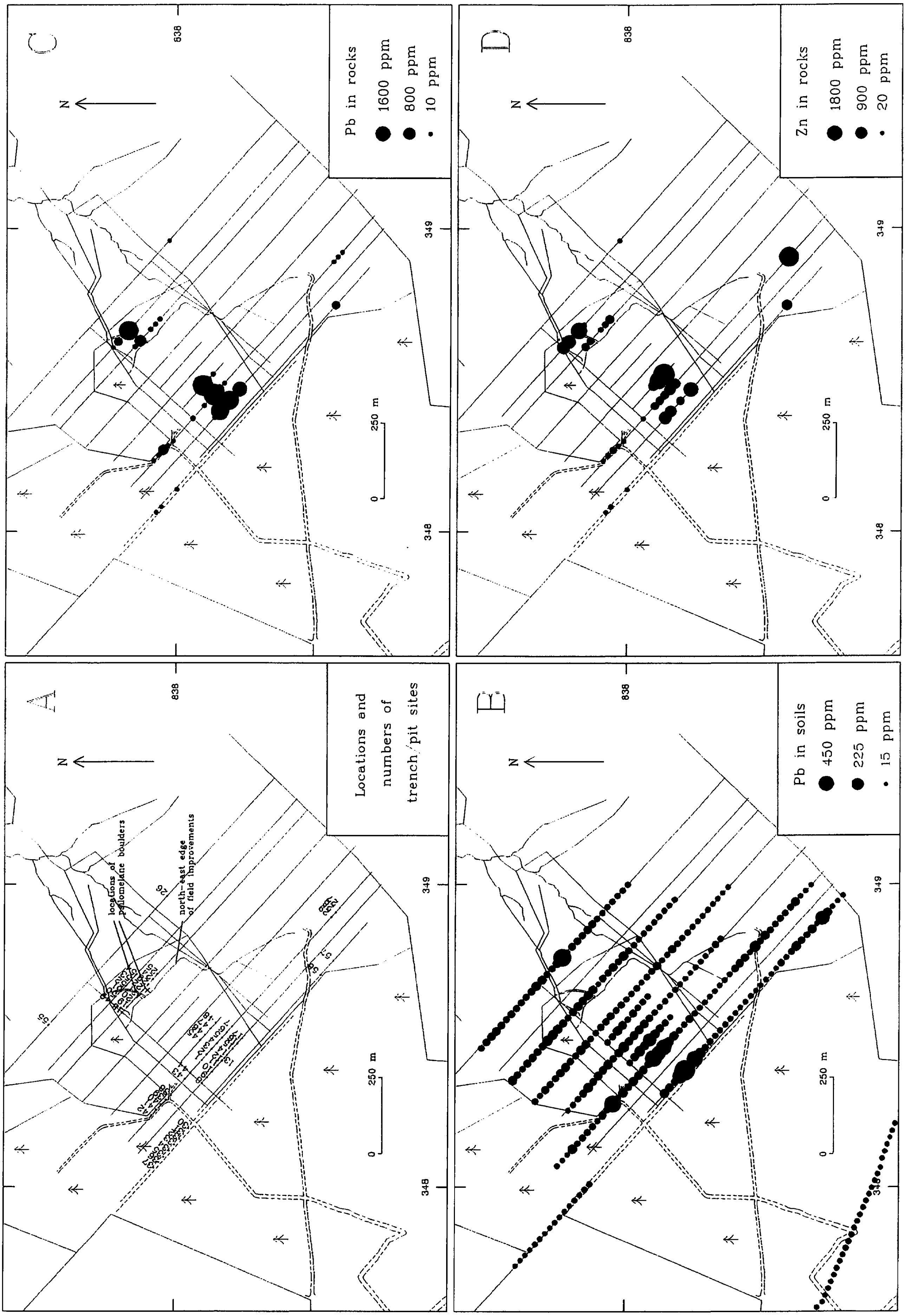


Figure 20 Follow-up trenching and infill soil geochemical survey results, Wellheads

Marked variations in Pb levels occur within the psammitic lithologies. To the north-east of the main Pb anomaly, samples of this lithology from Pits 50 and 53 contain Pb values of 53 and 98 ppm respectively. It is not clear whether the changes in Pb level are attributable to facies variation, or if the samples represent different psammites within the same suite.

Adjacent to the main Pb-enriched zone in a north-westerly direction pelitic rocks contain low Pb (29, 27 and 24 ppm in pits 1 and 2). These mark the transition to much lower Pb values in the north-western part of the area. At only one excavated location within this part of the area (Hole 40) is there significantly elevated Pb in bedrock (619 ppm), and this is coincident with enrichment in the overlying soil. Samples of graphitic pelite from Hole 33 and 23 contained only 11 ppm and 16 ppm Pb respectively.

Zinc. Zinc values form two populations with a break at around 1000 ppm. Slight Zn enrichment occurs in the semipelitic and pelitic lithologies within the central Pb-enriched zone, where values are generally in the range 300–700 ppm. The main zone of Zn enrichment occurs immediately south-east of this, (Figure 20, D) in reddened, altered pelites and mica schist.

The highest Zn value (1982 ppm) occurs in a clast of crenulated mica schist (KJR 4060) from Hole 47 (NJ 48520 37880). Heavy black/brown staining by Mn and Fe secondaries, and accordingly high levels of these elements, together with Ba, indicate the influence of supergene scavenging.

Barium. Barium levels are fairly high, with a median value of 743 ppm. The highest Ba value (57261 ppm) came from the same clast containing the highest Zn value (KJR 4060). Most other samples with Ba >1000 ppm cover a wide range of lithologies from Pits 4, 14, 21, 24 and 50.

Additional rock samples

Three angular boulders of unusual composition occur within the detailed sampling area (Figure 20A). These boulders are of local origin, having been amassed with other rocks during field improvement work. The largest of these boulders is c. 1.5 m in diameter. The boulders are very dark grey with powdery brown patches on fresh surfaces and extremely hard. They comprise botryoidal masses of very fine-grained, amorphous Mn and Fe minerals. Two of the boulders contain many cm-sized angular rock fragments of psammite and pelite which are irregularly disposed within the undeformed rock matrix. Analyses of these boulders showed enrichment in Ba, Mn, Fe, Co, Cu and Zn compared with trenched samples. One sample contained over 10% Ba and a second 1573 ppm Zn.

Discussion

The highly anomalous Pb and Zn in soil concentrations from the Wellheads valley cannot be traced further west than the edge of the coniferous forest north of Kye Hill, a distance of about 1 km. These anomalies are within the mapped outcrop of the Corinacy Pelite Member (A G Gunn, personal communication) and, in particular, over the thin quartzites revealed by trenching. Sampling within the forest along rides and tracks south of Bailiesward revealed no anomalies. Results from the traverses over the pebbly quartzites on Muckle Long Hill showed very low levels of Zn and Pb, indicating that these rocks cannot be correlated with the quartzites at Wellheads, or those within the Corinacy Pelite Member at Succoth–Gouls. Similar levels are recorded in the soils over the quartzite unit within the Clashindarroch Formation on Kye Hill. In the Succoth–Gouls area the soils over the Corinacy pelite can have elevated levels of Zn (up to 604 ppm) and Pb anomalies are also seen at the margins of the quartzite units (up to 326 ppm Pb).

The geochemical anomalies seen at Wellheads and to a lesser extent at Succoth–Gouls are confined to the Corinacy Pelite Member of the Blackwater Formation and, despite evidence of hydromorphic transport, are probably sourced within that member. The nature of the mineralised source is not clear but it has similarities to that seen in the Glas Moal Schist at Glenshee (Coats et al., 1987 b, Pease et al., 1986), and in the Ben Eagach Schist at Dericambus (Coats et al., 1984 a, b). At these localities the mineralisation is dominantly Zn-Pb located within quartzite units in pelite formations.

The results of the trenching show that low-tenor enrichment in Pb occurs within a clearly-defined zone of pelites and psammites to the south-west of Wellheads Farm. Enrichment of the more mobile elements, Zn, Co and Cu, occurs in a parallel zone immediately south-east of the main zone of Pb enrichment.

Localised low-tenor upgrading in the more mobile elements may have been facilitated by groundwater flow from a stratabound source in psammitic and pelitic lithologies. As a result of a combination of favourable geometry and bedrock chemistry, a variety of supergene Fe and Mn oxide precipitates, locally enriched in Zn and other mobile elements, have accumulated within a relatively small area.

The Mn-rich boulders show consistently high Ba levels, suggesting that psilomelane is a primary constituent of these rocks. It is likely that these occurrences, along with the highly anomalous Zn levels in overburden from earlier sampling at Wellheads (Coats et al., 1987 a), are the products of supergene or hydromorphic enrichment processes. Similar Fe and Mn cemented breccias are known from other localities in the East Grampians and look very similar to the Lecht breccias, which are also enriched in Mn, Fe, Ba and Zn.

Geophysical surveys

Previous work

Following the discovery of sphalerite in black shales at outcrop in Gouls Burn [NJ 427 834], and elevated Pb and Zn values in soils, a trial VLF-EM survey was carried out in 1985 by the BGS along five survey lines 250 m apart with the origin centred over the mineralised outcrop. No significant steeply dipping conductors were found but the data were useful in mapping the general strike of the rocks over poorly exposed ground.

The following year reconnaissance and detailed geophysical surveys were carried out some 6 km further along strike to the north-east of Gouls (Figure 18), and at Wellheads in 1986 and 1987 over high Zn (>1000 ppm) geochemical drainage and soil anomalies. Total field magnetic, Very Low Frequency Electromagnetic (VLF-EM), and Induced Polarisation (IP) techniques were employed along six north-east oriented traverse lines approximately 1 km long and spaced 250 m apart. The survey details and results are included in an MRP Data Package (Coats, et al., 1987a).

The IP method proved to be the most useful geophysical technique at Wellheads because of its ability to detect disseminated sulphides, and because it was the only available method capable of penetrating the deep conductive overburden. A zone of high chargeability (60–80 Msec) was identified on the southernmost two geophysical survey lines at depth and this was subsequently drilled at its shallowest part on traverse line +1000S at +320W (borehole 7). Disseminated sulphides (pyrite) in association with brecciated quartzite and pelitic and graphitic schists were intersected at a depth of approximately 50 m. The anomaly continued at a greater depth further to the south onto traverse line +1250S. No IP anomalies were discovered on the remaining survey lines except for a small increase in chargeability towards the serpentinite. The magnetic and VLF-EM methods, taken alone, contributed very little apart from delineating underground water pipes, and indicating the serpentinite/schist contact.

Geophysical data, including BGS and EVL surveys, were re-evaluated in the light of new geological mapping undertaken since 1986 as part of the BGS East Grampians Project. The recently digitised EVL reconnaissance IP data for the Huntly-Portsoy region showed a pronounced zone of high chargeability (> 40 Msec) and low apparent resistivity (< 250 ohm-metres) at shallow depth (n=2) immediately west of the 1986 Wellheads survey grid, along the eastern margin of the serpentinite and adjacent metasedimentary rocks of the Blackwater Formation. The drilled Wellheads chargeability zone could also be identified although its surface expression was weaker because of its greater depth. In addition, the IP data identified another area of high chargeability around Muckle Long Hill over rocks of the Southern Highland Group which had not been previously investigated.

It was therefore decided to carry out further surveys in the Wellheads area to determine the lateral extent and depth of these EVL IP anomalies, to see if they could be related to the geochemical anomalies, and to close off the drilled IP anomaly to the south of traverse line +1250S. Geophysical coverage was also extended along the strike length of the Corinacy Pelite Member and Southern Highland Group metasedimentary rocks over poorly exposed ground as far as the mineral locality and previous geophysical survey at Gouls, to identify potential mineral targets and map the geology.

Methods
Approximately half of the ground between Gouls and Wellheads lies within the Clashindarroch Forest, where the location and orientation of survey lines was restricted to thinly forested areas and clearings. In densely forested areas, notably between Bailliesward and Wellheads, survey lines were run along suitably orientated fire-breaks.

Three separate survey grids were established with traverse lines orientated perpendicular to the local strike. On the Succoth–Gouls section (Grid 1 on Figure 21) seven survey lines up to 1500 m in length were surveyed to cover the outcrop width of the Corinacy Pelite Member and part of the Southern Highland Group. Traverse line +900 passed 20 m east of the sphalerite occurrence found in Gouls Burn [NJ 427 834]. The south-east ends of the survey lines were situated within young forest and, for logistical reasons, were run down slightly curved ploughed gulleys between the trees. The geochemical data are plotted in their true positions but the geophysical profiles (Figures 21 to 25) required plotting as straight lines. Traverse lines over the Muckle Long Hill section (Grid 2 on Figure 21) were located at approximately 250 m intervals to cross the south-east margin of the serpentinite, Blackwater Formation pelites, and overlying quartzites of the Southern Highland Group. Traverse line +1500E crossed the anomalous EVL high chargeability zone. Two more lines were surveyed along fire-breaks in heavily forested ground further to the north-east near Bailiesward. At Wellheads (Grid 3 on Figure 21) an 1800 m long traverse was surveyed across the EVL IP zone, followed by infill lines 100 m or 200 m apart.

Reconnaissance total-field magnetic, and VLF-EM magnetic and electric field components were measured simultaneously at 10 m intervals along all traverse lines in the Succoth–Gouls and Muckle Long Hill sections using the Scintrex MP4 VLF4 combined magnetometer/VLF receiver. The Rugby transmitter was used as the signal source for the VLF. At Wellheads the VLF electric field was measured on selected lines only, because of the dense forest floor debris. This caused poor electrode contact with the ground, which artificially distorted and amplified the electric field signal.

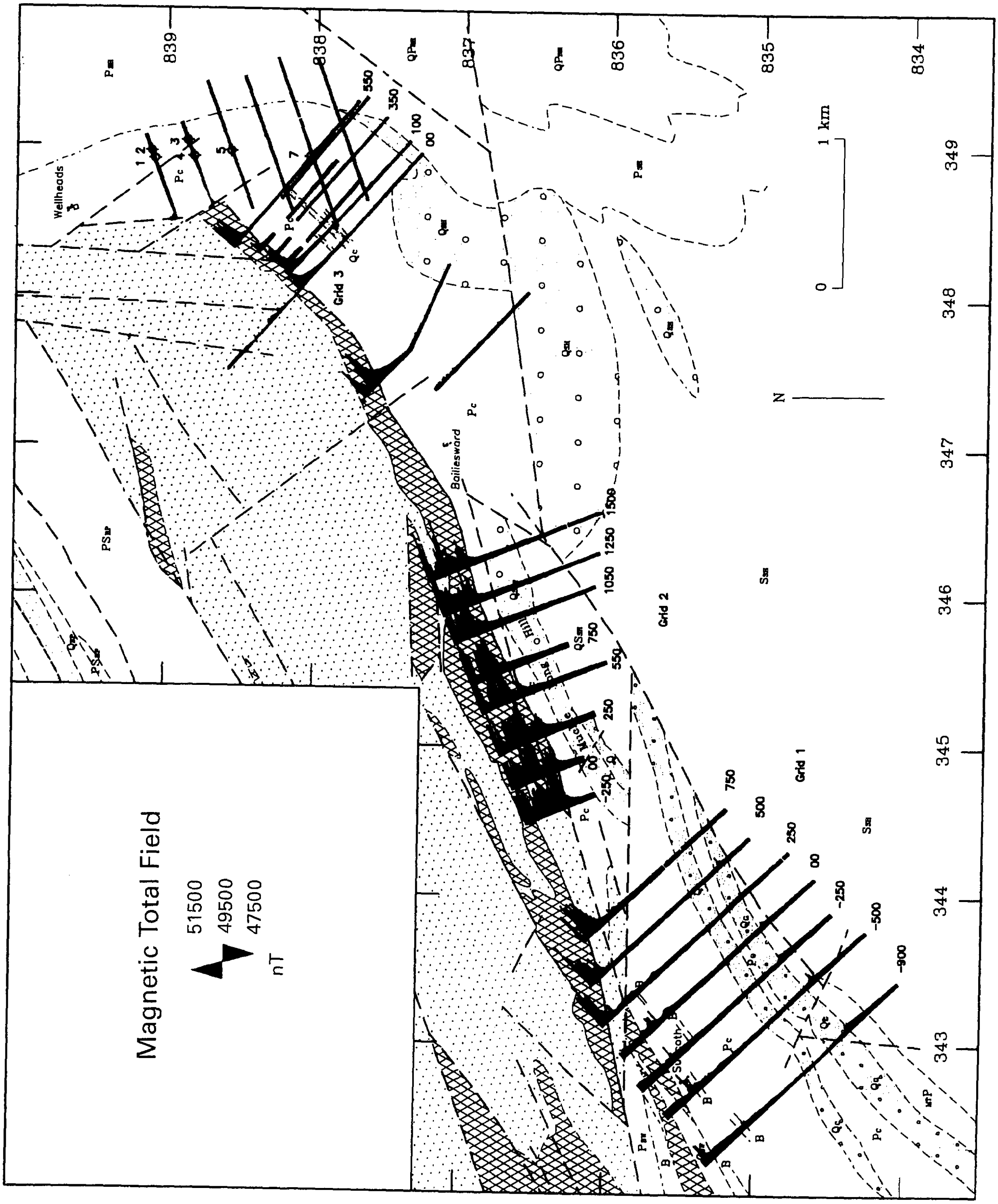


Figure 21 Magnetic total field data, Succoth–Gouls to Wellheads

The magnetic field was chosen to map the boundary of the magnetic serpentinite, and to detect any pyrrhotite present which may be associated with sulphide mineralisation. The VLF magnetic and electric fields were used to identify steeply dipping conductors, such as a mineralised horizon or fault, and to map lateral changes in resistivity which should occur between conductive pelites and resistive quartzites.

The IP measurements were made along alternate lines using a dipole-dipole array with a centre-to-centre electrode separation of 50 m and a dipole depth to n=6. This provided the best lateral resolution and depth of penetration (max. 150 m) for the amount of ground covered. Measurements were made with a Scintrex IPR11 digital IP receiver, and a Scintrex TSQ transmitter powered by a 3 kw generator provided the current source. The time domain method was employed using a 2 second transmitter/receiver time delay. Traverse line +500E at Gouls and line +1050E at Muckle Long Hill were surveyed using a less powerful battery powered Lopo transmitter because of generator failure.

The SP method was run along all IP lines to identify negative anomalies which often occur over a weathered sulphide zone or over geological conductors such as graphitic schist or a shear zone.

Magnetic survey results

Total field magnetic data for the whole area are plotted as stacked profiles overlain on a geological basemap (Figure 21). No diurnal corrections were applied to the data. The 1986 Wellheads survey data (near east–west lines) were network adjusted to correct for a change in the Earth's magnetic field of approximately −130 nT which has occurred between 1986 and 1993/94.

The magnetic method successfully mapped out the boundary between magnetic serpentinite and non-magnetic rocks of the Corinacy Pelite Member through the Succoth–Gouls and Muckle Long Hill sections. Magnetic anomalies over the serpentinites are approx 2000 nT in amplitude. There is a discrepancy between the magnetic boundary and the mapped serpentinite boundary at the north-western end of the Gouls section where the serpentinite appears to be continuous and has a more east–west trend. There are minor local magnetic highs of around 500 nT in the north-west part of the Succoth–Gouls section which are probably due to basaltic lavas or sills near the base of the Corinacy Pelite Member. These do not continue across adjacent survey lines. The magnetic Garn Burn Pelite Member does not show up as a significant magnetic anomaly in this area. Very-short-wavelength features, coincident with VLF M field anomalies, are caused by wire fences. At Wellheads the longest traverse extending onto the metagabbro outcrop suggests that the serpentinite here is narrower than mapped (approximately 100 m wide). The metagabbro has only a weak magnetic expression. There do not appear to be any local magnetic anomalies indicative of pyrrhotite mineralisation.

VLF-EM results

The in-phase component of the VLF electric field, measured in ohm metres (ohm m), and the VLF magnetic field expressed as a percentage are displayed as stacked profiles in Figures 22 and 23.

The electric-field data (Figure 22) show an excellent correlation across all survey lines at Succoth–Gouls and Muckle Long Hill. A broad zone of high resistivity above 1000 ohm m is associated with quartzite units within the Blackwater Formation. These range from smaller individual units some 20 to 30 m thick, to more persistent massive units higher up in the sequence, notably the Grumack Hill

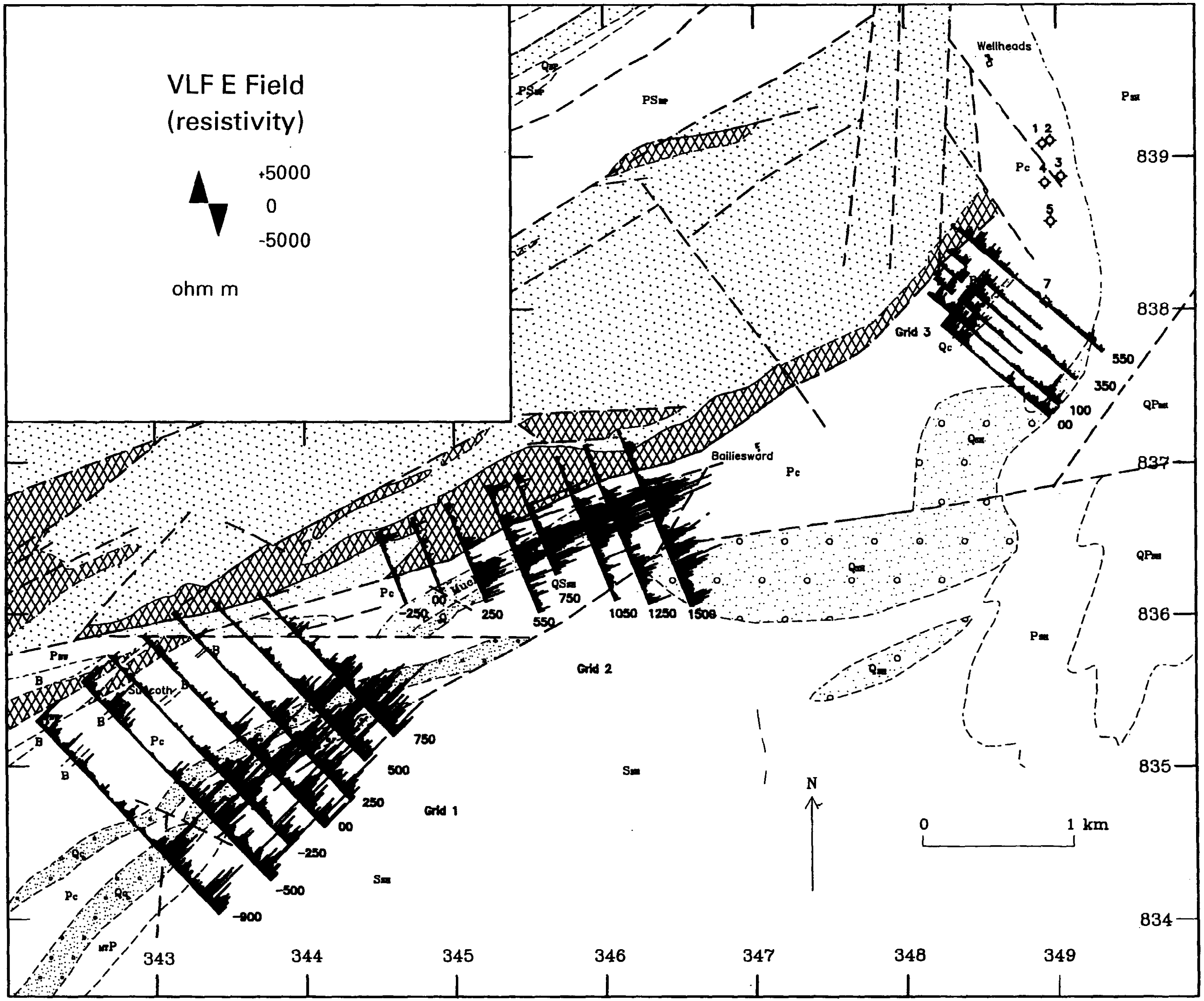


Figure 22 VLF-EM electric field data, Succoth–Gouls to Wellheads

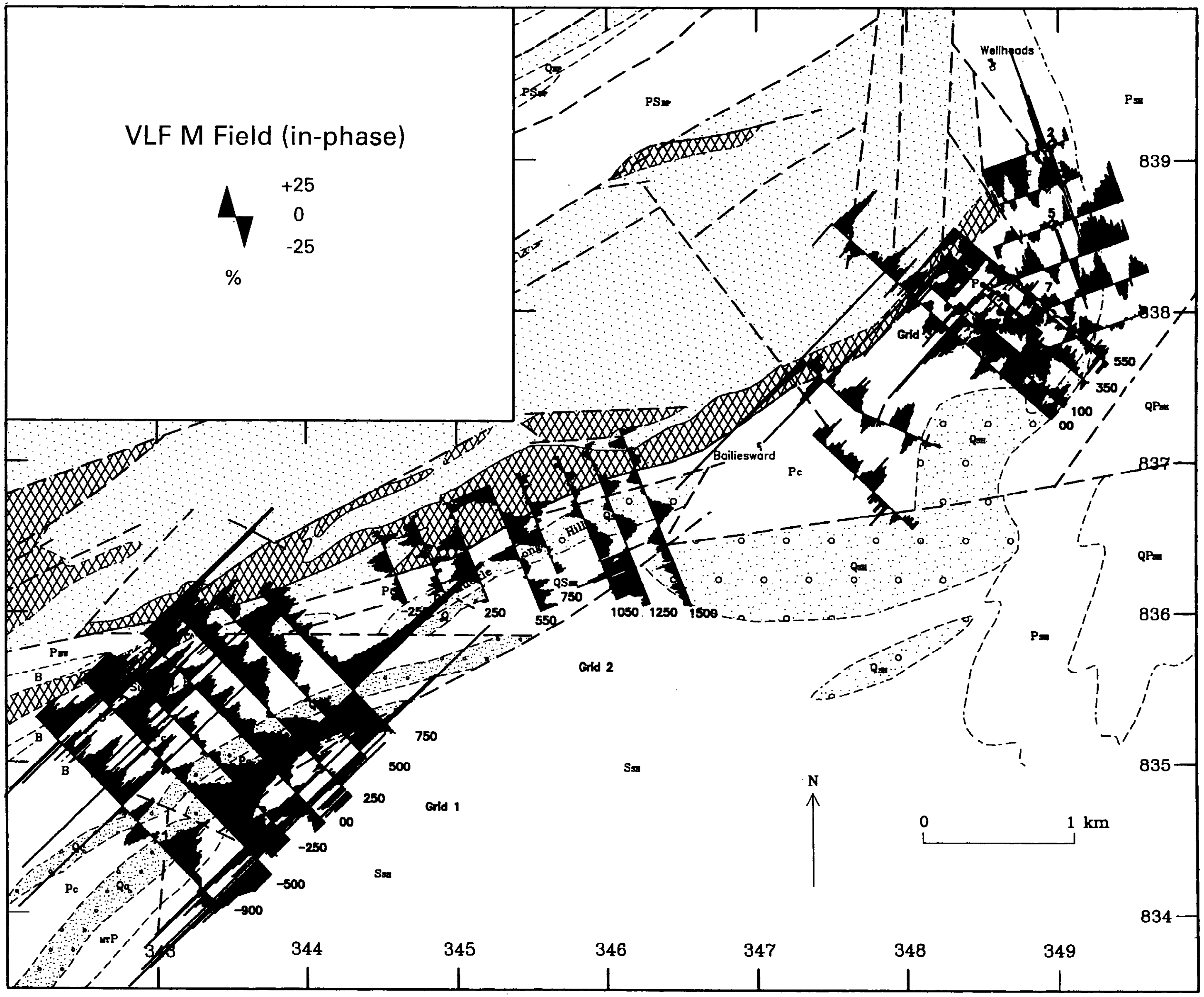


Figure 23 VLF-EM in-phase data, Succoth–Gouls to Wellheads

Quartzite Member which forms a highly resistive unit (2000–3000 ohm m) approximately 150 m thick. This anomaly pattern is repeated on Muckle Long Hill where the quartzite is clearly identified as a persistent highly resistive massive unit (c. 3000 ohm m) increasing in thickness from 150 m to 200 m along strike towards the north-east. At Succoth–Gouls Pb anomalies in soils occur within a few metres down-slope of the high resistivity values (>1000 ohm m), which suggests that they are probably derived from quartzites within the Corinacy Pelite Member. The Corinacy pelite generally exhibits low resistivity (200–400 ohm m) but the lower part is distinctly more conductive with resistivity values in the range 100–200 ohm m, and as low as 50 ohm m over graphitic schists seen at outcrop in newly excavated drainage channels. The lower part of the Corinacy Pelite Member is therefore more graphitic than previously recognised. A local resistivity and magnetic high near Succoth is probably caused by a mafic intrusive body.

At Wellheads a distinctive 300 m wide zone of high resistivity (1000–3500 ohm m) occurs in the western part of the survey area towards the serpentinite. At least three separate continuous units 50 to 80 m wide can be identified and traced along strike for over 200 m in a north-east to north-north-east direction. Trenching has confirmed that the high resistivity units are due to quartzites which are coincident with high Pb anomalies in soil (Figure 24). Low resistivity values between the quartzites are due to graphitic schist or pelite units, with a notable resistivity low (< 200 ohm m), and accompanying high Zn in soil anomaly, over graphitic schist at easting 348250.

To the east of the quartzites low resistivity values correlate with low Pb values over boggy ground in the central part of the area, but beyond this a zone of variable resistivity (200–500 ohm m) correlates with further high Pb and Zn in soil anomalies. Here, there is again a general association between high resistivity and high Pb, and low resistivity and high Zn. Further high resistivity values up to 3000 ohm m are related to quartzites within the Clashindarroch Formation in the eastern part of the area.

The magnetic field anomaly pattern is less readily interpretable but some general inferences can be made. At Succoth–Gouls, positive in-phase VLF magnetic field anomalies are associated with the highly resistive quartzite units. A pronounced dip to low or negative in-phase, indicating a sharp change in conductivity, occurs at the contact with the more conductive Corinacy Pelite Member and this contact can be readily correlated across all seven survey lines. Pb anomalies in soil are located on this feature but there is no direct relationship between the magnetic field anomaly and sulphide mineralisation.

Within the Corinacy Pelite Member several other positive in-phase anomalies located over the zone of very low resistivity are thought to represent local changes in conductivity reflecting alternating graphitic and non graphitic horizons. Very short wavelength features are caused by wire fences which act as vertical conductors masking any vertical geological conductors that may be present.

Over Muckle Long Hill changes from positive to negative in-phase occur over the contact between pelite and quartzite but individual peaks and troughs correlate across only short distances. At Wellheads VLF magnetic field measurements were affected by man-made sources, although the general strike of the rocks can generally be determined.

Induced Polarisation results

Chargeability anomalies are shown in plan view (Figure 25) for a dipole depth of n=2, and chargeability time slice 5. Selected pseudosections of chargeability (slice 5) and apparent resistivity over the main Pb and Zn soil anomalies at Succoth–Gouls and Wellheads are shown in Figure 26.

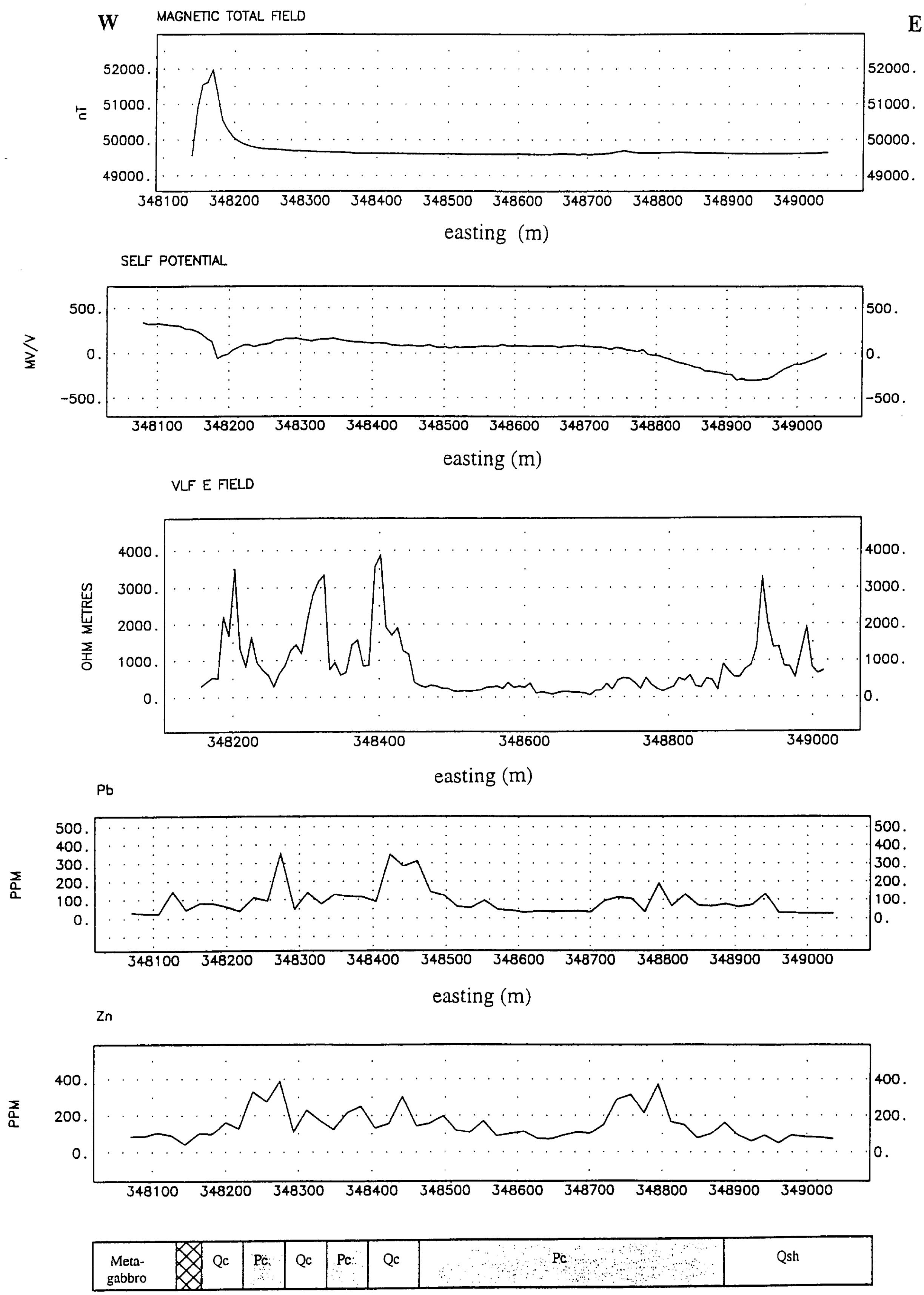


Figure 24 Geophysical and geochemical profiles, Wellheads. See Figure 17 for key to the geological units

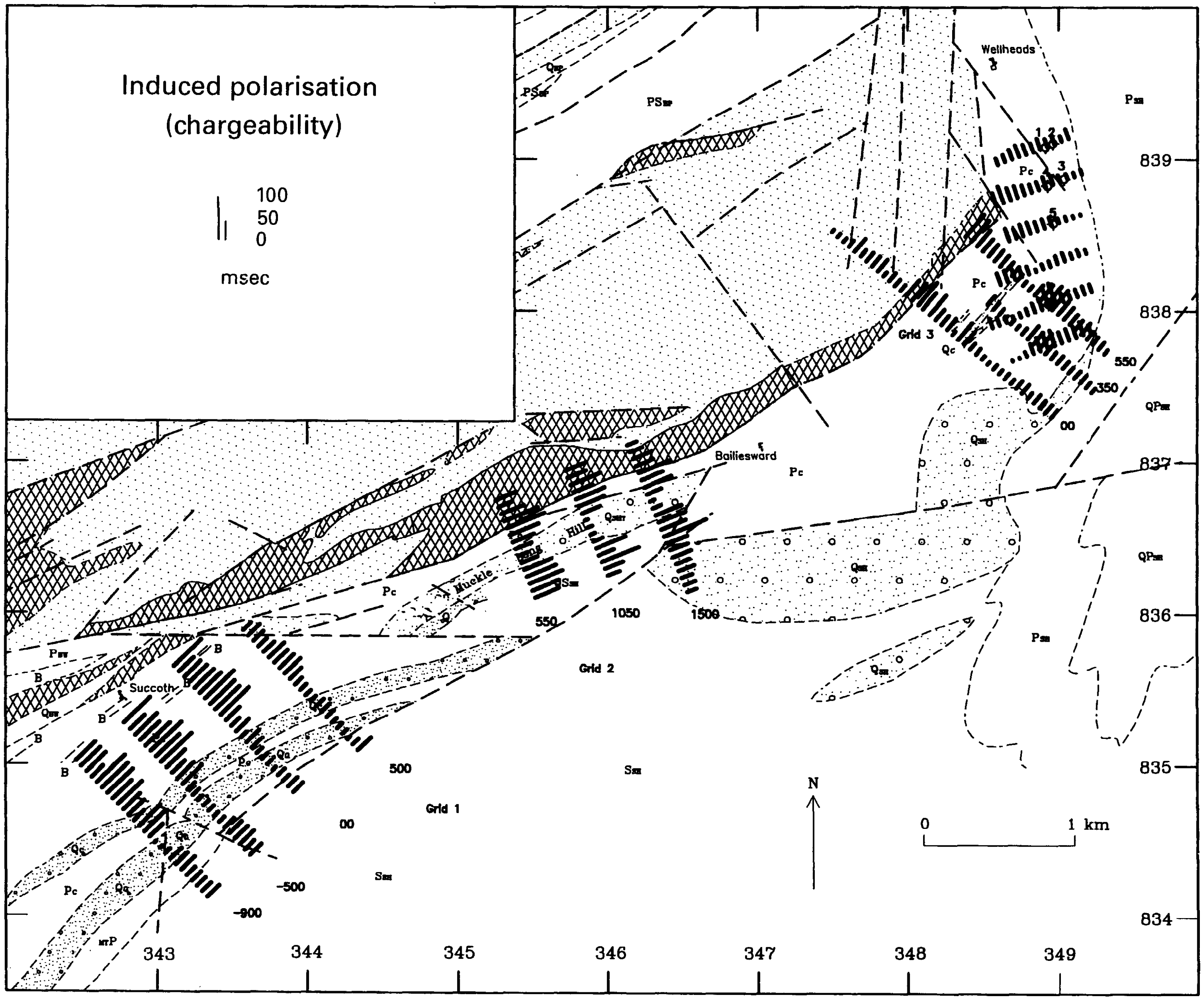


Figure 25 Induced Polarisation chargeability data, Succoth–Gouls to Wellheads

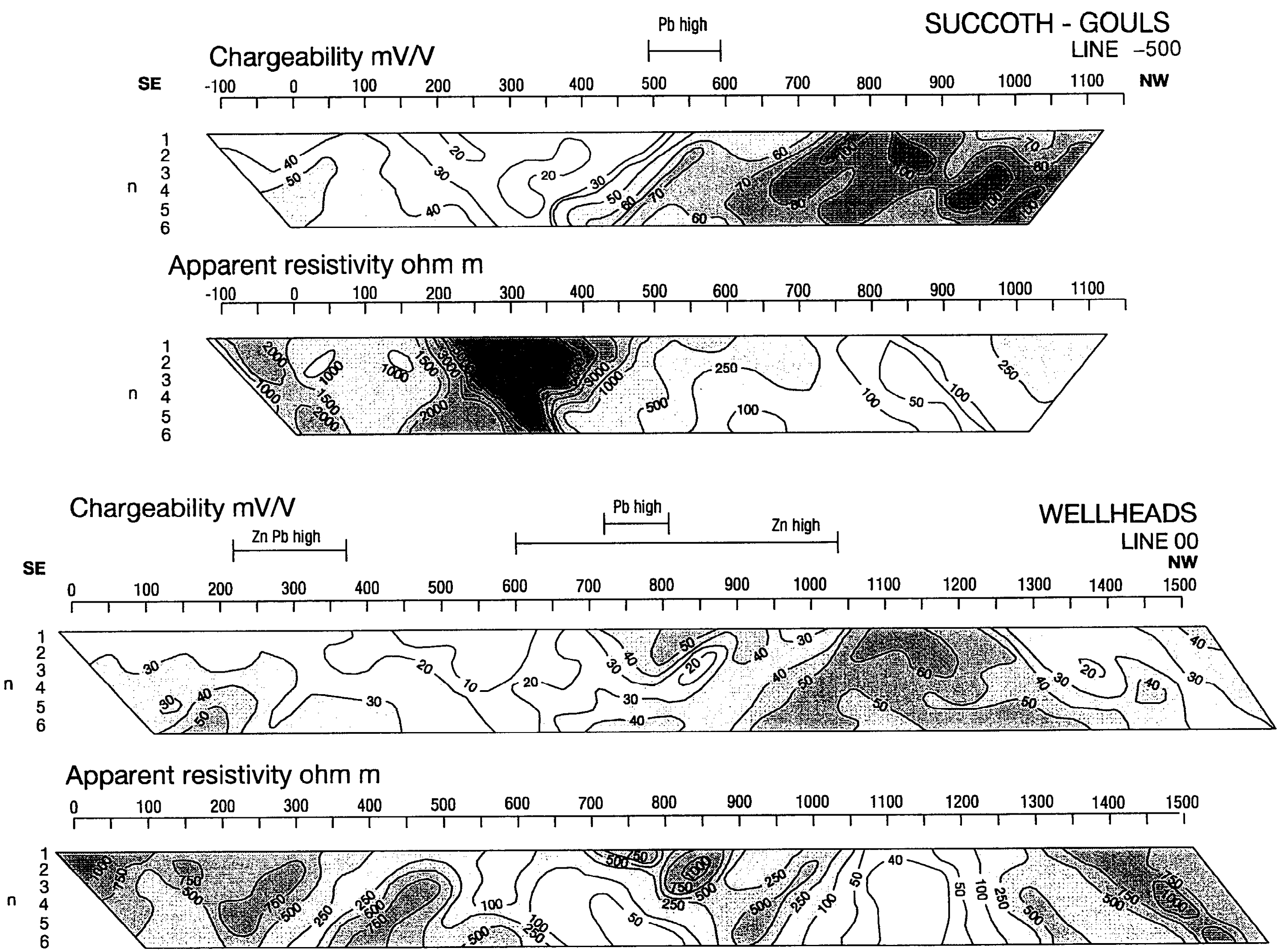


Figure 26 Induced Polarisation pseudosections for traverse line −500 at Succoth–Gouls, and line 00 at Wellheads (Figure 21)

In the Succoth–Gouls section very high chargeability values up to 100 msec and coincident low apparent resistivity (50–100 ohm m) occur over the Corinacy Pelite Member and are attributed to graphitic schist. Conversely, low chargeability (c. 30 msec), and very high resistivity (up to 5000 ohm m) values occur over the Grumack Hill quartzite with resistivity values consistent with VLF E field measurements. The Garnel Burn Pelite Member and pelitic rocks of the Southern Highland Group are characterised by moderate chargeability (30–40 msec) and moderately high resistivity (1–2000 ohm m). The overall dip inferred from the pseudosections is towards the south-east.

Most of the chargeability anomalies can therefore be explained by the known geology. There is however a subtle, local, narrow chargeability high (60–70 msec) at +550 m on traverse line –500, separate from, and to the south-east of, the main area of high chargeability. The anomaly is accompanied by moderately resistive rocks (ca. 750 ohm m) and the resistivity profile suggests that it occurs at or near the contact between pelite and quartzite within the Corinacy Pelite Member, although the dipole spacing is too coarse to determine its precise stratigraphical position. The conductor has a south-easterly dip consistent with the geology, and its projected surface location lies within the Pb in soil anomaly. The chargeability anomaly is accompanied by higher resistivity which suggests that disseminated sulphide may be present near or along the pelite/quartzite contact, rather than a graphitic schist horizon which would be more conductive.

On Muckle Long Hill a c. 100 m wide zone of high chargeability (60–100 msec) and low resistivity (75–150 ohm m) is located over pelites adjacent to the south-east margin of the serpentinite. The high chargeability suggests the presence of graphite. The anomaly dips to the south-east beneath quartzite, which exhibits low chargeability (13–40 msec) and high resistivity (ca 3000 ohm m) comparable to the Grumack Hill quartzite. To the south-east of the quartzite a second high chargeability (110–120 msec), low resistivity (50–60 msec) zone occurs over schists mapped as Southern Highland Group. There is no obvious explanation for the very high chargeability in this region since no anomaly of this amplitude has been observed elsewhere at this stratigraphical position.

In the Wellheads area chargeability anomalies occur in three distinct areas. The most extensive is the chargeability high (50–60 msec), resistivity low (c. 50 ohm m) zone between +1100 and +1200 on line 00 (Figure 26) which forms part of the EVL IP anomaly located adjacent to the south-east margin of the serpentinite. The anomaly displays the classic pant-leg form indicative of a narrow vertical conductor. Trenching of the anomaly at +1080 revealed graphitic schist which is probably the source of the anomaly, although high chargeability values continue over the serpentinite margin and it may therefore also be related in part to a conductive shear zone.

The second anomaly between 700 and 800 m on line 00 shows a small chargeability high (40–50 msec) in moderate to highly resistive rocks (500–1000 ohm m) close to a trenched quartzite, and coincident with the Pb in soil anomaly. The anomaly forms part of a broad zone of moderate chargeability on the south east margin of the high chargeability zone and has a broad Zn in soil anomaly associated with it.

The third chargeability anomaly (40–60 msec) with accompanying low resistivity, not seen on line 00 but prominent on the other IP lines, overlaps with the previous drilled IP anomaly on lines 1000 and 1250 south (borehole 7). It appears to be a local feature some 50 to 100 m wide and 200 m in strike length and shows a strong correlation with Zn in soil anomalies. Trenching of the anomaly revealed graphitic schist as the most likely source although disseminated pyrite recorded in borehole 7 would also produce a chargeability anomaly.

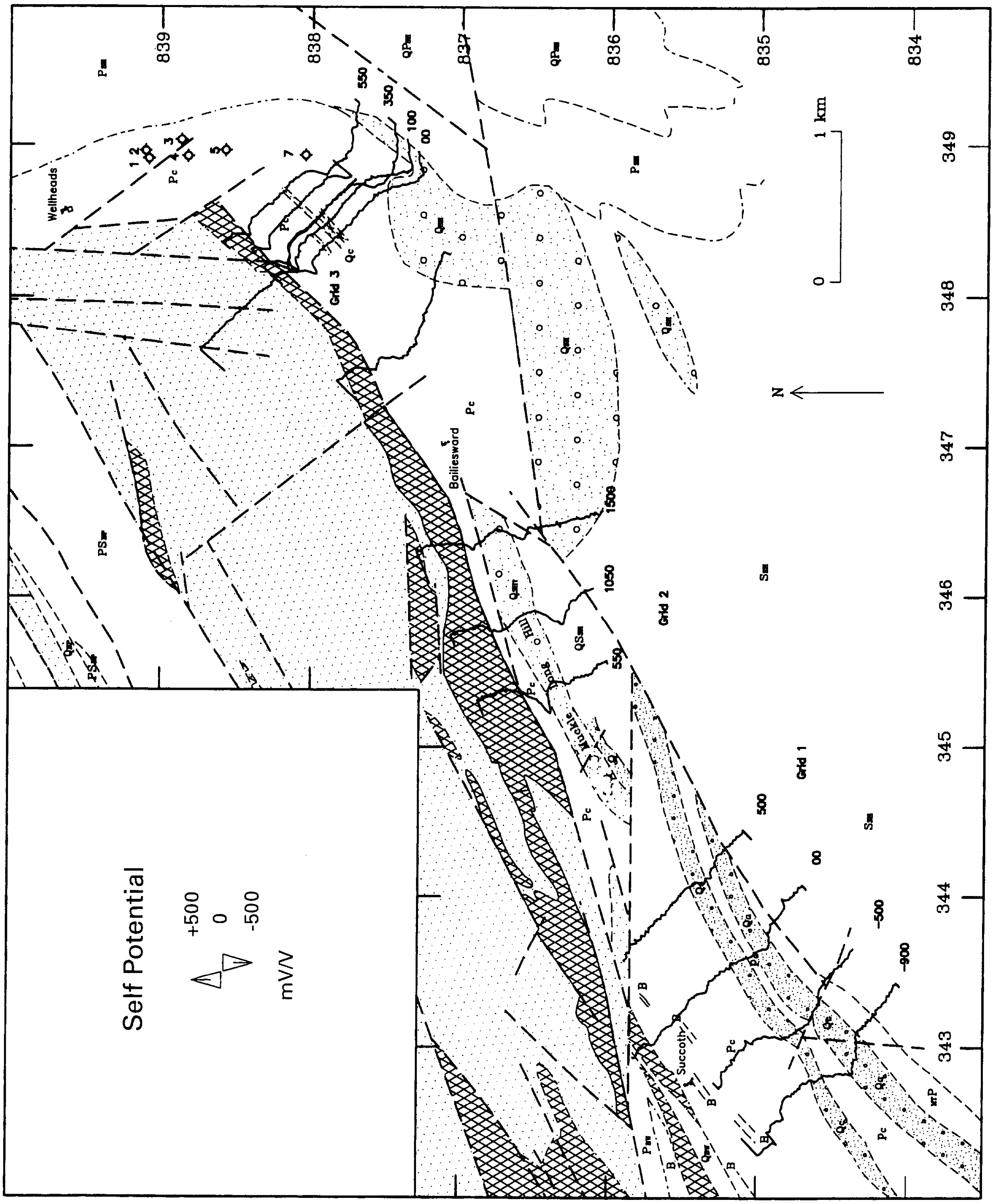


Figure 27 Self Potential data, Succoth–Gouls to Wellheads

Self Potential results

Broad negative SP anomalies in the Succoth–Gouls area (Figure 27) occur near the top of the Corinacy Pelite Member with the lowest values centred over pelitic rocks at the base of the Grumack Hill Quartzite Member. Their broad wavelength and location on a steep topographic slope suggests that they are probably related to anomalous local groundflow conditions rather than to a weathered sulphide zone. Elsewhere, SP lows occur over pelitic rocks on Muckle Long Hill and at Wellheads, caused by the presence of graphitic schist which has been proven by trenching.

Conclusions

Geochemical anomalies at Wellheads and at Succoth–Gouls are confined to the Corinacy Pelite Member of the Blackwater Formation. Mineralisation is dominantly Zn-Pb and is probably located within quartzite units and adjacent pelites. The nature of the mineralisation is similar to that seen in the Easdale Subgroup at Glenshee and Dericambus.

The VLF electric field has proven very effective at mapping the resistive quartzite units through poorly exposed ground throughout the area. There is a good correlation between high resistivity and Pb anomalies at Wellheads and to a lesser extent at Succoth–Gouls. Most of the IP chargeability anomalies at Succoth–Gouls and Muckle Long Hill are caused by conductive graphitic schist within the Corinacy Pelite Member. However, a narrow chargeability zone in moderately resistive rocks identified towards the top of the Corinacy Pelite Member, is coincident with a Pb anomaly and may be related to sulphide mineralisation. At Wellheads, trenching of the shallow zone of high chargeability and low resistivity adjacent to the serpentinite contact on line 00 has identified graphitic schist as the probable source of the EVL chargeability anomaly. However a smaller anomaly located within more resistive quartzites on the south-east margin of the EVL anomaly is coincident with a Pb anomaly and may be a sourced by further sulphide mineralisation.

Further IP survey lines and trenching of the deeper chargeability anomaly previously investigated by borehole 7 at Wellheads showed that this anomaly is about 300 m in strike length and probably caused by graphitic schist in addition to the previously identified disseminated pyrite. There is also a strong spatial correlation of the anomaly with high levels of Zn in soil. Background chargeability values within the Corinacy Pelite Member at Wellheads were far lower than those found at Succoth–Gouls, suggesting that the Wellheads sequence is generally far less graphitic, which may indicate a rapid lateral facies change. Magnetic surveys proved useful in mapping the serpentinite boundary but no anomalies indicative of pyrrhotite mineralisation were found. VLF magnetic field measurements relate in general terms to lateral changes in conductivity but produced less meaningful results, and at Wellheads were affected by wire fences and buried pipes.

HUNTLY-PORTSOY

The Huntly to Portsoy area was the most difficult part of this project area to explore for stratabound base-metal mineral exploration. The covering of thick drift means that there is little exposure away from the coast. Consequently the stratigraphy is poorly understood and the outcrop of the Easdale Subgroup cannot be traced along strike with any certainty for more than a few kilometres, because of lateral displacements due to faulting and shearing.

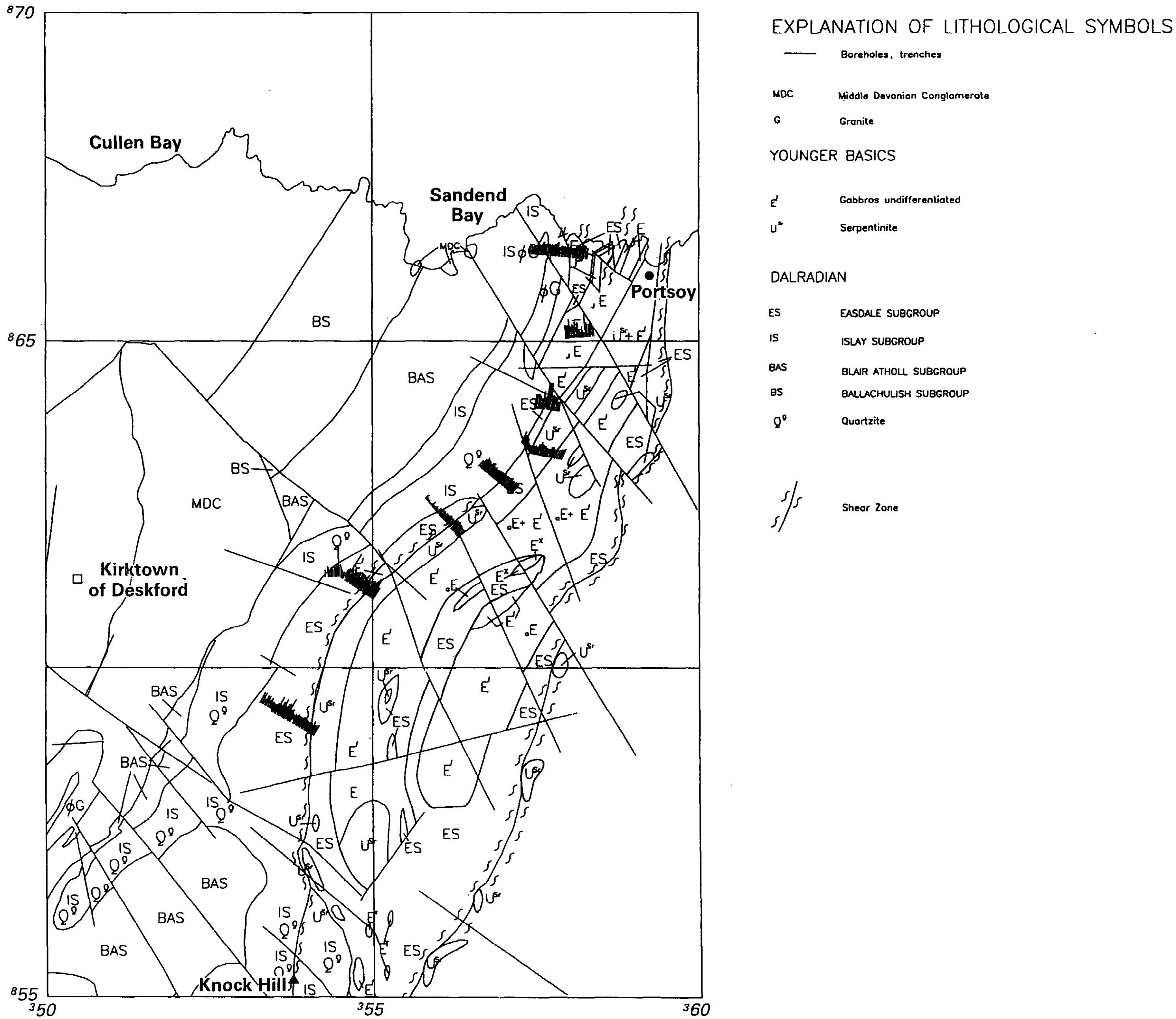


Figure 28 Geological map of the Huntly-Portsoy area showing the location of BGS reconnaissance soil geochemical survey lines

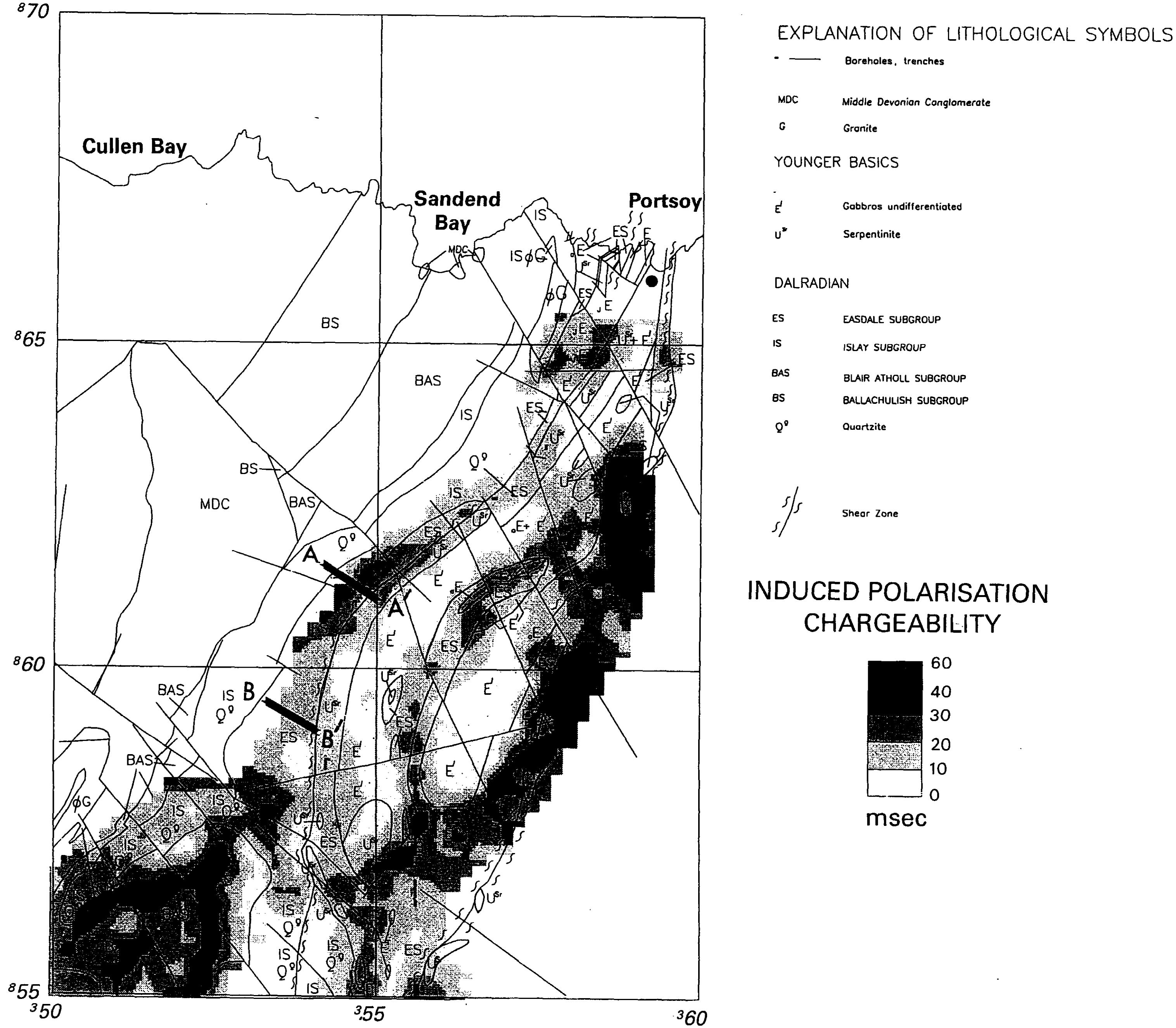


Figure 29 EVL Induced Polarisation chargeability map of the Huntly-Portsoy area and location of 1994 MRP traverses.

Geology and previous work

The Portsoy coastal succession comprises an assemblage of mica schists, calcareous flags, and limestones with black graphitic and pyritic schists in the lower part of the sequence. The rocks belong to the Easdale Subgroup. The Portsoy 'group' of Read (1923) has recently been subdivided into a lower pelitic and graphitic schist unit, the Castle Point Pelite Formation, possibly equivalent to the Glenbuchat Graphitic Schist, and an upper calcareous unit, the Portsoy Limestone, equivalent to the Badenyon Calcareous Schist Formation. Two minor sphalerite occurrences were found in the pelites in the coastal section and slightly further south.

Traverse-based soil sampling was carried out in the 1980's across the Easdale Subgroup as part of a previous MRP investigation (Figure 28), and a geochemical/geophysical megatraverse was also surveyed along an old railway line near Portsoy, inland from the mineralisation in the cliffs at Portsoy. The soil geochemical survey showed a general enhancement of Zn over the pelitic rocks but only isolated high Zn-Pb values. The geophysical megatraverse showed that geophysical methods could be used as a mapping tool over these lithologies, but that the graphitic schists were not as graphitic as those of the Glenbuchat and Ben Eagach schists and were non-magnetic.

The EVL reconnaissance IP survey covers most of the area between Huntly and the coast at Portsoy. The survey was carried out using Huntec geophysical equipment and measurements were made using a single dipole spacing (n=2) of 60 m. Survey lines were spaced 310 m apart. Chargeability and apparent resistivity maps were digitised by BGS from 1:10560 or 1:63360 scale maps. The digitised IP data were integrated with digital geological and soil geochemical data as part of the initial desk study to identify anomalous chargeability zones within Easdale Subgroup rocks.

The EVL apparent resistivity and chargeability datasets enable the geology to be mapped in broad brush terms. The graphitic schists within the Easdale Subgroup can be distinguished from other rocks types because they produce characteristic linear zones of low apparent resistivity (50–100 ohm m), and are non-magnetic. This distinguishes them from conductive serpentinites which are strongly magnetic. Chargeability values are generally low (10–20 msec) as the Portsoy megatraverse has shown that the pelitic rocks are generally less graphitic than the equivalent Glenbuchat Graphitic Schist Formation.

Newton-Fordyce anomaly

A linear chargeability high of over 40 msec within the Easdale Subgroup near Newton-Fordyce, coincident with a Pb and Zn anomaly, was identified from the desk study as a potential target for stratabound mineralisation. Two trial lines were surveyed (Figure 29), line A–A' across the coincident anomaly and line B-B' across a second Pb and Zn anomaly in an area of low chargeability.

The results from traverse A–A' showed a classic pant-leg IP anomaly, indicative of a shallow artificial source, coincident with a large short-wavelength VLF anomaly. No geochemical soil anomalies were recorded over the geophysical anomaly: Pb and Zn values did not exceed 75 ppm and the large anomaly from the previous survey was not reproduced. It is therefore assumed that the chargeability high is due to an artificial source. The VLF electric field proved useful for geological mapping as it identified a quartzite unit beneath thick overburden (Figure 30). The second traverse B-B' did not produce any notable geochemical or geophysical anomalies. Further work may be needed in this area to fully explore the mineral potential as the soil traverses were very widely spaced.

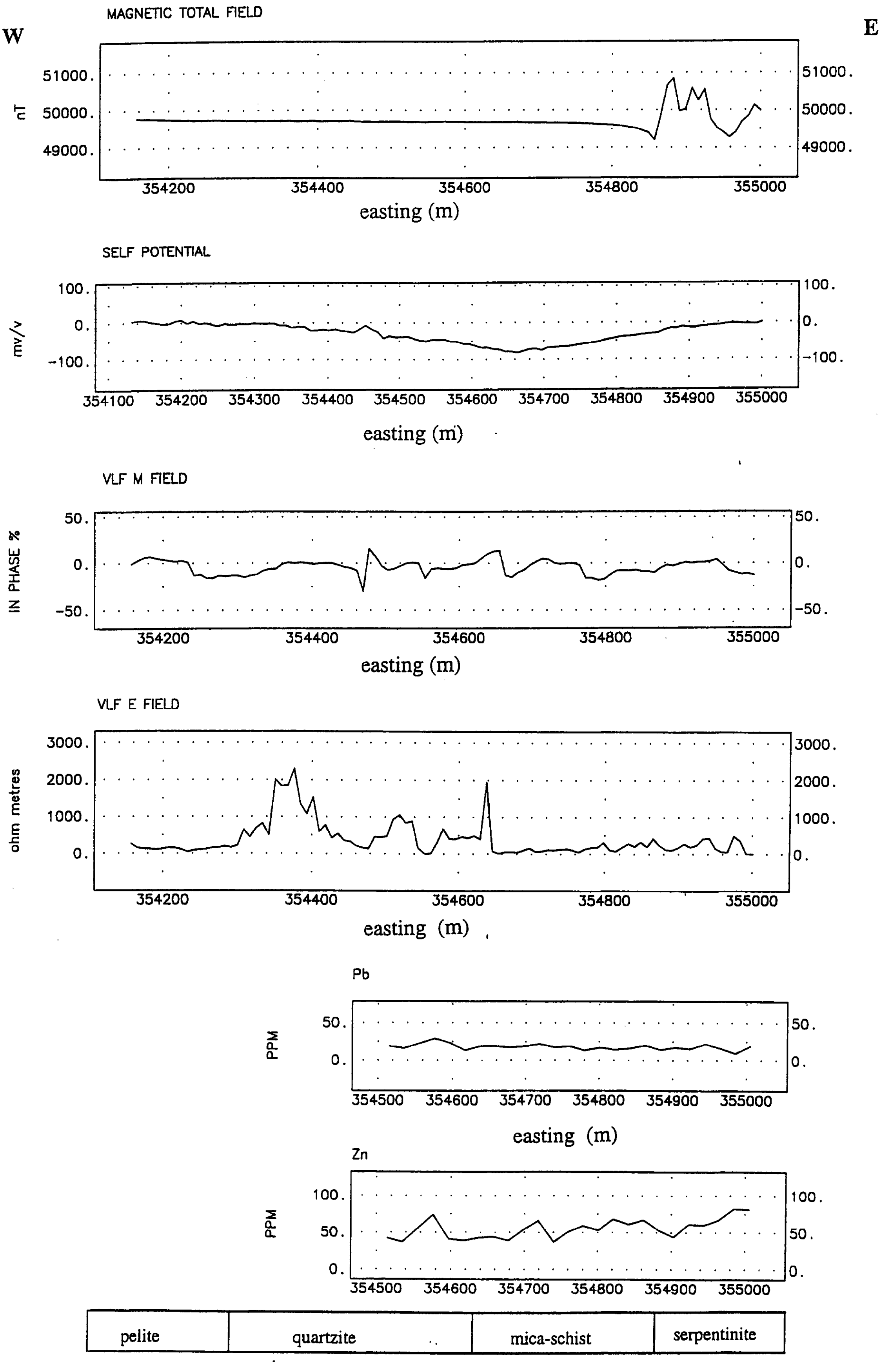


Figure 30 Geochemical and geophysical profiles, traverse line A-A' (Figure 29), Newton Fordyce

CONCLUSIONS AND RECOMMENDATIONS

The most promising area for stratabound mineralisation is in the Upper Deveron, near Wellheads. Although the soil anomalies are enhanced by hydromorphic processes, the high Pb is derived from quartzite units, and the high Zn from adjacent pelite units, within the Corinacy Pelite Member of the Blackwater Formation. The mineralisation is predominantly Zn-Pb and is similar to that in the Easdale Subgroup at Glenshee and Dericambus.

At Wellheads the VLF-EM electric field was particularly successful in mapping the highly resistive mineralised quartzite units for several tens of metres beneath thin to moderate drift cover. Within thicker drift covered areas the IP method identified small local chargeability highs at depth, which may represent disseminated sulphide mineralisation, as they are accompanied by moderate to high resistivity, in contrast to the very low resistivity values characteristic of graphitic schists.

Detailed geophysical surveys at Wellheads using the VLF EM electric field to map the extent of the mineralised quartzites, and IP surveys using a closer line spacing and electrode separation of 25 m to resolve the IP anomalies in more detail, are recommended in order to define more specific targets. The combination of the smaller Pb anomalies and coincident IP anomaly at Succoth–Gouls on line –250 is also a reasonably well defined target meriting a small amount of geochemical and geophysical follow-up.

In the Ballater–Strathdon area the large EM/magnetic anomaly on line +200 at Creagan Riabhach, although apparently low in base-metal content, merits further investigation as a significant amount of sulphide mineralisation is present at shallow depth and the rocks are thought to be similar to the Ben Lawers Pyrite, where Cu mineralisation is known to occur sporadically (Smith et al., 1977; Smith et al., 1978).

Elsewhere in the Ballater–Strathdon region few geological and geochemical anomalies have been found from the reconnaissance surveys and, with earlier MRP megatraverse and EVL surveys at Glenbuchat Lodge, suggest that the Glenbuchat Graphitic Schist Formation in the Glenbuchat area is not prospective.

Very little mineral exploration has been carried out over the c. 10 km strike length of the Argyll Group in the Upper Donside region, where several Pb-Zn anomalies have been identified from drainage geochemical sampling. The Glenbuchat Graphitic Schist Formation here has a volcanic component providing the potential for hydrothermal mineralisation. In the Glen Avon region further Pb-Zn drainage geochemical anomalies have been identified, and the close proximity to the Lecht renders this a further prospective area.

In the Huntly-Portsoy region reconnaissance surveys over the most promising EVL IP anomaly suggests that the chargeability anomaly is caused by cultural noise and no evidence of mineralisation was identified.

In general terms, this study shows that the areas with the most potential for stratabound mineralisation occur in Argyll Group rocks which lie to the east of the Portsoy Lineament. These rocks tend to be lithologically different from the typical Argyll sequence, and difficult to correlate in detail.

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