British Geological Survey

Mineral Reconnaissance Programme

Platinum-group elements in ultramafic rocks of the Upper Deveron Valley, near Huntly, Aberdeenshire

Department of Trade and Industry

MRP Report 115
Technical Report WF/90/9

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BRITISH GEOLOGICAL SURVEY

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GLOSSARY

PGE	Platinum - group element(s)
PGM	Platinum - group mineral(s)
EGP	East Grampian Project
EVL	Exploration Ventures Ltd
GFAAS	Graphite furnace atomic absorption spectrophotometry
ICP-MS	Inductively-coupled plasma mass spectrometry
NAA	Neutron activation analysis
MIRO	Mineral Industry Research Organisation

SUMMARY

A programme of exploration for the platinum-group elements (PGE) in the upper part of the Deveron valley south-west of Huntly is described. The geology of this area, the Upper Deveron Belt, is reviewed in the light of recent mapping carried out by the multi-disciplinary East Grampian Project. The main focus of attention was a series of deformed mafic-ultramafic Caledonian intrusive bodies located within a major regional shear-zone, the Portsoy Lineament.

The importance in geochemical exploration for the PGE of obtaining high quality analyses to detection limits of a few ppb is stressed. This is particularly significant in view of the lack of knowledge regarding PGE distribution in the secondary environment and to the low background levels present in geochemical sample media.

Limited reconnaissance surveys were conducted in order to define the most promising target zones. The drainage data from partially panned concentrate samples showed a good correlation with the known geology but failed to identify any source of PGE or Cu-Ni mineralisation. In one area, however, a grain of sperrylite ($PtAs_2$) was recovered during panning at a site within a poorly-exposed serpentinite near Bridgend. Detailed follow-up using overburden and rock sampling, guided by a detailed ground magnetic survey, defined a zone of Pt enrichment in basal overburden close to the margin of the serpentinite.

Drilling was conducted to investigate a zone of potential in a similar setting near Kelman Hill. In one borehole a section of PGE-enriched serpentinite (up to 280 ppb Pt+Pd) was identified. The host rock has elevated Cr levels with sporadic enrichment in As. A new technique of automated searching for rare phases using the electron microprobe has been applied to this drillcore, resulting in the detection of several complex PGE-bearing grains intergrown with nickel arsenide. A hydrothermal origin for these grains and the observed PGE enrichment in the serpentinite is proposed.

Drilling was also undertaken in the Kelman Hill area to investigate a series of Dalradian (Argyll Group) mafic-ultramafic volcanic rocks which crop out in the southern half of the Belt. These were considered to have potential for the occurrence of PGE-bearing Cu-Ni mineralisation and, in altered sections, for the occurrence of Au. The results of the drilling were not encouraging for the precious metals, but provided useful sections through these poorly-exposed unusual lithologies.

The reconnaissance survey also demonstrated elevated PGE contents in clinopyroxene-bearing ultramafic rocks in the Succoth - Brown Hill intrusion in the north-east of the Belt. Investigation by drilling in one zone near Red Burn confirmed these enhanced background levels, with Pt/Pd around 1. Higher concentrations were revealed in some sections, up to a maximum of about 270 ppb Pt+Pd, with many values in excess of 100 ppb. The highest levels are often accompanied by an increase in Pd relative to Pt, and sometimes by elevated Au values. Automated searching on the microprobe revealed several grains of Au, together with Pt-Cu and Pd-Sb minerals, in association with base-metal sulphides in sheared and altered host rocks. A possible hydrothermal origin for this mineralisation is indicated.

INTRODUCTION

The investigations described in this report were undertaken in the upper section of the valley of the River Deveron, in an area extending southwestwards from Huntly for a distance of approximately 20 km. This area, hereafter referred to as the Upper Deveron Belt (or simply the Belt), is delineated on the regional geological map (Figure 1), occupying an area of approximately 60 km^2.

The surveys were carried out as part of the DTI-sponsored Mineral Reconnaissance Programme. Drilling was conducted in 1986 and 1987 to investigate encouraging data from surface investigations undertaken mainly during 1985.

The background levels of Pt and Pd in basic and ultrabasic rocks are generally significantly greater than the average crustal concentrations of less than 4 ppb. As a result these rocks have long been regarded as having the greatest potential for significant enrichments of the PGE. In addition an overwhelming proportion of the world's resources of these elements are found in rocks of this type, mainly in the layered basic-ultrabasic section of the Bushveld intrusion, South Africa.

For this reason reconnaissance investigations were initiated on the Caledonian layered mafic-ultramafic intrusions of north-east Scotland as they represent the largest development of rocks of this type in the UK. The main focus of attention in the Upper Deveron Belt was a series of intrusive rocks which, by virtue not only of their composition but also due to their deformational history, were considered to have some potential for the occurrence of the platinum-group elements (PGE).

PHYSIOGRAPHY

The Upper Deveron Belt (Figures 1 and 2) comprises ground adjacent to the River Deveron between Huntly in the north-east and the confluence of the Allt Deveron with the Black Water, some 20 km to the south-west. These hill rivers drain a 130 km^2 tract of open moorland. Below this confluence the valley becomes narrower and more clearly defined, trending north-east for approximately 16 km to the point at which it is crossed by the Huntly-Dufftown road (A920). This is defined as the northern margin of the Belt for the purposes of this report. The valley is flanked by broad hill ridges some 4-5 km apart. The east ridge is the more clearly defined, rising from the valley floor at around 200 m to a sometimes craggy ridgetop at 390-525 m.

The area is sparsely populated, with farms and other dwellings close to the riverside road. Land use is given over to mixed valley farming, with forestry and rough grazing on higher ground.

The region was repeatedly covered with ice during periods of maximum glaciation, but the localised glacial deposits are not common in areas of higher relief. Drift thicknesses vary from less than 1 m on hilltops to 10 m or more in the Deveron valley. Where drainage has been impeded areas of peat have developed and these can be of substantial thickness. In the course of the work described in this report drift profiles were obtained in some zones. The clasts are generally of local

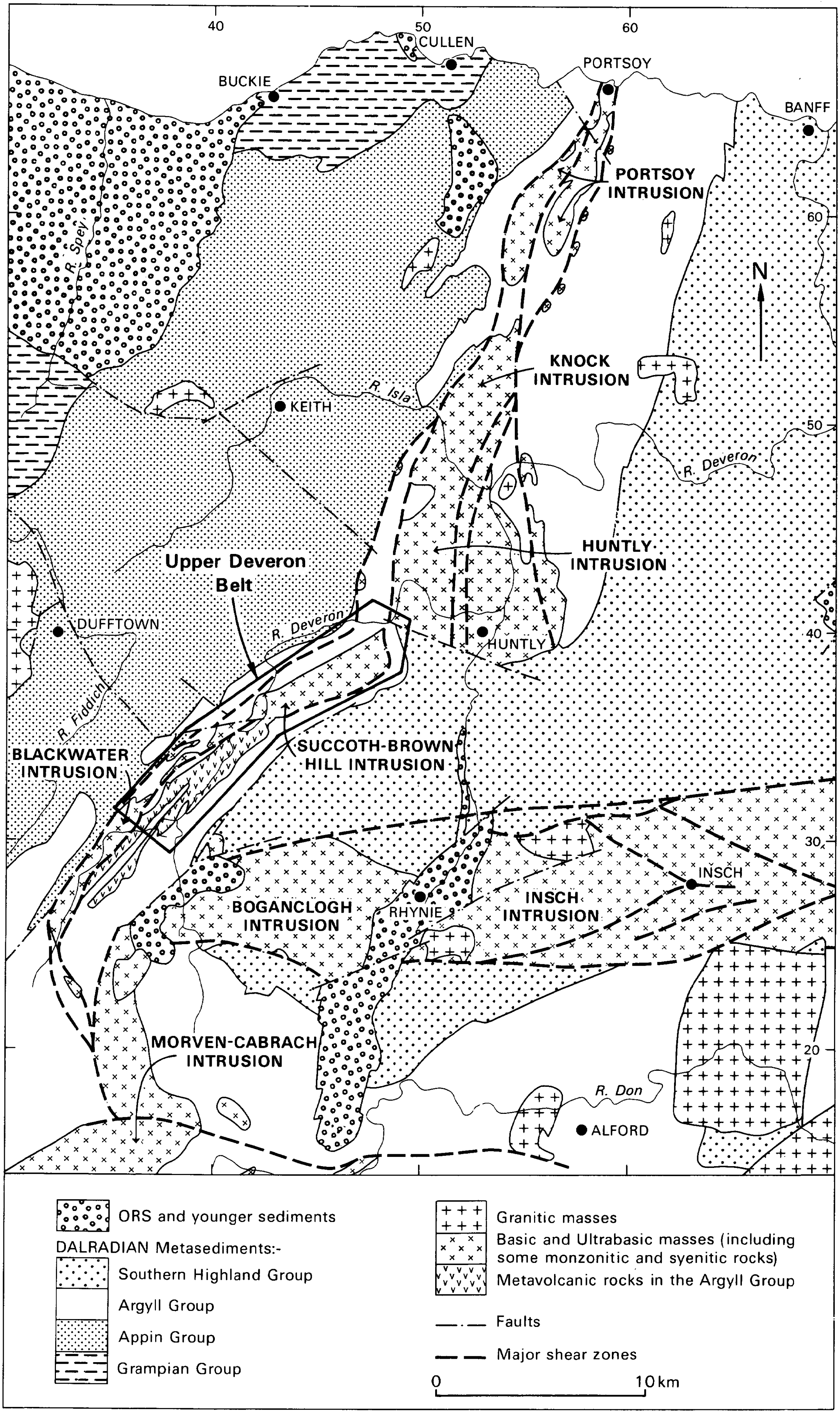

Figure 1 Regional geological map showing the location of the Upper Deveron Belt

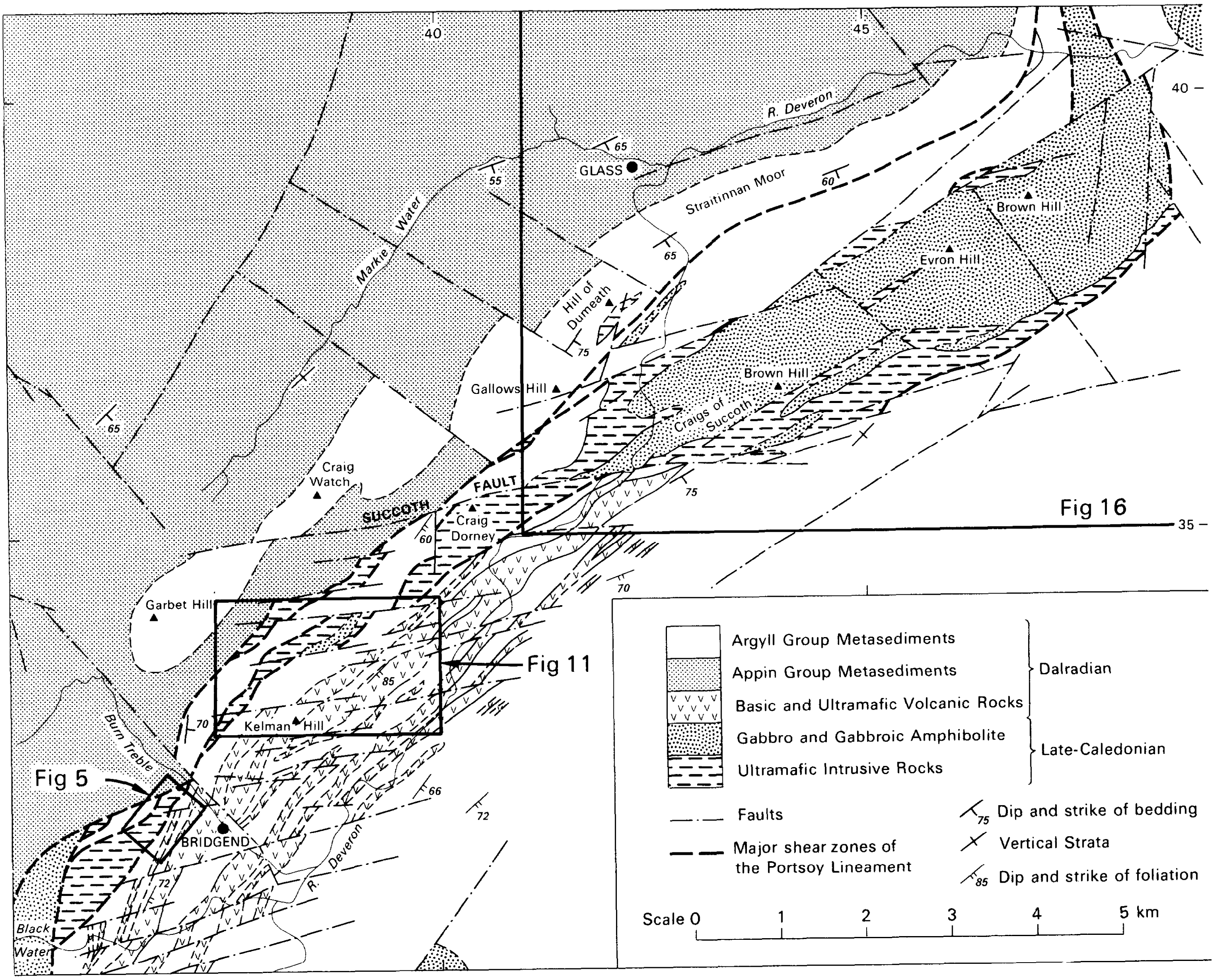

Figure 2 Geological map of the Upper Deveron Belt showing areas of detailed investigations

origin, in most cases comprising a mixture of the dominant lithologies present in the Belt. On ridge tops and flanks eluvial processes have controlled the main drift development, whereas mixing becomes prevalent where the terrain steepens or the drift thickens.

There is some duplication of place names in the Upper Deveron valley which is likely to cause confusion for the reader not familiar with the area. The name 'Succoth' is the main problem as far as this report is concerned. On the south-east side of the River Deveron, some 11 km west-south-west of Huntly, is located one of the Succoth farms [34276 83546] from where the Burn of Succoth flows north-west to the River Deveron. The Craigs of Succoth are found approximately 1 km north-east of the farm, forming a conspicuous craggy ridge which extends for about 1 km east-north-east culminating at an elevation of 485 m on Brown Hill [3440 8365]. These Craigs of Succoth are located at the south-west end of the intrusive body referred to herein as the Succoth - Brown Hill intrusion. It should also be pointed out that near the north-east end of this intrusion there is also a second 'Brown Hill' [3470 8390]. The second 'Succoth' is located a further 3.7 km to the south-west, [33964 83335], approximately 1.3 km north-east of Kelman Hill. The Burn of Succoth passes just to the south of the farm, flowing eastwards towards the Deveron. The second Craigs of Succoth are situated about 1 km north-west of the farm, around [3388 8340]. These are much less prominent and extensive than the other Craigs to the north-east.

PREVIOUS WORK

In 1969 Rio Tinto Zinc and Consolidated Goldfields formed a consortium known as Exploration Ventures Limited (EVL) for the purpose of conducting a major programme of mineral exploration over a large part of the Grampian region, within an area bounded by the River Dee to the south and the River Spey to the west. The principal target for this programme, which ended in 1973, was Cu-Ni mineralisation associated with the Caledonian basic-ultrabasic rocks. A limited amount of effort was directed towards investigating the potential of these bodies for the occurrence of the PGE.

A wide variety of techniques was employed in the course of the EVL investigations, including mapping, geochemistry (mainly drainage and soil sampling) and geophysics (mainly magnetic, electromagnetic and IP). Available records of this programme are incomplete and, as a result of the large scale of the operation, are difficult to evaluate in detail. Many maps and reports relating to the programme are held on open-file by BGS, but it is often difficult to ascertain what investigations were carried out in any particular zone and what results were obtained. The most useful document is an excellent compilation by Wilks (1974) of the activities and results obtained in the western part of the survey area. EVL collaborated with workers at Aberdeen University on certain aspects of the investigations, notably airborne geophysics and drilling, and some records remain there (Gallagher, 1983).

The Upper Deveron Belt was included in a primary stream sediment reconnaissance of the region carried out by EVL. Some slightly anomalous Cu and Ni values were reported from the area around Craigs of Succoth and Gordonsburn [3430 8365 - Figure 4] by Fox (1970). Follow up work involved the collection of soil and rock samples and the conduct of a ground magnetic survey in the

Craigs of Succoth area. The results indicated the presence of only minor quantities of copper sulphides, with nickel levels typical of those expected in silicates rather than sulphides. A small number of rocks were analysed for the PGE but no significant values were reported.

The value of any PGE determinations from this era conducted for EVL remains in serious doubt. At that time the analytical technology for PGE exploration was in its infancy, with generally high detection limits and poor precision. EVL encountered major problems in substantiating their anomalous results (Wilks, 1974). The present authors have been unable to confirm any enhanced PGE concentrations from surface outcrops originally sampled and analysed by EVL.

EVL also undertook limited IP surveys in the far north of the Belt, in the zone between Brown Hill [3470 8390] and Artloch on the south side of the River Deveron. The minor anomalies revealed were ascribed to heavily serpentinised zones within the ultramafic units of the area.

In 1969 EVL initiated a soils research project with Bedford College, London University. The aims of this project were to improve geochemical interpretation in glaciated areas underlain by mafic and ultramafic rocks, in particular to discriminate between Ni in silicate and Ni in sulphide. The area around Brown Hill [3440 8365] was one of several chosen for a pilot survey. The results were never fully documented, but in the Brown Hill area it was concluded that there was little potential for base-metal mineralisation.

A detailed helicopter magnetic and EM survey was flown by Barringer Research in 1970. The results of this survey are held by BGS and are currently available as high quality contoured overlays at a scale of 1:25000. Unfortunately the cover within the Upper Deveron Belt is restricted to a small area to the north-east of Brown Hill [3470 8390].

The Belt straddles the boundary between geological map sheets 85 and 86. Sheet 86 (Huntly) was last mapped by Read, who produced the present one inch to the mile map. The geology is described in the Memoir for sheets 86 and 96 (Read, 1923). The section of the Belt to the southwest of the Craigs of Succoth lies within the Rothes map sheet (85). The last published geological map of this sheet was produced in 1898 and is currently out of print. It is available only as a photocopy from BGS.

Since 1983 a major programme of re-mapping in this region has been undertaken by the BGS. This survey, known as the East Grampian Project (EGP), is a large multi-disciplinary programme, involving the use of ground geophysical techniques and soil geochemistry to supplement conventional field mapping. The Upper Deveron Belt was completely re-mapped by 1987 and the geological, geophysical and geochemical data generated by that work have been valuable in guiding the investigations described in this report and in the interpretation of the results. Two of the authors (DS and AGG) were involved in the mapping activities within the Belt.

GEOLOGY

Regional geology

The rocks of the area consist of tightly-folded metasedimentary and metavolcanic rocks of the Dalradian Supergroup with a north-east strike (Harris and Pitcher, 1975; Harris et al., 1978; Anderton, 1985). These were intruded by a variety of mafic and ultramafic igneous masses during the late stages of the Caledonian Orogeny (Wadsworth, 1982; Brown, 1983). A broad zone of steeply-inclined anastomosing shears trends north-east - south-west through the area and forms part of a major regional dislocation known as the Portsoy Lineament (Ashcroft et al., 1984; Fettes et al., in press). This lineament divides rocks of the Appin Group (formerly known as the Lower Dalradian) and lowest Argyll Group to the north-west from the distinctly different lithological assemblage of the Argyll Group (formerly Middle Dalradian) and Southern Highland Group (formerly Upper Dalradian) rocks to the south-east. Undeformed minor intrusions occur to the north-west of the lineament, but major intrusions are confined to the area south-east of it and are disrupted and deformed by the shear-zones. A set of late, brittle faults trending east-north-east is widely developed within the Belt. One of these, the Succoth Fault, has a dextral displacement of 1.5 km and constitutes a major tectonic divider of the area.

The recent re-mapping by the East Grampian Project has allowed the compilation of the geological map of the Upper Deveron Belt presented in Figure 2. A map of the total magnetic field intensity at 2 m above ground level derived from the EGP magnetic databank is shown in Figure 3. The ground magnetic profiles are presented as wiggle traces with zones of total intensity above 49 600 nT shaded black. The magnetic method is especially effective in delineating zones underlain by ultramafic lithologies which may contain PGE-bearing Cu-Ni mineralisation. In such lithologies, with high amplitude magnetic anomalies, the wiggle trace presentation is preferable to contour display in terms of defining geological contacts and identifying the magnetic signature of layered or composite bodies. By adjusting the wiggle trace datum and the anomaly amplitude gain particular features of the magnetic field can be emphasised or attenuated.

Structure

The succession immediately to the north-west of the Portsoy Lineament is believed to young to the north-west, due to the postulated presence of a tight syncline in that zone. Within the Portsoy Lineament and over most of the area to the south-east, the strata dip steeply to the south-east. Owing to the high strain, all structures and cleavages are coplanar, so that a single strong fabric is common to the whole area. South-east of the lineament, there appear to be no repetitions or reversals of stratigraphy and the rocks all young to the south-east.

Shearing along the Portsoy Lineament post-dates the regional folding and the major intrusions, although movement may have commenced much earlier (Baker, 1987; Beddoe-Stephens, in press; Fettes et al., in press). Several major anastomosing shears and numerous minor shears occur in a zone between 1 km and 3 km wide. The late-Caledonian major intrusions within the area of investigation are confined to this zone of shearing. The east-north-east late brittle faults elsewhere contain quartz-dolerite dykes of the late Carboniferous swarm. They are therefore thought to be of

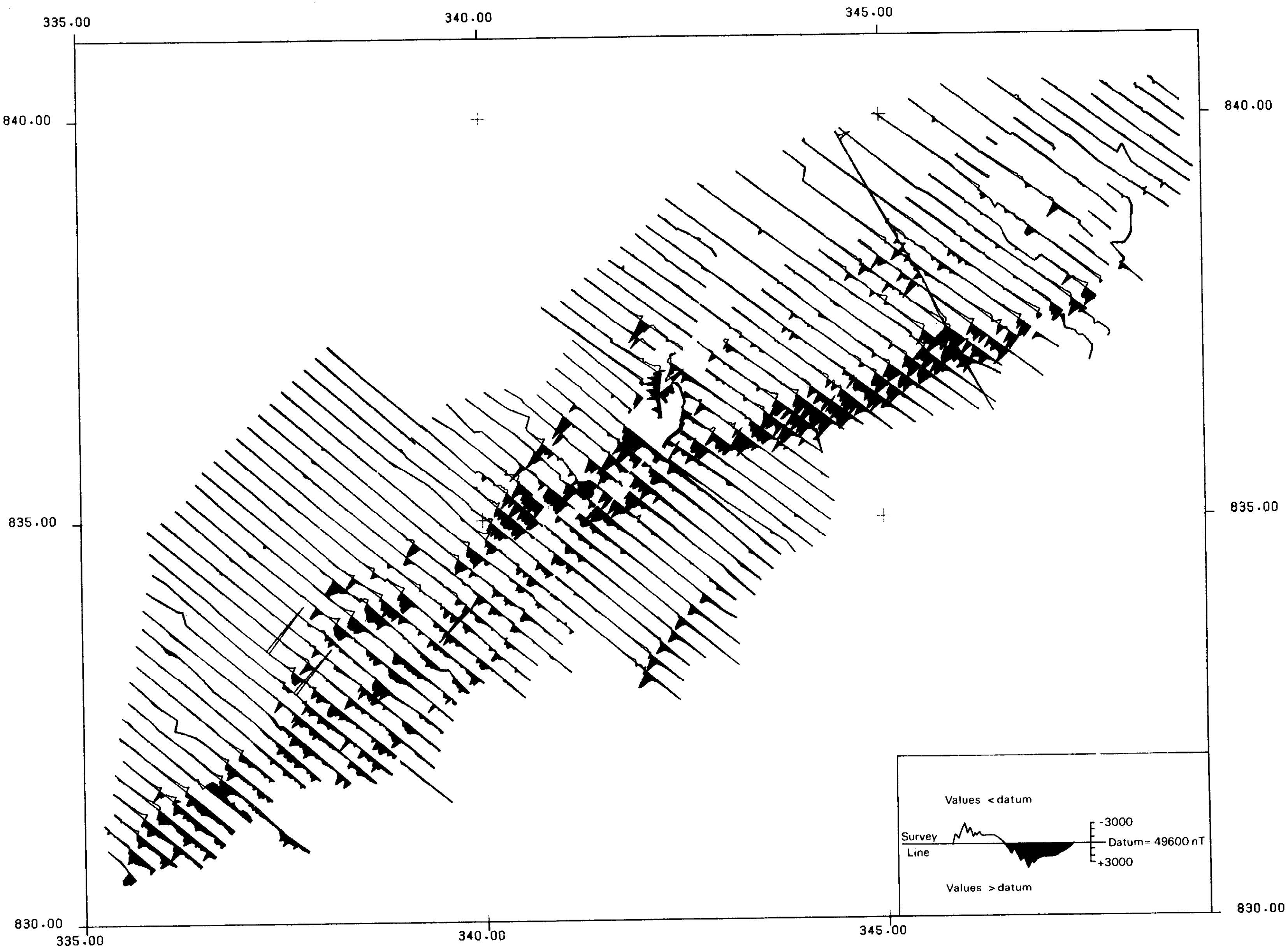

Figure 3 Total field magnetic data for the Upper Deveron Belt

this age in the Upper Deveron Belt.

Dalradian

North-west of the Portsoy Lineament

Dalradian metasedimentary rocks to the north-west of the Portsoy Lineament form a generally coherent stratigraphical succession which can be traced southwards towards the Central Highlands and correlated with the established successions of Harris and Pitcher (1975). Certain units can also be traced northwards to the Moray Firth coast (unpublished BGS mapping). Within the area of study the Blair Atholl and Islay subgroups are represented. Sediments in this part of the succession are in general of marine, shallow water shelf facies, comprising mainly quartzite and pelite with subordinate semi-pelite and psammite.

South-east of the Portsoy Lineament

Within and to the south-east of the Portsoy Lineament the metasedimentary lithologies are typical of the higher parts of the Argyll Group elsewhere, and consist of deep water basinal sediments characterised by turbidites. Local successions are highly variable and no detailed correlation is possible with the Argyll Group west of the lineament. This feature underlines the fundamental importance of the Portsoy Lineament as a major regional dislocation (Fettes et al., in press).

A basal predominantly pelitic unit is widely present throughout the area. A good 20 m section in Kelman Hill borehole 3 reveals many sedimentological features characteristic of turbidites, including grading which indicates a younging direction to the south-east. Above this unit, the succession consists of alternations of greywacke-grits, pelites and a variety of metavolcanic rocks, collectively referred to as the Blackwater Formation (Fettes and Munro, 1989; Fettes et al., in press.). The best section is seen in the Black Water, from where the formation extends north-eastwards with an average outcrop width of 1500m, over Tom na Vowin and Kelman Hill to the River Deveron and terminates at the Succoth Fault. To the north of the fault and the Succoth - Brown Hill intrusion this formation is not recognised. Magnetic signatures allow delineation of the metavolcanic units and mapping of the boundaries with the sediments in the poorly-exposed ground underlain by the Blackwater Formation.

The metavolcanic rocks fall into two compositional types which allow three volcanic members to be defined within the Blackwater Formation. The lower, Lynebain Member, and the upper, Ardwell Bridge Member, are composed of metabasaltic rocks. A middle, Kelman Hill Member is composed predominantly of ultramafic rocks but with some metabasalts. The ultramafic types comprise a suite of variable character, ranging from massive to highly fragmented, the latter showing considerable variation in clast shape and composition. They are exposed sporadically between Shenval [3368 8308] in the south-west and the Succoth Fault. Excellent sections were recovered in two boreholes near Kelman Hill described in a later section of this report. The metabasalts are predominantly aphyric, although distinctive pyroxene-phyric varieties crop-out west of Shenval and have been found as float around the site of Kelman Hill borehole 1 [33962 83344]. Pillow lavas are well exposed at Blackwater (=Ardwell) Bridge [3378 8308] (MacGregor and Roberts, 1963). Fragmental pillows occur in various places, but are particularly well developed in the River Deveron at Lynebain [3412 8351]. Vesiculation is common in all members and there is little doubt that they are of volcanic origin, although some of the more massive units may have been shallow sills.

Above the highest volcanic member the lithology changes quite abruptly to a more persistent pelite, the Corinacy Pelite, which forms the hill slopes south-east of the River Deveron. Sheets of fine-grained metabasalt are abundant in the lower part of the unit, and the pelites have a hard, slaty, hornfelsed appearance in outcrops close to the River Deveron. Above the pelites are a series of quartzites and massive psammites, the Grumack Hill Quartzite, which forms the high ridge to the south-east of the River Deveron. These in turn pass upwards to the south-east into turbiditic Southern Highland Group lithologies outside the Belt.

Mafic-ultramafic intrusions

Within the study area these comprise the Succoth - Brown Hill intrusion in the north-east, the north-eastern part of the Blackwater intrusion in the south-west and a series of smaller ultramafic pods betweem the two (Figure 2). External boundaries are almost all shears, related to the Portsoy Lineament. Zones of intense shearing also occur within the intrusions, which are also amphibolitised and serpentinised. This alteration and deformation led Read (1919) to classify them all as 'Older' intrusions, predating the main phases of regional deformation and metamorphism. However, it is now recognised that much shearing and amphibolitisation took place after the emplacement of the 'Younger' basic intrusions in general, and along the Portsoy Lineament in particular (Ashcroft et al., 1984; Munro and Gallagher, 1984; Fettes et al., 1986).

The Blackwater Intrusion has recently been reinterpreted as part of the 'Younger' suite (Fettes and Munro, 1989), while the ages of the Succoth - Brown Hill mass and other smaller pods remain in doubt.

Succoth - Brown Hill intrusion

This body occupies some 14 km^2 and consists of amphibolites, serpentinites, partially amphibolitised pyroxenites and a range of peridotitic rocks (Figures 2 and 16). The overall shape is that of an elongate pod with a north-east trend, swinging northwards with the regional strike at its north-east end. It is bounded on both its north-west and south-east sides by sinuous major shears which are splays of the Portsoy Lineament. These have been modified by later east-north-east-trending straight brittle faults, in particular the Succoth Fault which displaces the south-west end of the intrusion dextrally by 1.5 km.

About 70% of the intrusion is composed of metabasic amphibolite derived from gabbroic rocks. Amphibolitisation of mafic minerals is always total and no relics have been found. Textures vary markedly, dependent on the degree of deformation and recrystallisation, ranging from good cumulates to strongly foliated amphibolites. Where present, foliations strike parallel to the margins of the intrusion and generally dip steeply to the south-east or east.

In several places on the north-west flanks of Brown Hill [3440 8366] trails of quartzite debris within the area of gabbro-amphibolite suggest the presence of screens of country rock. These may have been emplaced tectonically along shear planes or be relics of a sheeted intrusive complex.

Ultramafic rocks are found in elongate masses on the north-west and south-east margins of the intrusion, converging towards the south-west. Other smaller pods occur, probably elongated along shear-zones within the intrusion. Strong foliations and joints are sub-vertical or steeply-inclined to the south-east, as in the gabbro-amphibolites. Indistinct igneous layering is visible in some of the outcrops on the Craigs of Succoth [3438 8364], dipping to the south-east at a moderate angle. The primary orientation of the mafic pods and bands is difficult to determine. Borehole and magnetic evidence suggest that they too dip south-east, at a lower angle than the foliation. Many of the ultramafic bodies consist of massive serpentinite, some with visible pseudomorphs after olivine and some with small relict cores of olivine. Other bodies, notably near Red Burn, south of Beldorney and at the Craigs of Succoth, consist of pyroxenite, olivine pyroxenite and less commonly wehrlite. These rocks commonly retain an igneous texture with well-preserved clinopyroxene and variable amounts of replacement by tremolitic amphibole. Relict orthopyroxene lamellae within clinopyroxene are visible in some rocks and chrome-spinel is a common accessory. Orthopyroxenites occur in a highly altered fault-zone along the Succoth Fault where it cuts Tammies Burn [3416 8356].

Smaller tectonic pods

At the south-west end of the Succoth - Brown Hill intrusion, where it is displaced by the Succoth Fault, a pod of ultramafic rocks extends from Lynebain to Craig Dorney [3405 8353], tapering out south-west of Linn Burn. The rocks are mostly serpentinite with some lenses of pyroxenite. The sheared south-east margin is well exposed at Bridge of Ardgallie [3401 8347].

Other shear-bounded, tectonic pods occur along the western edge of the Portsoy Lineament to the south-west and on parallel shears in a zone 1 km wide. Most are of massive serpentinite with only a few bands of gabbro-amphibolite. These pods form prominent outcrops at Craigs of Belcherrie [3391 8346], the other Craigs of Succoth [3388 8340] and Craig Luie [3382 8337]. Between these exposures the presence of serpentinites is indicated by the very high total magnetic field in some zones. To the north-west of the Succoth - Brown Hill intrusion, isolated small pods of serpentinite occur in shear zones at Terryhorn [3470 8403] and in the Burn of Backside [3456 8396]. A sheet of gabbro-amphibolite cutting the River Deveron at [3427 8372] has a plagioclase-cumulate texture similar to those found in the main Succoth - Brown Hill intrusion, although the plagioclase is less calcic. Highly-foliated amphibolites to the north-east of Westerpark [3437 8383] may belong to the same or a related sheet. This sheet is over 500 m from the margin of the Succoth - Brown Hill body and may be an isolated sheet intrusion of a more evolved magma. A very coarse-grained sheet or pod of peridotite on Dumeath Hill [3421 8374] forms small but prominent topographic features. It is unusual in that it lies 150 m to the north-west of the main Portsoy Lineament.

Blackwater intrusion

This intrusion has been described by Fettes and Munro (1989). It consists mainly of medium-grained gabbro, sheared and amphibolitised in places, with a few scattered ultramafic bodies. At its north-eastern end a large body of serpentinite extends into the area of investigation around Cachnamuin Stripe, Bridgend (Figure 2). Little detail has been discerned within this ultramafic body apart from a few pods of amphibolite.

As with the Succoth - Brown Hill mass, the Blackwater intrusion is bounded almost entirely by shears, and mylonites are exposed in places. Its north-west margin coincides with the western edge of the Portsoy Lineament and an absence of hornfelsing near the contacts suggests that considerable displacement may have occurred. Mineral compositions quoted by Fettes and Munro (1989) are comparable with the 'Middle Zone' of other intrusions in the region, such as nearby Boganclogh (Busrewil et al., 1973), Insch (Wadsworth, 1988) and Morven-Cabrach (Allan, 1970).

Minor intrusions

A swarm of metadolerite dykes or sheets occurs to the north-west of the Portsoy Lineament, concentrated in Glen Markie and in the River Deveron between Edinglassie and Aswanley, outside the main area of investigation. These sheets are amphibolitised, but retain a wide range of igneous textures as they post-date the major folding and are affected only by local minor shearing. They are considered to be relatively late intrusions, contemporaneous with or even later than the major mafic-ultramafic masses.

CHEMICAL ANALYSIS

It was considered necessary from the start of the PGE investigations in north-east Scotland to establish background concentrations of the PGE in different types of geochemical sample. To date little baseline or case-history work describing exploration methodology for the PGE has been published. It was therefore considered important to obtain high quality chemical data to detection limits of a few ppb in order to establish a basis for PGE exploration in this region.

Due to the very low levels of PGE present in geochemical samples, the importance of the 'nugget effect' in sampling and sub-sampling cannot be overemphasised. Great care was taken in all field and laboratory procedures to minimise these effects. The great diversity of PGE-bearing species and the lack of detailed knowledge regarding the behaviour of these elements in the secondary environment combine to make the sample collection and analysis stages the most crucial in any programme of geochemical exploration for the PGE.

In the first MRP surveys conducted for PGE in this region in 1983 a small number of samples were collected from the Upper Deveron Belt. They were analysed by a nickel sulphide fire assay method on 50 g of sample, followed by neutron activation analysis for the determination of the six PGE (Ru, Rh, Pd, Os, Ir, Pt) and Au. Acceptable data were acquired only for Ir and Au by this method. Severe interference effects were encountered in the determination of Pt and Pd giving rise to highly variable detection limits. The values for Au and Ir were confirmed by non-destructive NAA (neutron activation analysis).

Subsequently, in order to obtain good quality data and to reduce the high costs involved with the nickel sulphide fire assay, analyses were conducted for Pt and Pd only by a lead fire assay method followed by graphite furnace AAS determination (GFAAS). This method is very reliable and widely used, giving detection limits of 5 ppb for Pd and 10 ppb for Pt. The PGE data reported here for all the reconnaissance samples in the Upper Deveron Belt and for the overburden samples collected in the follow-up surveys were obtained by this method. The analyses were conducted by

Alfred H. Knight International of St. Helens, Merseyside.

Since 1986 there has been a high level of commercial exploration for the PGE, especially in North America. This has led to a demand for cheaper high quality PGE analyses. As a result there have been significant improvements in the field of PGE analysis, in particular the application of ICP mass spectometry (ICP-MS) which allows rapid and highly sensitive determination of Pt, Pd, Rh and Au down to levels of 1-2 ppb following lead fire assay. Hall and Bonham-Carter (1988) reviewed the methods in use in Canadian laboratories for the detection of low concentrations of the PGE and Au in the ppb range. The cost in Canada of these analyses are much lower than in the UK where the market remains very small. Accordingly, since 1987 most samples generated by the PGE studies in the MRP have been analysed by Acme Analytical of Vancouver.

The drillcore samples derived from the two drilling programmes in the Upper Deveron Belt were analysed by Acme Analytical. The PGE determinations for the first programme conducted at Red Burn were carried out by ICP-MS, while the samples generated by the second programme (Kelman Hill) were analysed by GFAAS. The lead fire assay step involved the fusion of 30 g of sample powder in all cases. The detection limits of 1 ppb for Pd and Au and of 2 ppb for Pt and Rh are the same for the two determinative methods and replicate analyses showed similar precision in the range of concentrations likely to be encountered within exploration programmes (up to 1 ppm).

An estimate of the analytical precision of the GFAAS method employed by Acme was obtained by submitting a single batch of 40 sample pairs for PGE-Au determination in the normal way. These samples were chosen to represent a wide variety of sample matrix compositions and, from previous analysis, were known to contain levels of these elements in the range 2-1000ppb. Only two samples with concentrations greater than this were included. The precision was computed according to the method of Garrett (1969), which gave the following results at the 95% confidence level:

Pt - 25.8%
Pd - 22.3%
Au - 29.6%
Rh - 55.5%

It should be noted that the figure for Rh is spuriouly high due to the highly skewed nature of its distribution with many values close to the detection limit (2 ppb). The precision levels for the other elements are considered satisfactory for PGE exploration. High values reported are always checked, either by a repeat analysis at Acme or at another laboratory.

The availability of low cost reliable PGE analyses has enabled exploration work of the type described herein to generate good quality exploration data on large numbers of samples. It has allowed the avoidance of undue reliance on potential pathfinder elements which will not only differ from area to area but also in many cases according to the sample types collected.

XRF analysis on pressed powder pellets was the usual method of trace element analysis. All borehole samples were analysed in this way by the Analytical Chemistry Group of the BGS.

Samples of other types collected in the early stages of the investigations were analysed by the same method by MESA, formerly of Long Eaton, Nottingham. Major element data derived in this way is neither complete nor wholly quantitative but is adequate for exploration work. Limited whole rock major element analysis on fused beads was carried out on a representative suite of the rock and borehole samples to assist in the petrogenetic and metallogenic studies of the area.

RECONNAISSANCE SURVEYS

Drainage Sampling

During 1985 limited reconnaissance drainage surveys were conducted in the vicinity of the Huntly, Knock and Boganclogh intrusions. In the Upper Deveron belt attention was focused on the tributaries of the Deveron draining from the Portsoy Lineament, especially in zones where bodies of mafic and ultramafic rock were known to be present.

Sampling was restricted to the collection of partial pan concentrates as described by Gunn (1989). This method involves wet screening in the field through nylon mesh to produce 8 litres of -2 mm material. This is reduced by washing and panning to a standard final volume (300 ml) which is much larger than that collected for conventional pan concentrate samples. This technique was employed in order to produce a sample representing a large initial volume of sediment and to allow the retention of some silicate material in order to increase the likelihood of retaining composite grains of PGM-bearing silicate. Previous studies in Unst had demonstrated the effectiveness of this method in the collection of very fine platinum-group minerals held in chlorite and serpentine which would have been lost in the conventional panning process (Gunn et al., 1985).

Samples were collected from 29 different sites as shown in Figures 4 and 6. All samples were analysed for a range of trace elements by XRF, while 21 were analysed for Pt and Pd by fire assay and either neutron activation or GFAAS. Simple summary statistics for these samples are presented in Table 2.

Within the Belt the majority of first order streams flow normal to the strike and those of higher order sub-parallel to it. The relative abundances of stream clasts of different types recorded in the field reflect the dominant rock types of the area, namely gabbro-amphibolite and metasediments of the Argyll Group (Middle Dalradian), and thus testify to their largely local derivation. The ultramafic rocks provide only a small and localised input of clastic material into stream channels, with massive serpentinite the most resistant to breakdown.

The distribution patterns of Fe, Ti, Cr, Zn and V reflect the presence of resistate oxides and spinels derived from mafic and ultramafic sources. The highest levels of Mg, together with enhanced Ni concentrations, found in Gordon's Burn [346 837] reflect the extensive exposure of serpentinite in that zone, with the presence of very little superficial cover. In contrast, the serpentinite exposed near Bridgend [336 831] gives rise to generally much higher Cr and Ni levels than elsewhere, up to maxima of 15.24% Cr and 1170 ppm Ni. In the vicinity of the Craigs of

Succoth and Red Burn high Ca reflects the presence of clinopyroxene in the olivine pyroxenites and pyroxenites developed in those parts of the Succoth - Brown Hill intrusion.

Sporadic enrichment of Pb occurs at Bridgend [336907 831761] (140 ppm), Bridge of Ardgallie [340235 834642] (55 ppm), and Burn of Gouls [34189 83498] (71 ppm). These are possibly associated with mineralisation as the levels are markedly lower than those normally associated with lead shot contamination. Arsenic concentrations are generally low with only two values greater than 10 ppm. The maximum concentration of 23 ppm is derived from the Burn of Succoth [34256 836041], at a site within gabbro-amphibolite of the Succoth - Brown Hill intrusion and a few hundred metres below mapped serpentinite. The second highest value (12 ppm) is derived from the Cachnamuin Stripe [336950 831892], near Bridgend, just downstream of exposed serpentinite.

Cu concentrations are generally low (mean 32 ppm) with no elevated values indicative of Cu-Ni mineralisation. The distribution of Zr reflects the widespread input into the streams of material of sedimentary origin with mean levels of about 300 ppm. The highest concentrations are derived from low-lying sites within the Portsoy shear belt in poorly-exposed ground underlain by schists and pelites.

The PGE levels are uniformly low with all reported values very close to or below the detection limits of 10 ppb Pt and 5 ppb Pd. It is not possible therefore to establish any meaningful distribution patterns for these elements either in terms of their relation to bedrock geology or to the other elements determined.

Although the sampling has not been exhaustive, it is apparent that drainage is not the most appropriate technique for locating mineralisation in the mafic and ultramafic rocks of this area. The element distribution patterns correlate well with the known geology, but further orientation work is required in this environment to establish the optimum sampling procedures for PGE exploration.

Rock sampling

Rock samples were collected from 74 sites, either during the course of the initial surveys or during follow-up stages in particular zones. These samples comprised 2-4 kg of unweathered rock taken from several points on a single outcrop, or from a number of closely-spaced outcrops, in order to obtain a representative sample. Rock samples were also collected from bedrock exposed in the bottom of pits excavated in the zones of detailed investigations.

The distribution of sample sites is shown in Figure 4. The locations of samples within the detailed survey areas at Bridgend and Red Burn are shown in Figures 6 and 19 and the results discussed more fully in later sections of this report.

As anticipated, analysis of the ultramafic intrusive rocks demonstrated that they were the most promising targets for the PGE, especially the clinopyroxenites and other pyroxene-bearing variants. The gabbro-amphibolites are uniformly low in precious metals with no values reported above 15 ppb Pt or above the detection limit for Pd (5 ppb). In contrast, the mean levels of Pt and

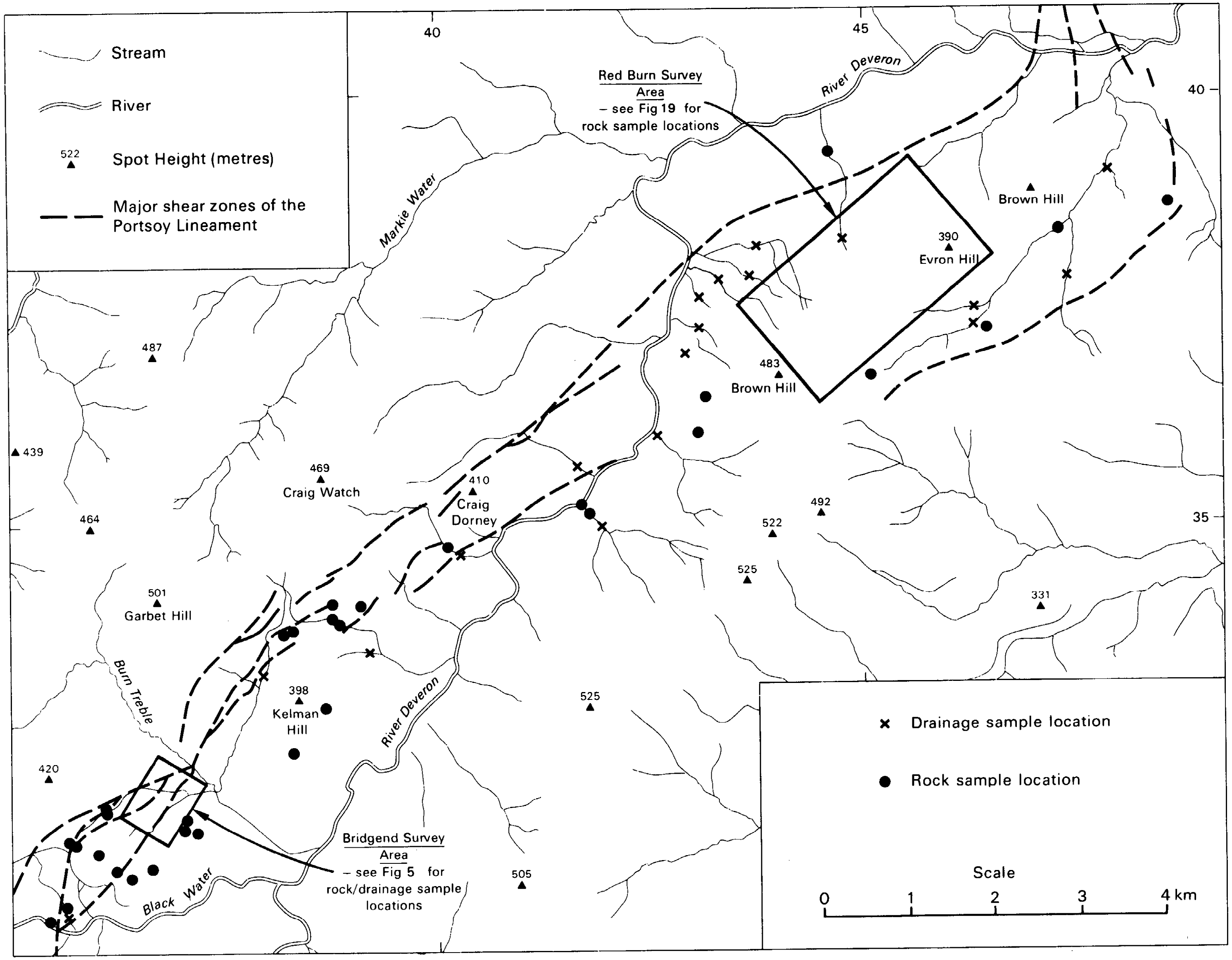

Figure 4 Distribution of reconnaissance drainage and rock sampling sites in the Upper Deveron Belt

Pd in 42 ultramafic intrusive rocks are 20 ppb and 15 ppb respectively. Simple univariate statistics for these samples are presented in Table 3. The 17 clinopyroxenites in this suite, derived entirely from the Succoth - Brown Hill intrusion, have mean concentrations of 38 ppb Pt and 32 ppb Pd. The geochemistry of these PGE-enriched lithologies is discussed more fully in later sections of this report dealing with the detailed surveys and drilling programmes.

Some initial encouragement for precious metal enrichment in the volcanic units of the Blackwater Formation was provided by analysis of a sample collected in the reconnaissance programme from near Shenval [3368 8308]. This ultramafic fragmental volcanic rock reported 64 ppm Sb by XRF analysis, although precious metal concentrations were not above background levels. Further limited outcrop sampling failed to reveal any similar enrichments in chalcophile elements commonly associated with Au and PGE mineralisation. Summary statistics for 10 samples of ultramafic volcanics and associated shallow intrusive rocks from the Blackwater Formation are presented in Table 4.

INVESTIGATIONS IN THE BRIDGEND AREA

Drainage survey

During the reconnaissance survey a panned drainage sample collected from the Garmuch Burn [33691 83177], near Bridgend, reported anomalous Pt levels (23 ppb) by NiS fire assay and NAA finish. This sample was also enriched in Ir, Rh, Ru, Os and Cr (15.2% Cr). Later re-sampling and analysis by lead fire assay and GFAAS failed to substantiate this PGE enrichment. However a single grain of sperrylite ($PtAs_2$) was recovered during collection of a sample from an adjacent stream, the Cachnamuin Stripe, at a point some 140 m from the original site on Garmuch Burn (Figure 5). This grain was of euhedral cubic form, some 150 microns in size and very fresh in appearance. It was therefore considered to be of local origin. Following this discovery several more closely-spaced samples were collected from this stream, within and downstream of an area of exposed serpentinite. No additional PGM grains were recovered and in six samples submitted for PGE analysis no values above the detection limits for Pt or Pd were reported.

It was considered that further evaluation of the serpentinite body as a host for PGE mineralisation was warranted. A detailed geochemical sampling programme and magnetic survey were therefore undertaken.

Geology

As depicted on the geological map of the Belt (Figure 2) the Bridgend area lies at the northern end of an extensive shear-bounded serpentinite developed at the northern extremity of the Blackwater intrusion. A detailed map of the local geology in the area of interest is presented in Figure 6. Outcrop in the map area is confined to intermittent exposures of serpentinite in the Cachnamuin Stripe over a distance of about 200 m, with a few small exposures of schists and pelites cropping out upstream of the serpentinite. No outcrop is present in the Garmuch Burn, nor in the zone between the two streams. To the south-west of the map area the serpentinite body extends for a further kilometre, broadening markedly and forming a conspicuous hill with smooth

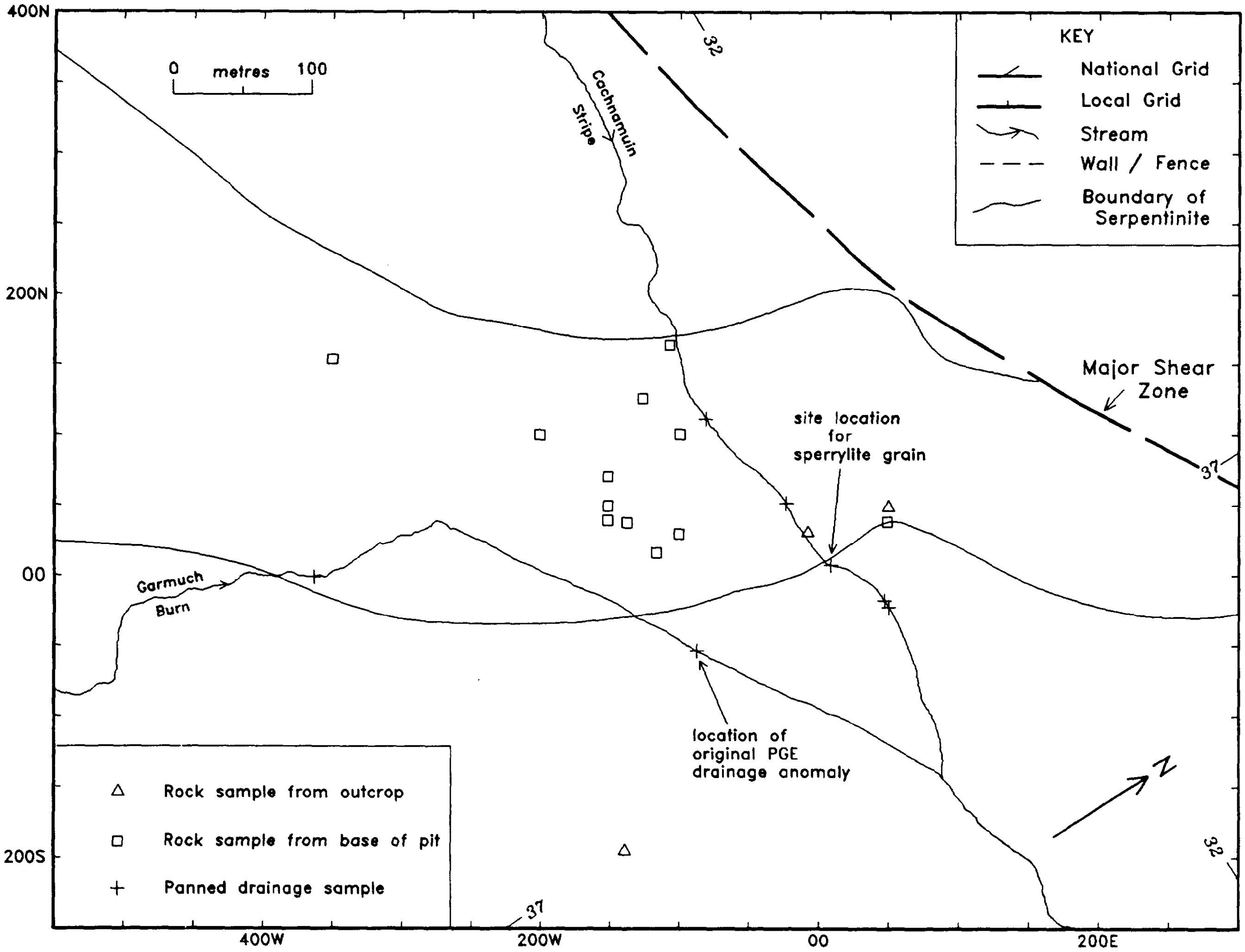

Figure 5 Location of rock and drainage sample sites in the Bridgend survey area

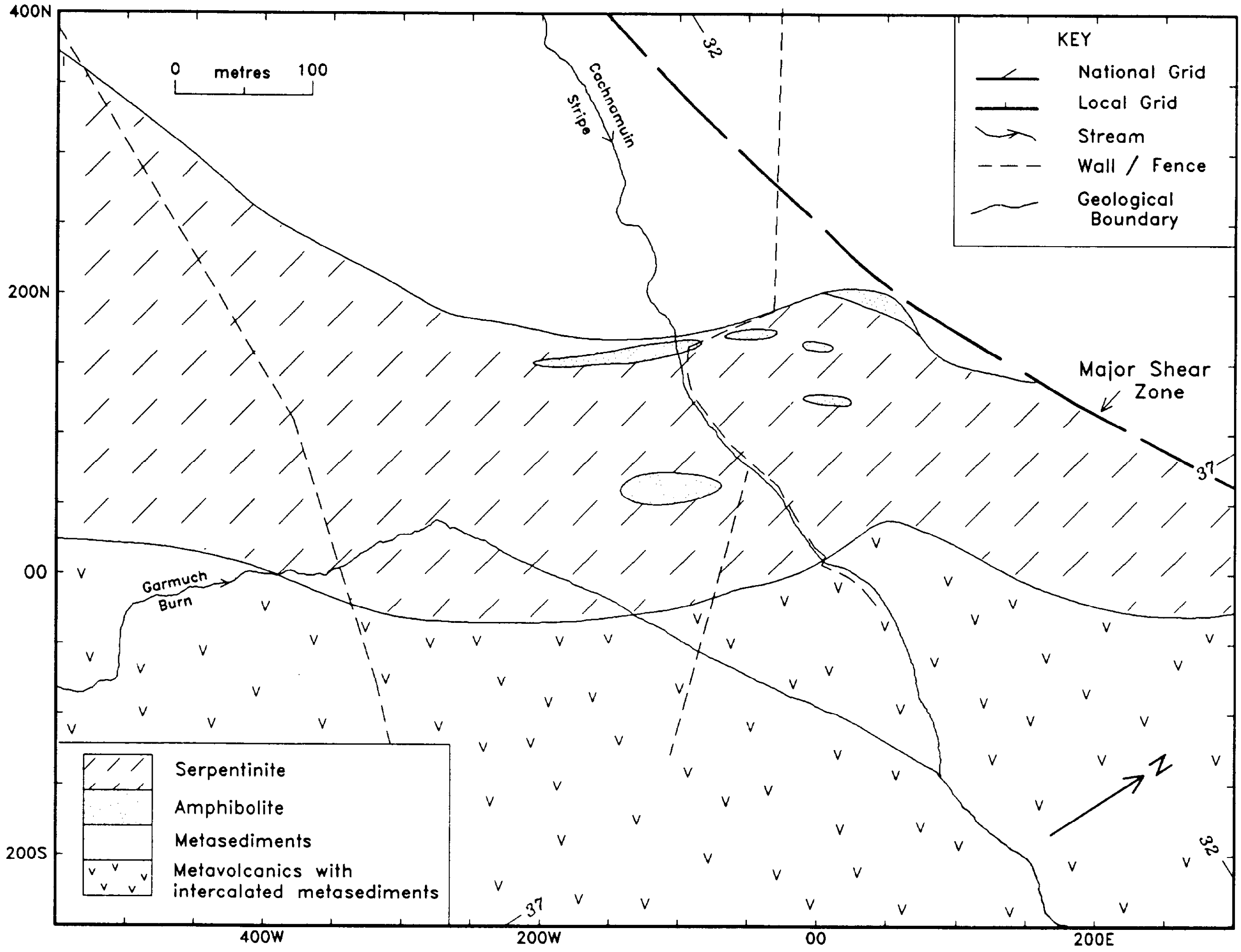

Figure 6 Detailed geology of the Bridgend survey area

slopes. To the south and east of the serpentinite a sequence of intercalated volcanics, schists and grits of the Blackwater Formation crop out sporadically. The geological boundaries shown in Figure 6 are based on the results of the detailed ground magnetic survey and the geochemical sampling carried out to investigate the bedrock in the zone between and adjacent to the two streams. This area is blanketed by a cover of boulder clay containing mixed clasts of mainly local origin. The thickness of this cover varies from less than 1 m on the elevated ground underlain by the serpentinite, increasing rapidly to the south-east along Garmuch Burn where up to 14 m was intersected by the power auger. Similarly on the north-west flank of the serpentinite there is a rapid increase in drift cover onto the Appin Group metasediments.

Magnetic survey

Total field magnetic measurements were made at 2 m above ground level using a proton precession magnetometer along 17 traverses as shown in Figure 7. Observations were made at intervals of 5 m along traverse lines spaced 50 m apart, surveyed by tape and compass/ line of sight and caned at 25 m intervals. A high degree of positional accuracy was therefore maintained throughout. Closely-spaced infill traverses were surveyed in zones of special interest. The diurnal change in total magnetic intensity was monitored by repeated observation at a local base station. The maximum diurnal variation observed was 120 nT. Since the maximum amplitude of the total field anomaly in this zone is approximately 4000 nT diurnal corrections have not been applied. A total of 5.8 line km was surveyed on the Bridgend local grid.

The magnetic data in this zone clearly define the boundaries of the main serpentinite body. Total field intensity varies from 50 500 nT to greater than 53 000 nT on the serpentinite, falling to 49 800 - 50 000 nT on the Blackwater Formation to the south, and to below 49 000 nT on the metasediments to the north. The magnetic data also suggested the presence of a number of small amphibolite lenses within the serpentinite itself. The presence of these bodies was subsequently confirmed by manual pitting in zones of thin superficial cover.

Overburden and bedrock chemistry

A detailed programme of overburden and bedrock sampling was undertaken in order to investigate the PGE distribution in this zone. The sampling was guided by the results of the magnetic survey and by geological observations made as the survey proceeded.

Basal overburden samples were collected with a Minute-man power auger or, wherever the depth to rockhead was less than 1 m, by manual pitting. The former method allows collection of samples beneath thick overburden, but often suffers from some uncertainty as to whether the basal sample is actually derived from the till-bedrock interface. This method generally only recovers a low volume of sample, but it is the usual practice to sample from 2-3 closely-spaced holes to ensure the collection of a representative sample of adequate size. Manual pitting, on the other hand, allows the retrieval of large samples from accurately documented positions in the profile. In addition it is usually easy to determine whether rockhead has been reached and to collect bedrock samples for analysis. Samples were processed by the method described by Gunn (1989) in which a partial pan concentrate is collected by constant reduction from a known starting volume. Where sufficient material was available, 4 litres of -2 mm material was washed and panned down to a final volume

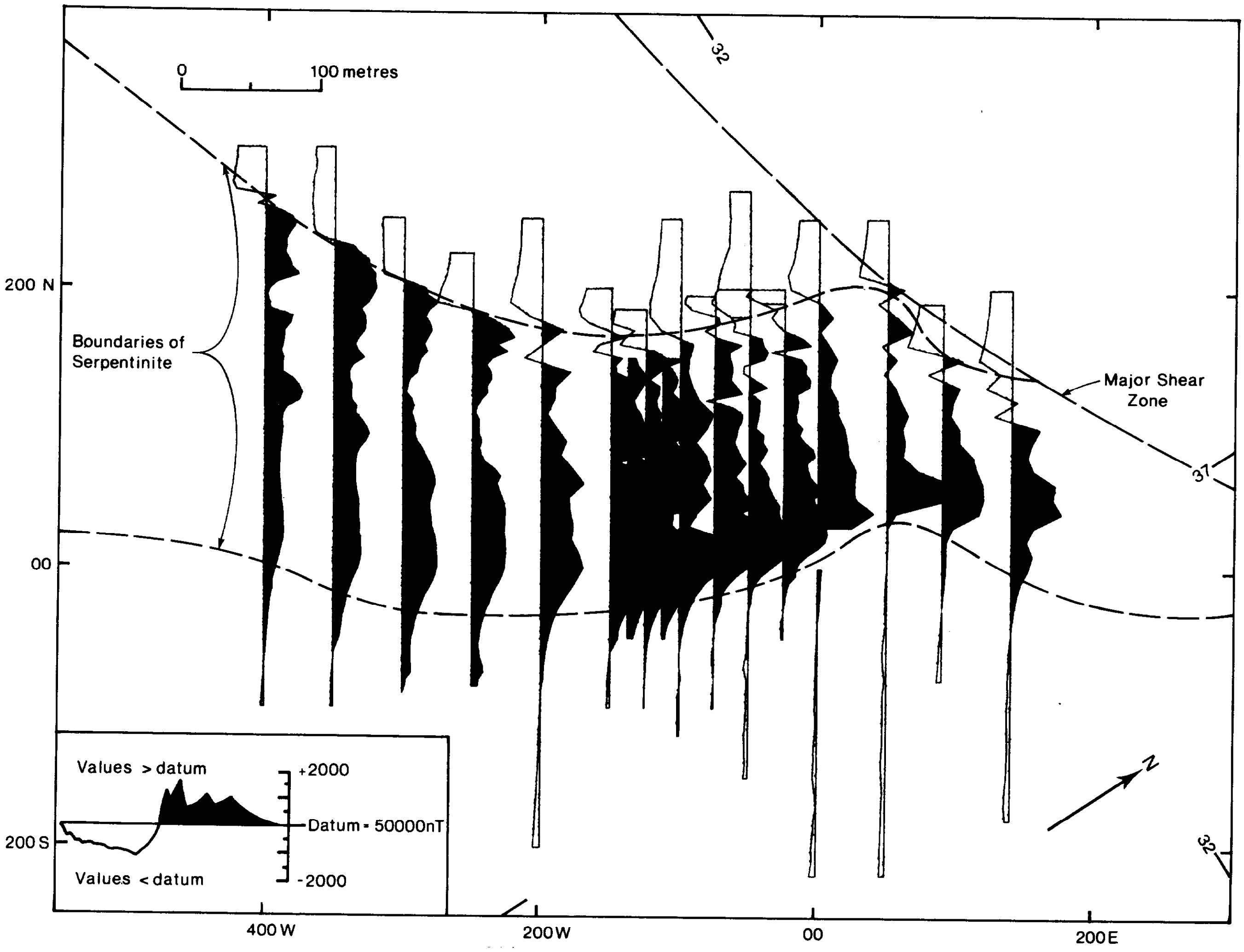

Figure 7 Total field magnetic data for the Bridgend survey area

of 150 ml. Suspended fraction (float) samples were also collected from each site. In addition, observations on the composition and relative proportions of clasts in the +2 mm fraction were recorded in the field to determine the source of the sample, and to evaluate the contribution from, and nature of, the bedrock.

During November 1985 a short sampling programme was undertaken which provided useful orientation data and which suggested some concentration of Pt near the south-east margin of the serpentinite in the zone between the two streams. Consequently the second overburden sampling programme focused particularly on this marginal zone on the eastern flank of the serpentinite. Overall, 283 samples were collected from 204 sites as indicated on Figure 8. At 20 sites multiple samples were taken from the overburden profile at intervals of 1-2 m down to rockhead. The sites of the original drainage anomaly and the source of the sperrylite grain are shown in Figure 5, together with the locations of sites from which rock samples were collected either from surface outcrop or, more usually, from exposure created by manual excavation. Summary statistics for these rock samples are presented in Table 6, in which the uniformly low levels of the PGE and base metals are evident. Local enrichment in As, up to a maximum of 20 ppm, is present.

The summary statistics for 151 panned basal overburden samples are presented in Table 5. For reasons of economy PGE determinations were only conducted on the most promising samples, based on an assessment of their trace element chemistry and their source. Pt and Pd determinations were derived by lead fire assay and GFAAS on a suite of 91 such samples. Although the mean level of Pt is only 8 ppb, there is a distinct cluster of high values near the south-east margin of the serpentinite between the two streams (Figure 9). The thickness of superficial cover developed along this boundary in the Garmuch Burn further to the south-west prevented the collection of suitable basal samples from this zone. It is therefore not possible with the present data to ascertain if PGE enrichment is developed elsewhere along the contact with the Blackwater Formation. Pt shows no significant correlations with any of the other elements determined in these samples, including Pd. There is a weak positive correlation with Cu, where the Spearman rank correlation coefficient (0.175) is significant at the 90% confidence level only. Cr shows a more uniform distribution with high values (> 4%) present widely over both the serpentinite and the ultramafic volcanics of the Blackwater Formation to the south-east. The distribution of Zr is particularly interesting, with concentrations in excess of 1000 ppm developed widely in overburden overlying the serpentinite and volcanic rocks. There is no correlation with Pt or Cr in overburden and the Zr concentration in the serpentinite bedrock is very low (mean 19 ppm in 13 samples). This highlights a problem in the interpretation of the data derived from samples of this type in this environment. A component of detrital zircon of exotic origin has obviously been incorporated into the samples. This surprisingly was even the case with samples from the thinly covered elevated section of the serpentinite where it was easy to excavate by hand to bedrock and obtain an apparently high quality sample of basal till, incorporating a high proportion of bedrock fragments.

The Pd distribution is distinctly different from Pt. The mean concentration is only 4 ppb and c.65% of samples analysed reported values below the analytical detection limit. Pd has significant correlations with Cr, Co, Ni, Fe, Mn, Mg and V, reflecting a probable primary magmatic association in the serpentinite. These correlations should however be treated with caution due to the very low levels present in many samples. In contrast the Pt pattern may be related to a later

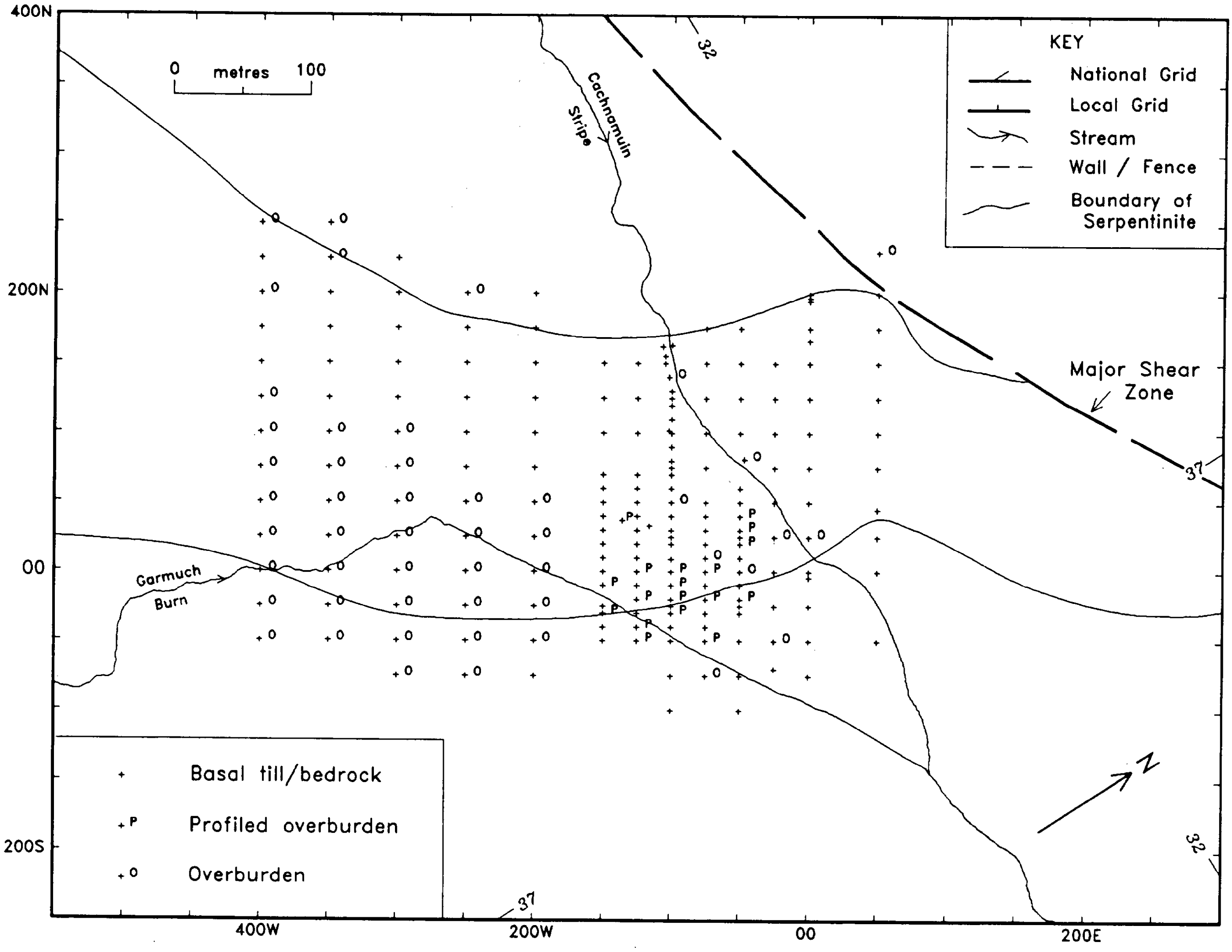

Figure 8 Distribution of overburden sample sites in the Bridgend survey area

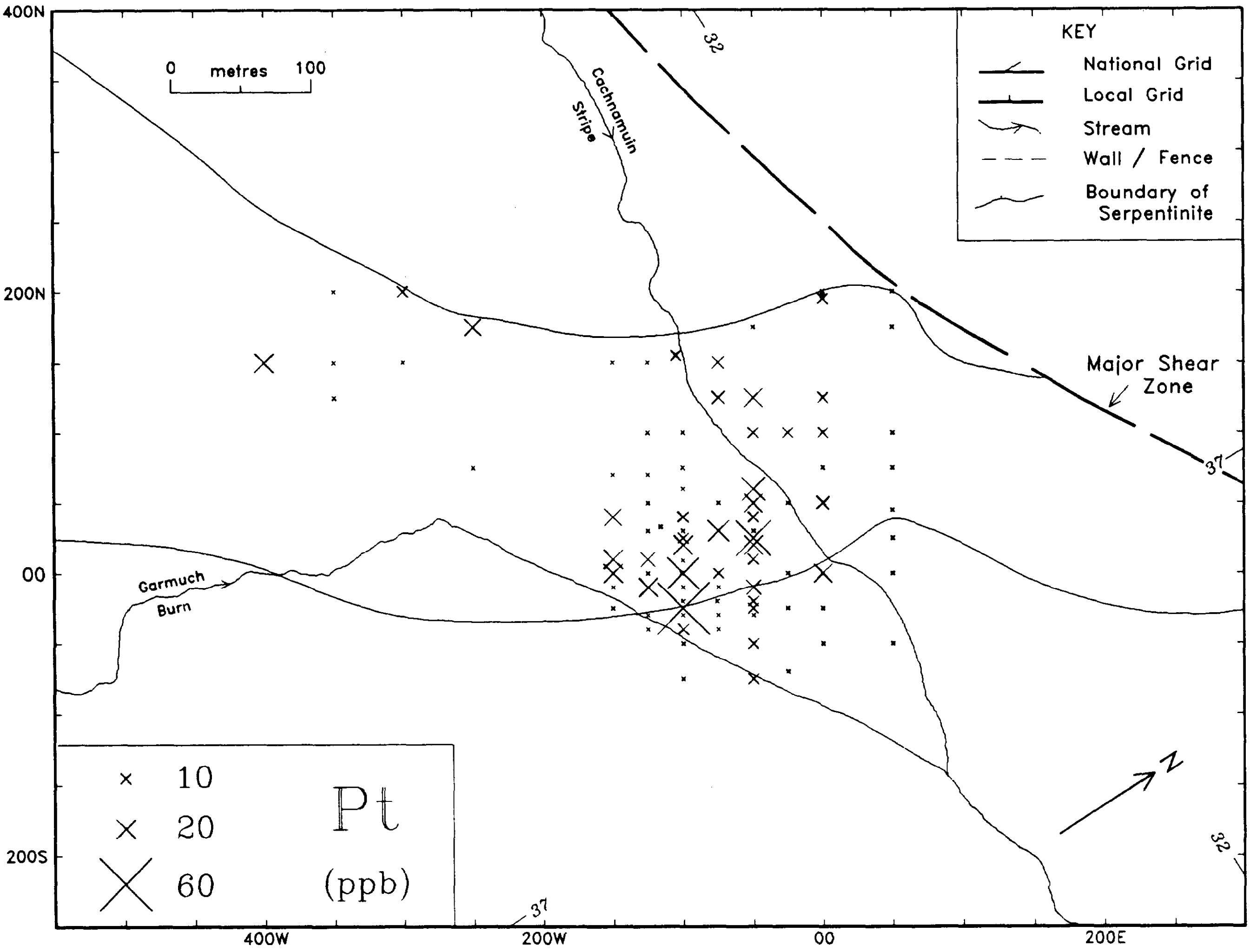

Figure 9 Distribution of Pt in overburden samples in the Bridgend survey area

redistribution, during serpentinisation or hydrothermal alteration. This hypothesis will be discussed further in the light of the results from Kelman Hill borehole 2. Evidence of significant base metal sulphide or arsenide mineralistion within the serpentinite from the overburden dataset is limited. Sporadic and unrelated enrichments in S and As are locally present, but without attendant enhancement in the PGE. The mean As concentration in 13 serpentinite rock samples from the Bridgend area is however 7 ppm, with a maximum value of 20 ppm. This could indicate local As-bearing mineralisation with which the PGE could be associated.

Apart from providing information regarding possible locations of PGE-bearing mineralisation, the overburden data is also useful in the characteristion of bedrock geology. The most diagnostic elements for the serpentinite are Cr, Ni and Zr. The volcanic rocks are enriched in the same elements, but are characterised by particularly high levels of Mg. The amphibolite is distinguished by high levels of Al and Ca, with low Ni. The metasediments are easily recognised by high Si and Al, with low contents of Ti, Fe, Cr, Ni ,V and Zr.

Overburden profiles were sampled at 20 sites within or close to the zone of high Pt values (Figure 8). Typical element distribution patterns in profiles from the marginal zone of the serpentinite are shown in Figure 10.

The site at 50W 20S is located some 30 m from the Garmuch Burn on a gentle slope near the edge of the serpentinite where drift cover is about 5 m thick. This profile illustrates a strong downward concentration in elements related to the ultramafic rocks and an accompanying depletion in elements, such as Al, derived mainly from sedimentary sources. Mg and Ca (not shown in Figure 10) show a gradual, but slight, fall off with depth.These patterns are typical of those sites on the serpentinite where the overburden is relatively thin.

The second profile is derived from a site (100W 20S) located 20 m from the stream where drift cover is around 9 m thick. A more complex profile with 2 distinct peaks is developed at this location. Between 2 and 4 m there is a marked double peak in Cr, Ni and Fe, with accompanying relatively low levels of Ti, Zr and As. Between 8 and 9 m there is a second pronounced peak with high concentrations of Cr, Ni, Fe, Ti,and Zr. These elements fall off very sharply in the basal sample at 9.5 m. As and S (not shown) behave similarly in the lower part of this profile showing a distinct peak about 1.25 m above the level of the main peak at 9 m depth. Mg and Al have fairly regular profiles increasing only in the basal sample.

The third profile illustrated is from a site (100W 30S) about 10 m from the stream where the drift is 8 m thick. This shows a marked single peak at around 3 m depth in Cr, Ni, Fe and Zr. Ti and Ca have more irregular distributions, but all the elements depicted decrease rapidly in the basal metre of the profile, as at 100W 20S.

These profiles are typical of those sampled in zones of thicker overburden. They indicate a well stratified till profile with distinct heavy mineral enrichment developed 2 - 4 m below ground level and sometimes also within the lower 1 - 2 m above rockhead. Basal samples are distinctly different and reflect the bedrock chemistry more closely.

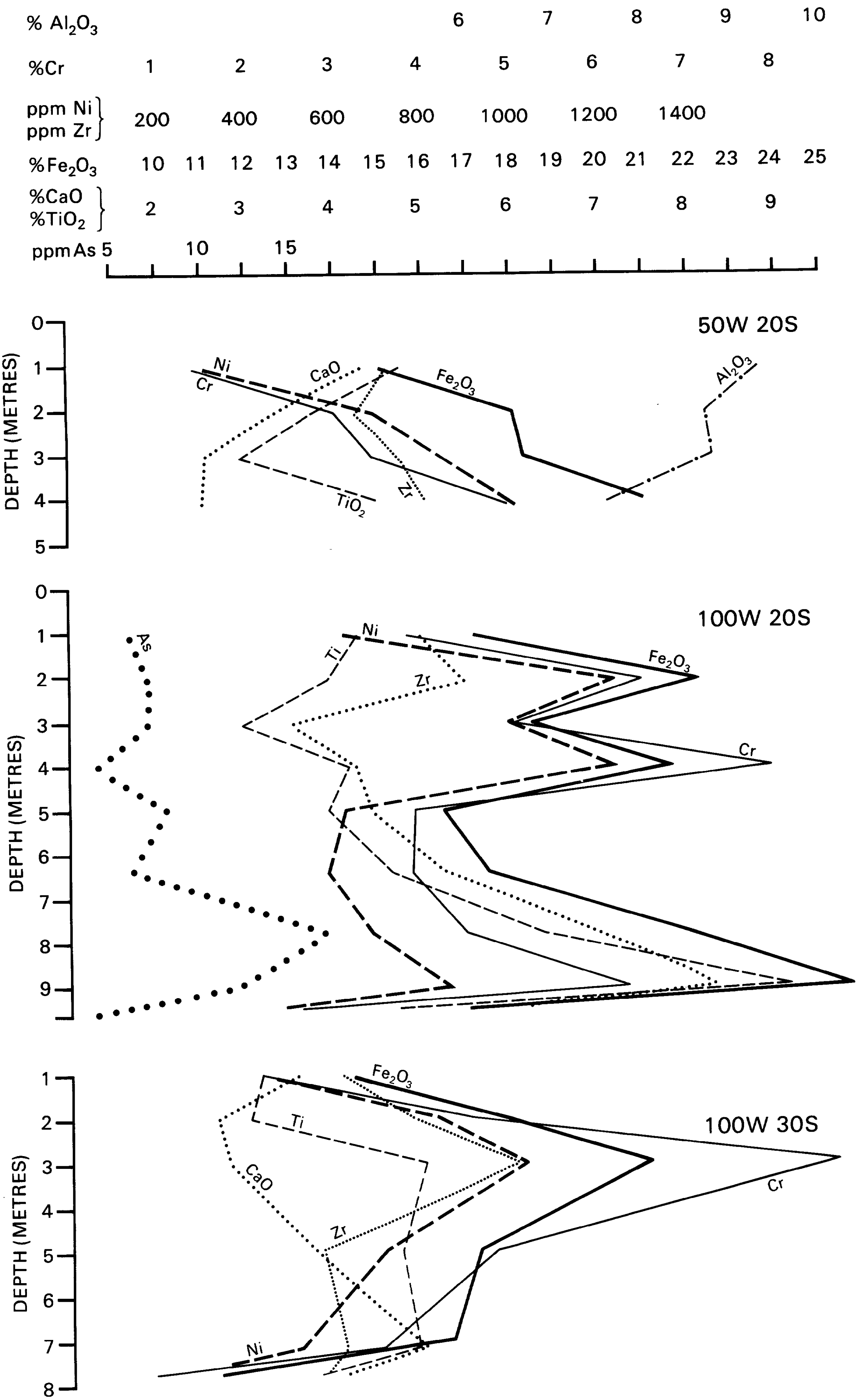

Figure 10 Distribution of various elements in the overburden profile at Bridgend

Discussion

While no source of PGE-bearing mineralisation was revealed in the course of this survey, it is suggested that the serpentinite remains a target which merits investigation by drilling, especially along its margins where structural controls on the distribution of hydrothermal concentrations may be important. The source of the sperrylite grain found in the drainage sampling has not been identified. It is probably of local origin as it has not suffered abrasion or attrition since liberation from its source. It is unlikely therefore to have been released through erosion from the heavy mineral-enriched layers in the stratified till. The Pd distribution may be controlled by detrital dispersion with elements such as Cr from a primary magmatic source.

INVESTIGATIONS IN THE KELMAN HILL AREA

Geology

Following evaluation of the results from the Bridgend area, it was considered worthwhile to undertake further investigations of the serpentinite bodies within the Belt. The structurally-controlled marginal zones were regarded as particularly favourable targets for the occurrence of remobilised PGE-bearing base metal mineralisation. Such deposits are known to occur in association with shear zones cutting mafic-ultramafic hosts, as exemplified by the New Rambler mine in southern Wyoming. In this disused mine high Pt and Pd concentrations occur in a hydrothermal copper ore within a sheared gabbroic host rock (McCallum et al., 1976).

The area around Kelman Hill - Craigs of Succoth was selected as a suitable zone in which to investigate the serpentinite-amphibolite association and the mineral potential of the volcanic units and associated shallow sills of the Blackwater Formation. This area, outlined in Figure 2, is situated 2 km along strike to the north-east of Bridgend. The detailed local geology is shown in Figure 11.

The fragmental volcanic units of the Blackwater Formation were considered to have potential for the occurrence of PGE-bearing Ni-Cu sulphide by analogy with deposits of this type which occur in komatiitic rocks at Kambalda, Western Australia and at Thompson, Manitoba. In addition, gold-antimony mineralisation associated with hydrothermally altered mafic and ultramafic komatiitic volcanic rocks is well known in South Africa and Zimbabwe (Pearton, 1982). Kishida and Kerrich (1987) have also intrepreted the mineralisation at the Kerr-Addison gold deposit, Ontario in terms of hydrothermally altered originally mafic and ultramafic volcanics and breccias. The potential for the occurrence of such Au-bearing mineralisation in the Blackwater Formation volcanic rocks was enhanced at an early stage in the reconnaissance survey by the detection of elevated Sb (64 ppm) in a rock sample collected 1 km south-west of Bridgend, as mentioned in the section on reconnaissance sampling.

In the south-east part of the map area (Figure 11) the Blackwater Formation crops out sporadically in stream sections and near the summit of Kelman Hill. The mapped divisions within this Formation are based largely on the regional ground magnetic survey conducted by the East Grampian Project. This data provides a ready means of distingishing ground underlain by the

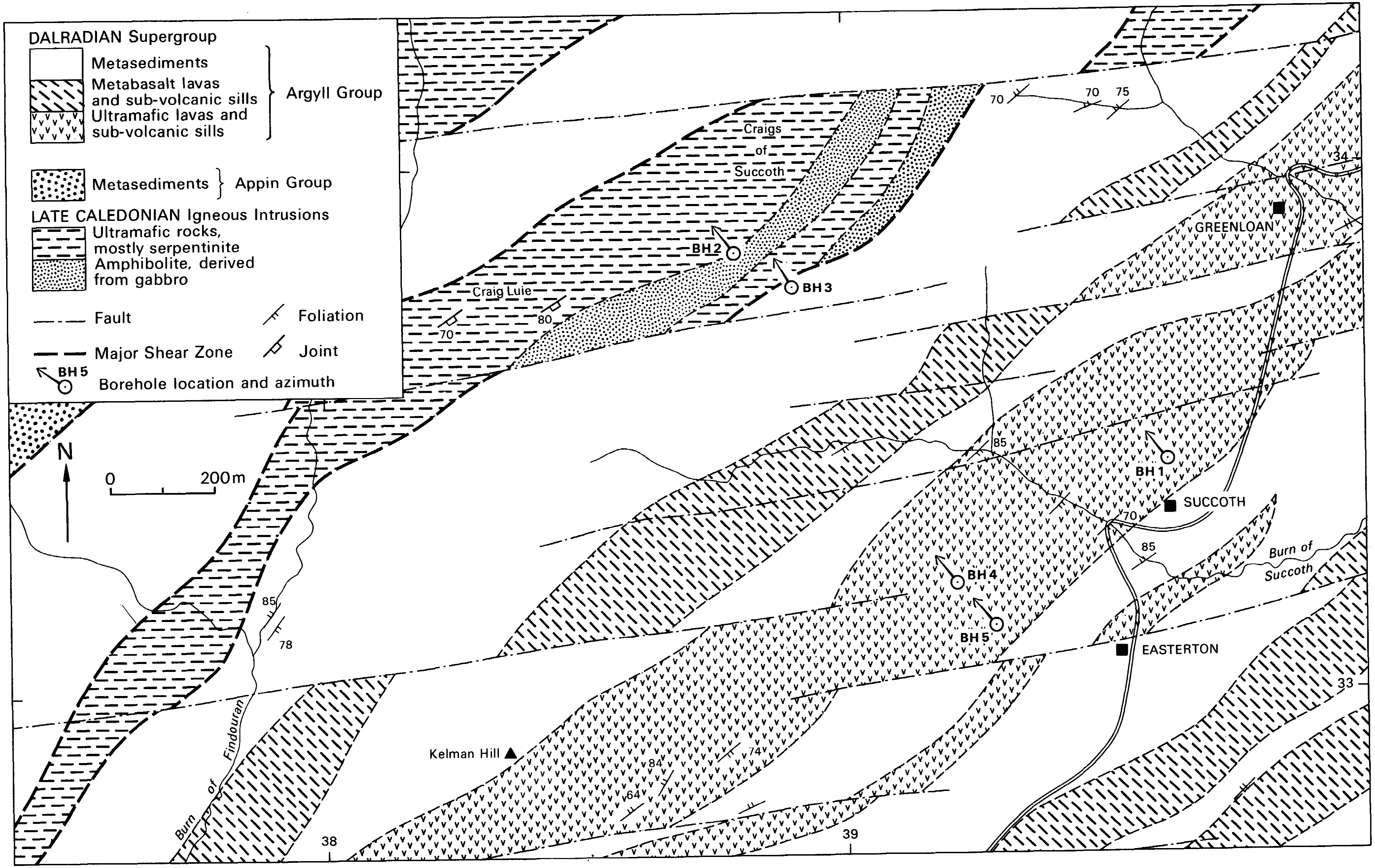

Figure 11 Geology of the Kelman Hill area showing borehole sites

ultramafic and mafic units and the sediments, mainly grits with subordinate banded pelites and semi-pelites. The finer-grained sediments commonly have a strong steeply-dipping penetrative foliation parallel to bedding which indicates younging towards the south-east. The serpentinites outcrop on the highest ground to the north-west as a discontinuous series of craggy outcrops bounded by shears of the Portsoy Lineament and later brittle faults. The limits of the individual serpentinite bodies are well defined by their strong magnetic signatures.

Borehole sections through the Blackwater Formation

Three boreholes (numbers 1, 4 and 5) were drilled to investigate the lateral and vertical variations within the fragmental ultramafic volcanic rocks which crop out on Kelman Hill itself and in the Burn of Succoth. Since these rocks were identified in the EGP mapping their origin has been the subject of much speculation on account of their unusual textural and geochemical features. The boreholes were drilled, with some financial assistance from the EGP, to shed new light on these problems as well as to evaluate their potential as hosts for precious metal mineralisation

A total of 230 samples from these boreholes was analysed for Pt, Pd, Rh and Au by lead fire assay with a GFAAS finish. Other elements were determined by XRF analysis on fused powder pellets. A small suite representative of the main lithologies and alteration types was also analysed by XRF on fusion beads. A total of 70 thin sections was examined, derived largely from boreholes 1 and 5, but also including a small number of surface samples.

Borehole 1

This borehole was sited on the north-east side of the Burn of Succoth at a point some 50 m below the inferred position of the top of the main unit of ultramafic volcanics, the Kelman Hill Member (Figure 11). It was drilled towards the north-west inclined at an angle of 60° from horizontal.

The section encountered in this borehole is summarised in Figure 12. The upper 8 m of core comprises a relatively massive fine-grained vesicular, sometimes porphyritic ultramafic rock. This is composed of pale coloured magnesian clinoamphibole intergrown with chlorite and often displaying a felted texture. In some samples there are large crystals of amphibole which probably replace original clinopyroxene phenocrysts. Below this section, and continuing to a depth of 53 m, fragmental textures are well preserved despite the often oxidised and broken nature of the core. These sections display fragments of varying type, up to several centimetres in size, which are generally flattened into parallel alignment and comprise 60-80% of the rock. The matrix to these clasts is highly sheared, streaky and chlorite-rich. The fragmental character is not conspicuous in thin section and it is very difficult to determine whether the rocks are of intrusive or extrusive origin as few original features are preserved at the microscopic scale. Some sections exhibit highly elongate opaque grains which could be indicative of rapid cooling and therefore of a volcanic origin. In others a variolitic texture is preserved, while some of the clasts were originally glassy and now have a grain size less than 10 microns.

One of the common fragmental types is composed of clasts of dark fine-grained amphibolite. This shows little or no sign of deformation, has a granular texture and a grain size around 20-30 microns. It is composed of green hornblende, plagioclase, quartz and abundant opaques, which are

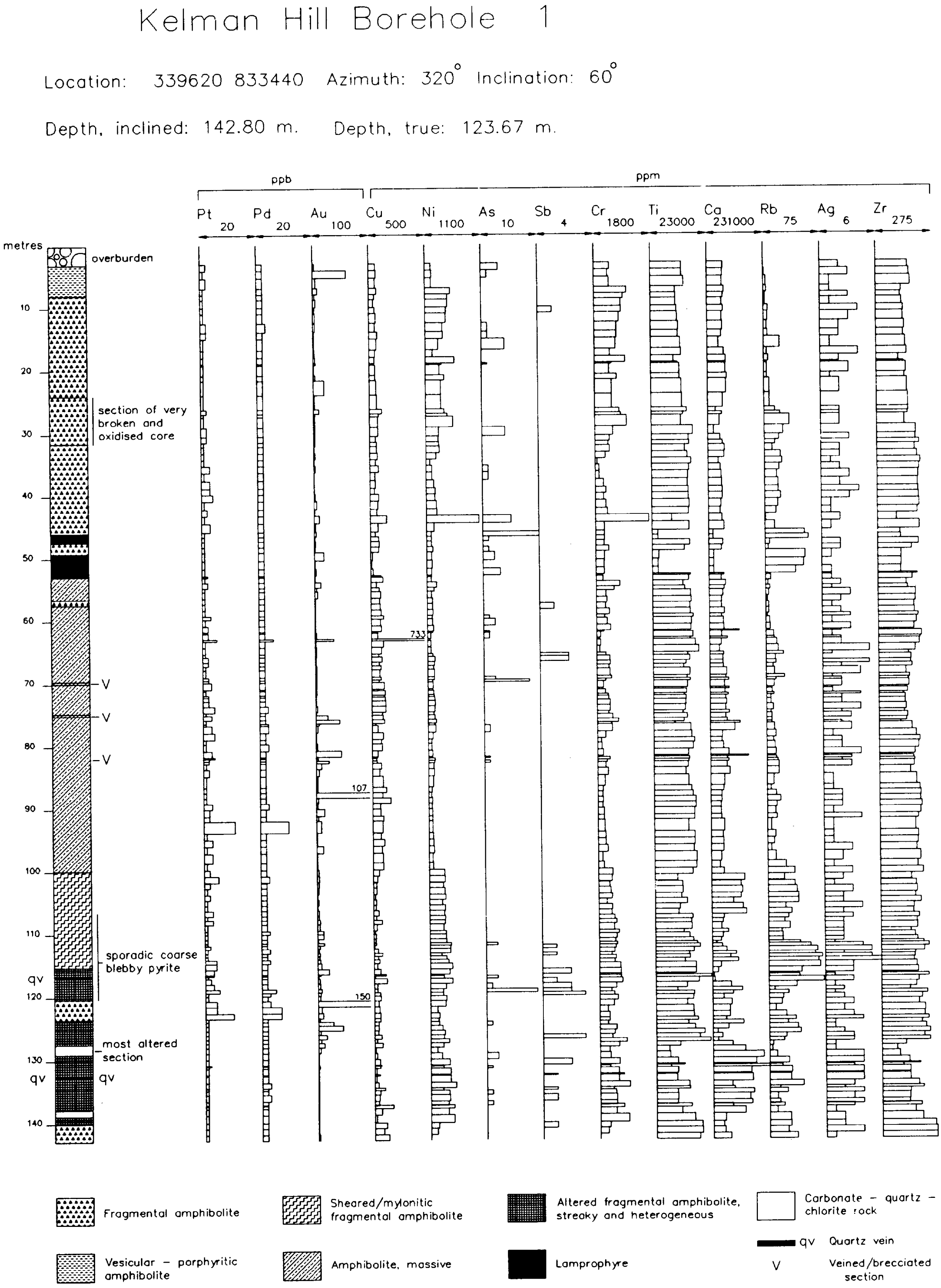

Figure 12 Summary lithological and chemical log of Kelman Hill borehole 1

largely ilmenite. Several samples have large hornblendes, as single crystals or clusters, which were originally phenocrysts of clinopyroxene. Many also have areas that may have been plagioclase phenocrysts but are now largely altered to epidote and quartz. Some have ellipsoidal areas filled with quartz which may originally have been vesicles.

Two sections of highly altered lamprophyric rocks were encountered in the interval between 43 and 50 m in this borehole. These lithologies are quite distinctive. They are pink-grey in colour and contain up to 10% of irregular, corroded amphibole-rich patches a few millimetres in size which are probably partially digested wallrock xenoliths. They are highly carbonated and epidotised and have a particularly distinctive chemistry (Figure 12). Similar minor intrusive bodies have been recorded elsewhere during the course of re-mapping in the Huntly area.

Below the lamprophyres, down to 100 m, the core is composed of a coarser amphibolite with a grain size around 1 mm. This lithology is generally massive and lacks any fragmental character. It is composed of hornblende, plagioclase, quartz and ilmenite, the latter often being rimmed, or totally replaced, by sphene. The original texture is not very clear but was possibly a fine-grained dolerite. This suggests that these rocks were either thicker lava flows or high level intrusions. They are little deformed except in local narrow zones of late brittle disruption with attendant veining and small-scale brecciation. There is no evidence of an original coarse gabbroic texture.

The features described above are seen in the freshest samples that have only been affected by static hydration. Many show much greater degrees of alteration. Some have been altered almost entirely to hornblende, with all the plagioclase replaced. This alteration permeates inwards from the margins of the fragments often leaving an unaltered core. The fragments thus take on an ultramafic character, but their mafic origin is evident from the remnants of bright green hornblende which remain in the cores. The colour differs markedly from the almost colourless iron-poor amphiboles present in the primary ultramafic types. A further stage of alteration is related to the widespread development of epidote which often forms as coarse grains in the extensively hornblendised fragments and, where abundant, can give them a bright green colour. In some sections the hornblende is altered to chlorite.

Below 100 m the fragmental character is again evident even though the core is highly altered. It is usually possible to see a gradual transition from clearly fragmental types through heterogeneous banded or streaky varieties into schistose carbonate-quartz rocks with a minor chlorite component. The most altered sections are developed around 128 and 139 m.

Many of the rocks between 100-120 m are extensively sheared and have mylonitic textures. They contain lozenge-shaped augen of mafic rock, often rather altered, in a quartzose or amphibolitic matrix with a strong schistose fabric. It is difficult to ascertain if these were definitely fragmental prior to shearing, but a fragmental nature would predispose them to the formation of this type of augened rock.

Biotite is found in some samples, particularly in the lower parts of the hole, where it occurs in both the matrix and clasts of the fragmental rocks. It apparently formed largely at the expense of hornblende and is often related to microshear zones. The introduction of potassium-bearing fluids along shear zones was probably responsible for the development of the biotite. Below 100 m the rocks are commonly carbonated, with the extensive alteration and veining often accompanied by chlorite and epidote. Some narrow zones exhibit much less alteration and resemble the lithologies present in the upper 50 m. Below 140 m some of the fragments comprise ultramafic material containing magnesian amphiboles similar to those in the upper 10 m of the hole.

Sulphide mineralisation is widespread but generally present in only trace quantities. Pyrite, with subordinate chalcopyrite, usually occurs as fine discontinuous stringers and veinlets. Local small-scale enrichment occurs in association with the late veining and brecciation developed in the massive amphibolites. A more conspicuous mode of occurrence is found in the altered and sheared fragmental type between 108 and 116 m where late blebby pyrite up to several centimetres in size is developed sporadically.

Borehole 4

The second hole collared to investigate the Blackwater Formation volcanic rocks was drilled from a point some 120 m down section in the Kelman Hill Member on the south-west side of the Burn of Succoth. This hole was terminated at 40.78 m due to severe technical problems encountered in drilling. Core recovery throughout was very poor, comprising a few short lengths up to 10 cm long and many 2-3 cm sized fragments, often recovered with large quantities of grey-brown clay. The fragments comprise various mafic and ultramafic types as seen in borehole 1, including some fragmental varieties. Rusty limonitic alteration is widespread and vein quartz sporadically present. No chemical analysis was carried out on this obviously faulted and incomplete section.

Borehole 5

As a result of the technical problems encountered in borehole 4, a final borehole was collared some 100 m further to the south-east in an attempt to avoid the faulted zone. This location is some 450 m from the site of borehole 1 and more or less on strike from it.

The rock types encountered in this hole (Figure 13) are broadly similar to those found in borehole 1. In the upper 50 m however the recovery is often poor and the core is highly shattered and sometimes altered. The upper part has fragmental ultramafic rocks with fragments composed of fine pale amphibole, chlorite and bladed opaques. The morphology of the opaque minerals could be remnant from rapid quench crystallisation but might be a metamorphic feature.

Below 56 m the original character of the rocks is quite varied, comprising either fragmental or massive fine-grained amphibolites in units up to 10 m thick. The true nature of the original rocks is commonly masked by later alteration and veining and by the incomplete core recovery. In general the distinctive volcanic characteristics evident in borehole 1 are lacking, but otherwise there are many comparable features including the type of alteration. The fragmental varieties include rocks where most clasts are the same and others where several fragment types are present. Around 84 m the rocks appear to be a highly carbonated version of the fragmental ultramafic type.

Between 76 and 83 m there is good evidence of small scale faulting with the development of pervasive iron staining, local brecciation and late quartz veining and fracture fill around carbonated mafic/ultramafic fragments.

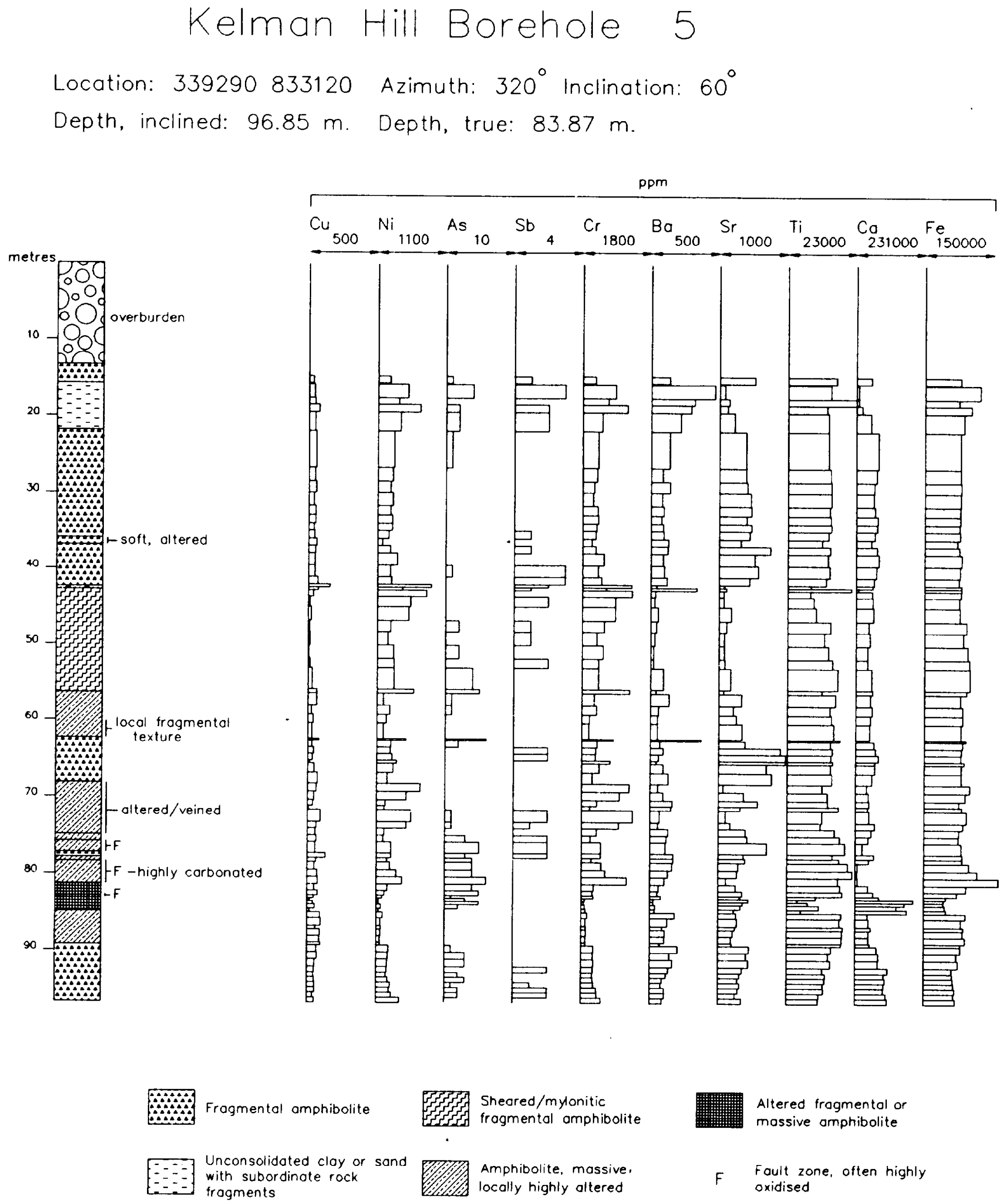

Figure 13 Summary lithological and chemical log of Kelman Hill borehole 5

In several thin sections small amounts of sulphide are present. This is dominantly pyrite with lesser chalcopyrite, although in some samples the proportions are reversed. As in borehole 1 most of this sulphide occurs as discontinuous remobilised veinlets and stringers.

The alteration patterns present in boreholes 1 and 5 may be summarised as follows:

1. Static hydration: formation of serpentinite and fine amphibolites, some original textures preserved.
2. Secondary hydration and mild metasomatism at moderate temperatures, leading to the formation of hornblende from feldspar and pre-existing amphiboles. Local development of biotite in amphibolites.
3. Epidotisation and chloritisation, probably occurring at lower temperatures than 2 and with higher water/rock ratios.
4. Carbonatisation and chloritisation, related in particular to the shearing events.
5. Oxidation and quartz veining related to the late brittle faulting. This is confined largely to borehole 5.

Chemistry of boreholes 1 and 5

Summary statistics for samples from boreholes 1 and 5 are presented in tables 7 and 8 respectively. The reported values for the PGE in borehole 1 are uniformly low with maxima of 11 ppb Pt, 10 ppb Pd and 5 ppb Rh. Au however shows sporadic enrichment in a few samples up to a maximum concentration of 150 ppb. The gold levels above 100 ppb are present without any attendant enrichments in base metals or chalcophile trace elements and occur in both massive and fragmental variants. The other elements plotted in Figure 12 reflect the alteration and original compositions of the lithologies now present. Cr and Ni are relatively depleted in the massive amphibolites, while Ca and Rb display generally enhanced levels in the more altered sections reflecting the introduction of carbonate and alkalis.

Due to the very low concentrations of PGE reported in borehole 1, samples from borehole 5 were analysed only for Au. The results however were uniformly very close to the 1 ppb detection limit and are therefore not presented in the graphic log (Figure 13). Summary statistics for the elements determined by XRF on borehole 5 samples are presented in Table 8.

Discussion

Komatiites are regarded as favourable hosts for PGE-bearing base-metal mineralisation because of their high backgound concentrations of the PGE. This results from their high eruption temperatures and their consequent ability to remain undersaturated in sulphur and thus to concentrate Pt and Pd in the melt (Keays, 1982). The ultramafic volcanic rocks exposed in the Belt and present in the boreholes described above are quite variable in chemistry, not least due to later alteration processes. Available whole-rock data does not allow them to be classified as komatiites on account of their relatively high levels of alkalis and of inert incompatible elements such as Ti and Zr (Le Maitre, 1989). Instead the high-Mg varieties ($>18\%$ MgO) should, on chemical grounds, be classified either as picrites ($Na_2O+K_2O>1\%$) or meimechites ($Na_2O+K_2O<1\%$). Many of the fragmental types present in the boreholes, however, are more basic in chemistry with higher levels of Si, Al and alkalis and lower Mg. As a result, together with the low precious metal concentrations present in boreholes 1 and 5, the potential of these units as hosts for PGE or Au mineralisation is diminished. Further work on the petrogenesis of these unusual lithologies is required before they can be entirely dismissed as being of no interest for metallic minerals.

Borehole sections through the serpentinite

Two boreholes (numbers 2 and 3) were drilled to examine the PGE distribution within and marginal to the serpentinite-amphibolite intrusion cropping out at the Craigs of Succoth [3388 8341]. Both holes were drilled in a northwesterly direction inclined at angles of 60° from horizontal (Figure 11).

Borehole 2

This borehole was collared on the edge of the main serpentinite body exposed at the Craigs of Succoth. Unfortunately no gabbro-amphibolite was recovered, the entire 96.85 m comprising serpentinite apart from a 1 m section of fine foliated amphibolite at around 6 m depth. The serpentinite is generally little deformed except in local narrow shear zones up to 50 cm thick. No original minerals are preserved, although the black spinels are probably altered chromites. The observed textural variations noted in the summary log (Figure 14) reflect both original compositional variation and the influence of later alteration processes. In many thin sections relict original textures indicate a dunite precursor. In the interval between 77 and 79 m, large altered pyroxene crystals, probably orthopyroxene, are the main constituent of a slighly carbonated pyroxenitic type with minor olivine. Some of the serpentinites have a mottled appearance, which is due to the presence of pyroxene pseudomorphs. More often, though, the mottling is due to the recrystallisation of serpentine and the attendant removal of fine magnetite produced in the original serpentinisation. In most rocks, however, there appears to have been only a single phase of serpentinisation with little recrystallisation. Within narrow shear zones the serpentinite is often bleached, altered and veined, with the development of talc, carbonate, chlorite and small quantities of sulphides.

Several of the serpentinites have widespread fine sulphides, with a grain size often less than 50 microns. The sulphides are pyrite and nickel sulphides, such as hazelwoodite, but have not all been positively identified. Some nickel arsenides and larger grains of native copper are also present. In some samples the pyrite has been extensively oxidised to magnetite.

Chemistry of Borehole 2

A total of 66 samples were analysed by lead fire assay and GFAAS for Pt, Pd, Rh and Au and for a suite of other elements by XRF analysis of pressed powder pellets (Figure 14). Summary statistics for this data are presented in Table 9, in which the 15 serpentinite samples analysed from borehole 3 are also incorporated.

The distributions of Pt and Pd are closely comparable, showing a marked increase above the mean levels of 17 ppb in many samples below a depth of around 50 m. In the same lower section of the borehole there is a fairly consistent enrichment in Cr concentrations, from around 2500 ppm in the upper section to values in the range 4-5000 ppm in the basal section. Arsenic, though never exceeding 4 ppm, shows a similar but more sporadic enrichment in the section below 50 m. Spearman rank correlation coefficients confirm the strong correlation between Pt, Pd and Rh and

Kelman Hill Borehole 2

Location: 338790 833830 Azimuth: 324° Inclination: 60°

Depth, inclined: 88.05 m. Depth, true: 76.25 m.

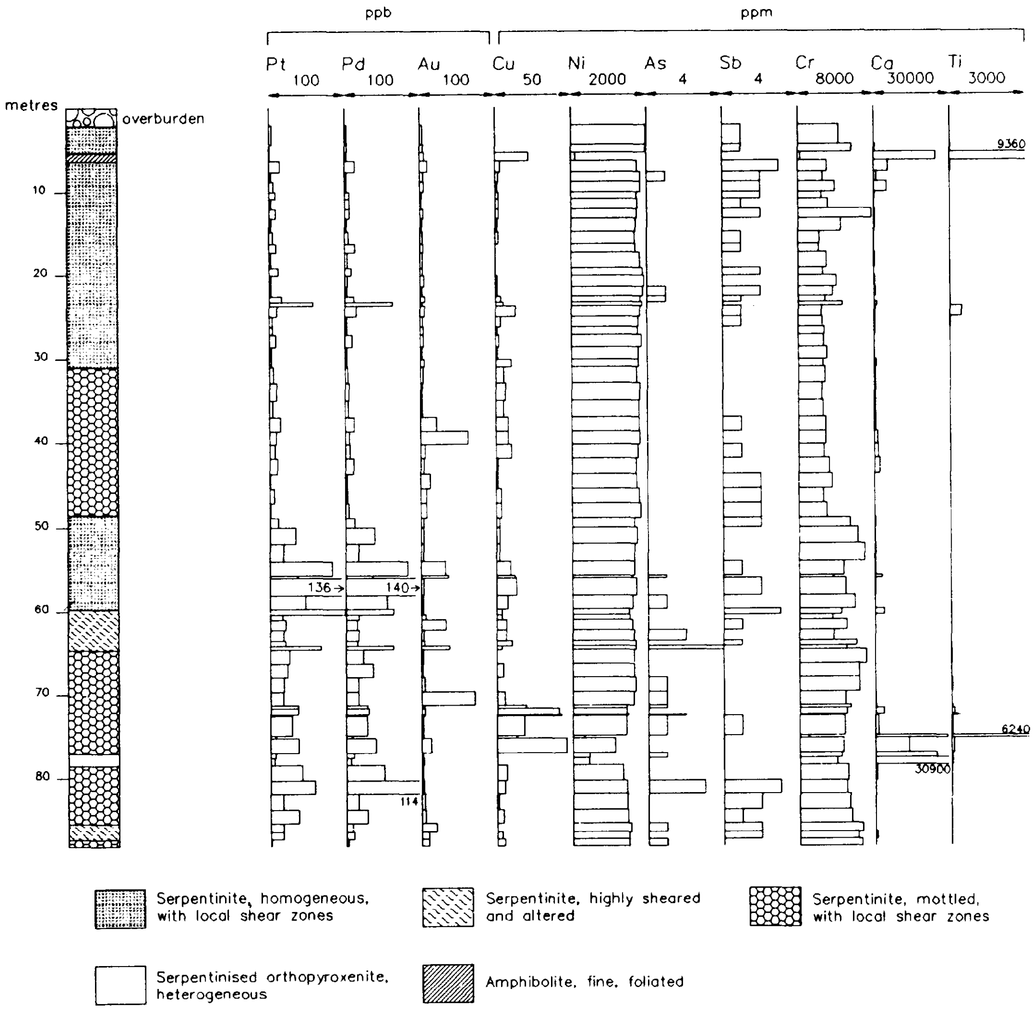

Figure 14 Summary lithological and chemical log of Kelman Hill borehole 2

between these PGE and Cr. They also indicate a significant correlation with Cu.

The most PGE enriched section occurs between 54 and 60.5 m, in which the combined Pt+Pd value exceeds 70 ppb in all samples and reaches a maximum of 280 ppb. This section has no distinctive chemical features but the detailed PGE distribution patterns and their controls may be masked by the size of the core samples. Small scale local developments of PGE-bearing mineralisation could give rise to the elevated PGE contents in the bulk samples, but would not necessarily change the overall concentration of an associated element such as arsenic which would already have background contents of a few ppm in the host rock.

Examination of the chemistry of the 8 samples from these boreholes with greater than 40 ppb Pt shows no systematic differences in the elements determined relative to the other members of the Cr-enriched suite present below 50 m. Pt/Pd values do not in general depart markedly from the mean level of about 1 for -the whole borehole.

In order to elucidate the nature of the Pt and Pd enrichment in this section of the borehole a new experimental technique of searching for rare phases using the automated electron microprobe was used. This is the software package 'Turboscan' which was developed at Imperial College, London with support from MIRO and the EEC. In one sample a single PGM grain was detected at the edge of an altered chromite in a small vein associated with chlorite and talc at the intersection of two sets of microfractures. This grain is ellipsoidal and approximately 6 x 2 microns in size. Microchemical mapping by electron microprobe revealed a very complex internal structure, with compositional zones less than 1 micron in thickness as illustrated in Plate 1. The core of the grain is composed of NiAs, with a partial overgrowth of $PtAs_2$. An outer rim of Pt-Cu alloy envelopes much of the grain. In another thin section similar Pt-Cu overgrowths on NiAs were revealed in four small (5 micron) grains, together with a single Pt-Fe grain. The textural, compositional and locational features of these PGM indicate formation during hydrothermal alteration. The formation of nickel arsenides during the process of serpentinisation is well known. The Pt-Cu and Pt-Fe alloys, and the associated native copper, are also consistent with reducing conditions accompanying serpentinisation. In another sample four small grains of Pd-Sb alloy and one of Ni-Sb, with significant Pt, Pd and Rh contents, were detected included within a grain of NiS.

The distribution of Au in this borehole differs markedly from that of Pt and Pd. There are only two values greater than 50 ppb. Both of these occur within zones of mottled serpentinite, but are not accompanied by any enrichment in the PGE, Cr or any other chalcophile trace elements. Automated scanning on the microprobe did not locate any gold grains in the thin sections examined.

Borehole 3

This hole was sited on the slopes below borehole 2, approximately 140 m to the south-east, to investigate the other serpentinite body and its contacts. A summary lithological and chemical log is presented in Figure 15. In this borehole the upper 20 m of core comprise a section of laminated and banded shales and semi-pelites. These lithologies are often contorted and disrupted by late deformation and are occasionally brecciated and silicified. Local examples of grading are preserved, supporting the inclusion of the sediments in this area within the Argyll Group. This

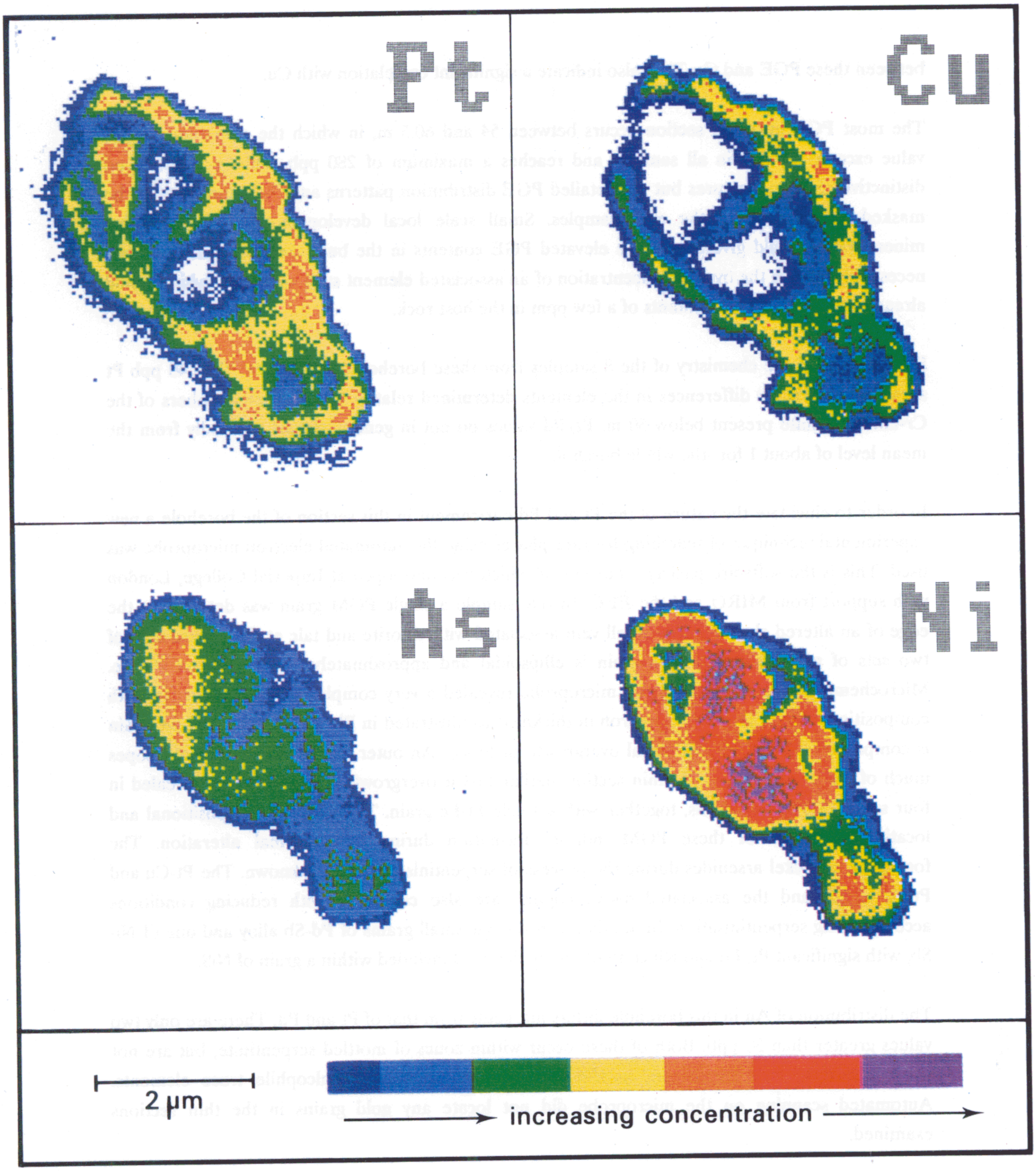

Plate 1 Micro-chemical maps of complex PGE-bearing grain from Kelman Hill borehole 2

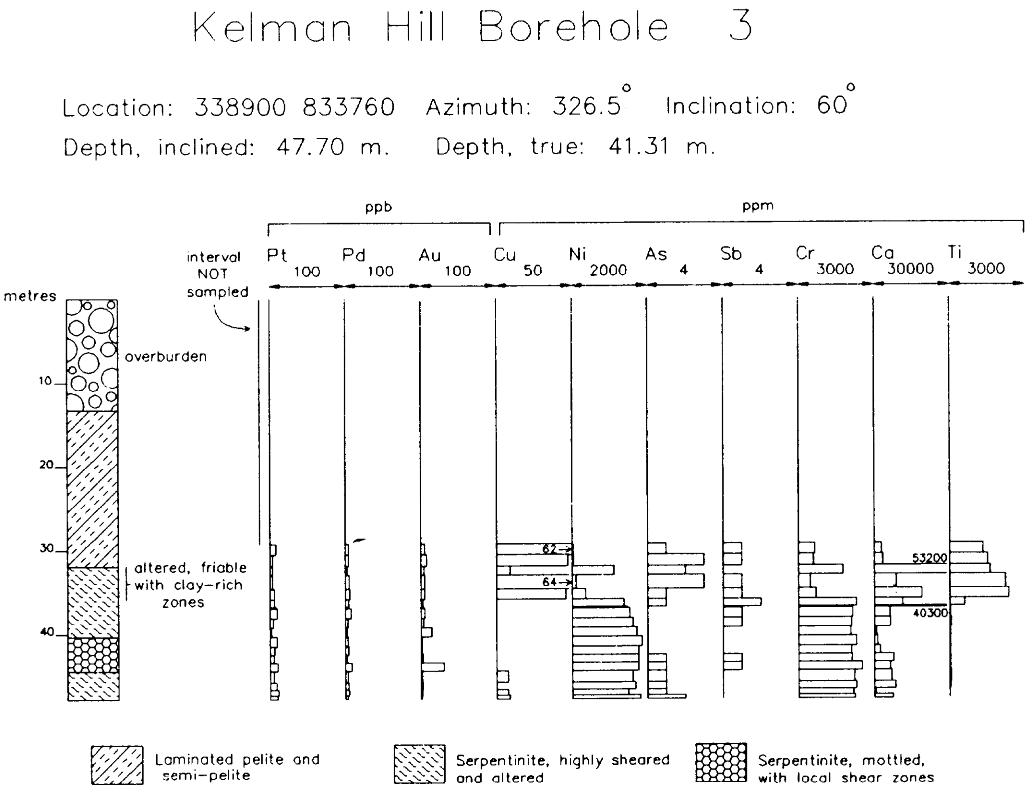

Figure 15 Summary lithological and chemical log of Kelman Hill borehole 3

section passes with a poorly preserved and altered contact into a generally sheared and altered serpentinite. The mottled texture evident in borehole 2 is present over a 4 m section below 40 m.

Chemistry of borehole 3

A suite of 18 samples derived from the serpentinite and its upper contact was analysed from this borehole.

The PGE levels are uniformly very low with maximum values of 11 ppb Pt and 8 ppb Pd. A single high value of Au (30 ppb) is found within the basal section of sheared serpentinite. The mean Cr concentration of about 2000 ppm in serpentinites from this borehole is comparable with that in the upper 50 m of borehole 2 and are markedly lower than in the PGE-enriched type in the lower part of that borehole.

Discussion

The presence of local minor enrichments in Pt and Pd related to hydrothermal processes in sheared serpentinite is highly significant. The process by which the PGE are mobilised and concentrated under these conditions are not well understood. Lydon has addressed this problem with regard to the Caledonian ophiolites of Newfoundland and Shetland, but his model has not been so far been substantiated (Hulbert et al., 1988). The association of chromite with this style of mineralisation is widely recognised but not understood. It is significant to record that in the Upper Deveron Belt this PGE enrichment occurs within the most Cr-rich section of serpentinite found in the study area. Examination of the reconnaissance data for ultramafic intrusive rocks outside the Succoth - Brown Hill intrusion shows a cluster of Cr-rich samples (>3000 ppm) in the Craig Luie - Craigs of Succoth area. Several of these samples also have slightly elevated PGE contents in the range 25 - 45 ppb Pt+Pd. Rock sampling has not been exhaustive, however, and so potential remains for the discovery of similar or higher grade PGE-bearing zones of this type.

INVESTIGATIONS IN THE SUCCOTH - BROWN HILL AREA

Geology

The geology of the Succoth - Brown Hill intrusion has been described above. A new geological map of this body, compiled from East Grampian Project mapping carried out by two of the present authors (DS and AGG), is presented in Figure 16.

Reconnaissance rock sampling during the drainage survey of the Belt led to the recognition of a widespread PGE enrichment in the clinopyroxene-bearing ultramafic lithologies developed in the Red Burn area and on the north-west flanks of Evron Hill.

Exposure within the intrusion is quite variable. Good outcrops are present sporadically on the summits of Brown Hill, Evron Hill and at the Craigs of Succoth. The River Deveron also provides a useful section through the ultramafic rocks at the western end of the intrusion. Elsewhere there is generally only a thin cover of locally derived till, normally less than a metre thick. Mapping of bedrock geology is assisted by recent forestry ploughing over most of the intrusion. This has

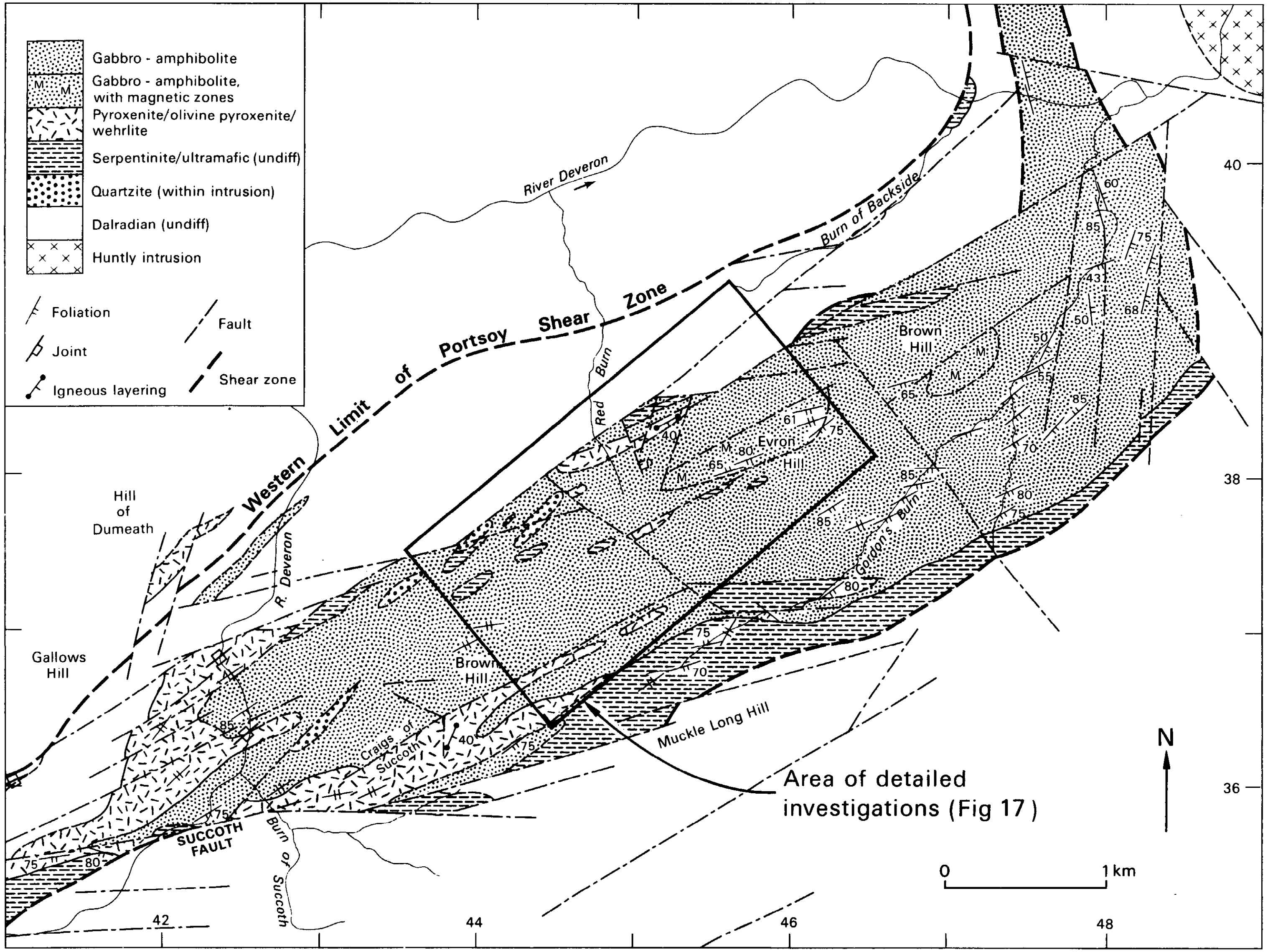

Figure 16 Geology of the Succoth - Brown Hill intrusion showing area of detailed investigation

thrown up abundant rock debris which generally shows a close correspondence with the underlying bedrock.

Follow-up surveys were conducted to investigate the PGE distribution in the Red Burn area, outlined in Figure 16.

Magnetic survey

A detailed total field ground magnetic survey was conducted along the traverses shown in Figure 17. Approximately 19.4 line km were surveyed on 29 separate traverses. The line spacing was normally 150 m, with closer-spaced infill wherever higher resolution of the bedrock geology was required. Observations were made at intervals of 10 m along the lines, which were surveyed by compass and pacing. Diurnal variation was monitored by repeated measurements at the start of each line. No corrections have been applied as the maximum observed diurnal variation is very small relative to the total field anomaly, which is greater than 4000 nT in this area.

The marked contrast between the magnetic susceptibilities of the gabbro-amphibolite (usually about 0.5×10^{-3} SI units) and the ultramafic rock types (usually in the range $15 - 65 \times 10^{-3}$ SI units) gives rise to total field patterns which allow ready discrimination between the major rock types present in the intrusion. The results of the detailed survey are presented in wiggle trace form in Figure 18, covering the same area as Figure 17. The most conspicuous feature is an elongate north-east-trending magnetic high about 100 m wide extending for over 1 km near to the north-west margin of the intrusion. This zone includes the outcrops of the PGE-enriched lithologies referred to above. Other high-amplitude, high-frequency anomalies close to the southern margin of the intrusion reflect the presence, either in outcrop or at shallow depth, of similar elongate ultramafic bodies.

A broad zone with several high-frequency positive anomalies on each line occurs at the north-east end of the local grid area, extending from the south-east flank of Tods Hill (around 1500N 800E) in a zone up to 450 m wide along strike to the north-east. In this zone there is rapid high amplitude variation in field strength both along and between lines. Correlation of individual anomalies between lines in the direction of strike is therefore not possible. Outcrop in this zone is restricted to the widespread typical non-magnetic heterogeneous and sheared gabbro-amphibolites. However, boulders of highly magnetic gabbro-amphibolite can be found locally in the forest ditches with the aid of a magnetic susceptibility meter. These blocks have magnetic susceptibilities averaging around 50×10^{-3} SI units, with values sometimes greater than 100. In thin section this rock type is found to contain up to 10% of primary magnetite. This unusual type of amphibolite is therefore assumed to be intercalated, in this small zone, with the normal non-magnetic variety found throughout the intrusion.

Rock and overburden geochemistry

A programme of geochemical sampling of overburden and bedrock was undertaken in an attempt to elucidate the PGE distribution within the main north-east-trending marginal pyroxenite body. A test programme of overburden sampling, guided by the magnetic data, was carried out by manual excavation of pits to bedrock. Samples were processed in the manner already described for the

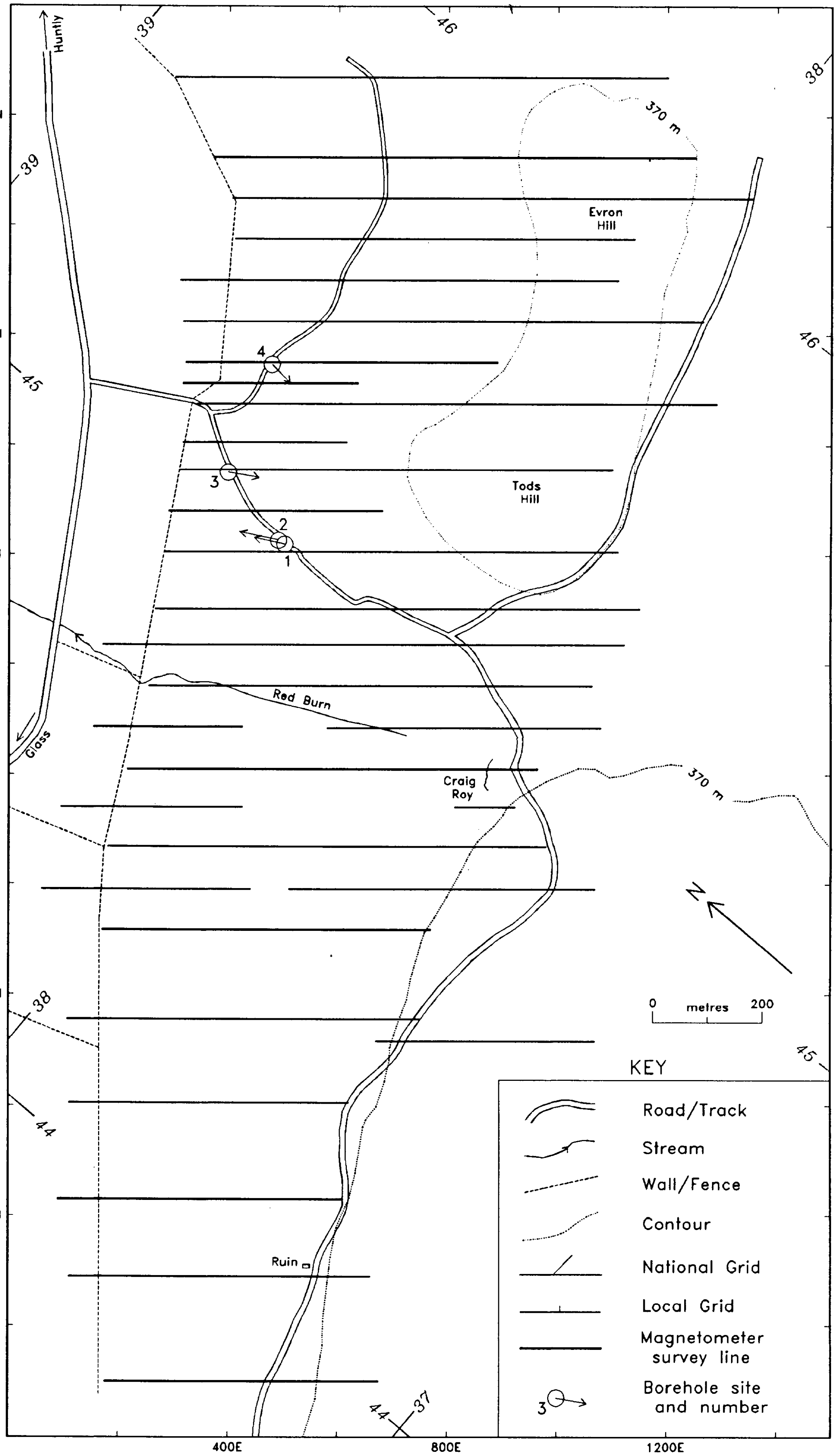

Figure 17 Location of magnetic traverses and borehole sites in the Red Burn survey area

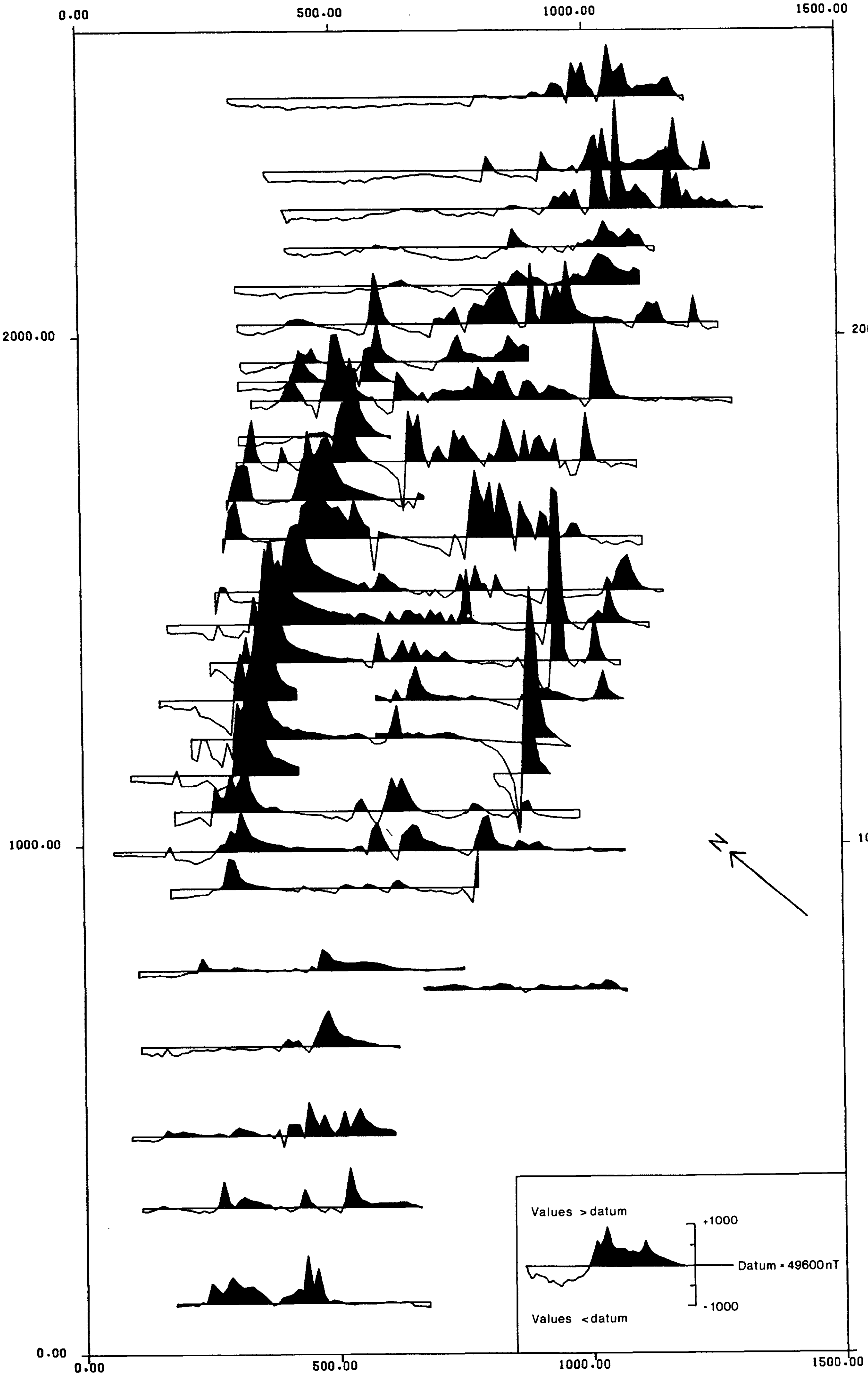

Figure 18 Total field magnetic data for the Red Burn survey area

Bridgend area. It was not feasible to use the power auger in this area because of the difficulty of moving it across the forestry ditches. The results for 25 trial pits to bedrock were disappointing. The chemical signature of the ultramafic lithologies is very indistinct due to the unavoidable inclusion in the sample of material derived from the more readily-weathered, and often finer grained, amphibolites. This is evident in the enhanced levels of Al, V and Ti in the panned samples. The PGE levels determined were very low, with a maximum value of 12 ppb Pd and 10 ppb Pt derived from a site overlying bedrock known to be anomalous in PGE.

Rock samples were analysed from 22 sites within the local grid area, mainly from outcrop but also from a few basal pit exposures (Figure 19). The PGE results showed a consistent enrichment in Pt and Pd over a strike length of about 600 m in the main pyroxenite body. At one point, about 35 m south of the small waterfall (400E 1380N) in Red Burn, a near continuous section is exposed in a ditch over a width of about 80 m. In a sampling traverse across this zone combined Pt+Pd values ranged from 30 to 150 ppb in a suite of seven samples which varied quite markedly in their contents of olivine and pyroxene. The PGE contents of the samples cannot however be related to this variation in modal mineralogy of the rocks. Overburden samples collected from pits adjacent to this sampling traverse revealed uniformly low PGE concentrations, thereby confirming the limitations of this technique in the area. The use of overburden sampling in the Red Burn area was therefore discontinued.

Rock samples from the conspicuous craggy outcrops of Craig Roy (875E 1200N) and from a serpentinite body exposed in pits around 325E 1700N failed to reveal any PGE enrichment above the analytical detection limits. On the other hand, a small pyroxenite cropping out around 565E 1500N showed enhanced Pt and Pd values comparable with those in the main pyroxenite.

An additional suite of samples from the south-west end of the intrusion collected during mapping were also analysed following recognition of the PGE potential of the pyroxene-bearing ultramafic rocks in the Red Burn zone. 2 samples of olivine-pyroxenite from Tomcur Wood [around 3420 8365] reported elevated PGE values up to 130 ppb Pt+Pd.

Borehole sections through the main pyroxenite near Red Burn

Four boreholes were drilled to provide sections through the main pyroxenite body on the north flank of the intrusion in order to investigate the PGE distribution. The location of the drill sites is shown on Figure 17.

A total of 312 samples, derived mostly from boreholes 2 and 3, was analysed for Pt, Pd, Rh and Au by lead fire assay with an ICP-MS finish. A wide range of other elements was determined by XRF analysis of pressed powder pellets. Major elements were determined on a representative suite of samples by XRF on fusion beads.

A total of 56 thin sections from the boreholes has been studied, while many more from samples collected during the EGP re-mapping have also been examined.

The location of the borehole sites was constrained by the previously mentioned forestry ditches

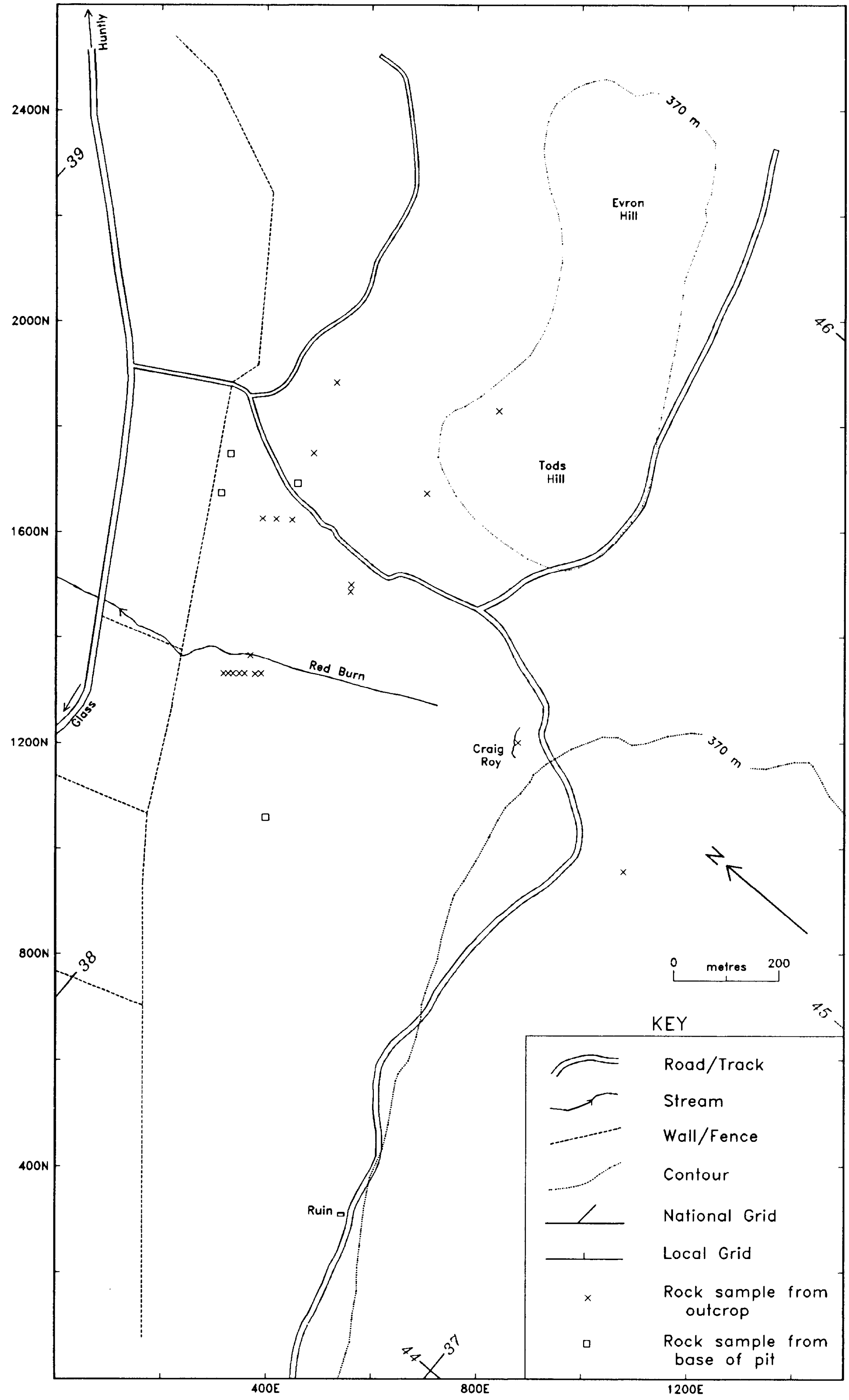

Figure 19 Location of rock samples from the Red Burn survey area

which cover almost the entire area underlain by the main pyroxenite. It was not therefore possible to gain access with the equipment to the optimum sites for drilling. The choice of sites was thus restricted to trackside locations.

The strongly developed and widespread shear fabrics in the gabbro-amphibolite are near vertical or steeply dipping to the south-east. In contrast the pyroxene-rich ultramafic rocks in hand specimen are much more massive and generally exhibit few thin shear-zone fabrics. Occasionally there is evidence in outcrop of an earlier fabric dipping at angles of about 40° to the south-east. This has been interpreted as a relic of original magmatic layering. Superimposed on these are the effects of late brittle faulting. As a result of these structural complexities, the gross disposition and attitude of the main pyroxenite were not well understood at the outset of the drilling. The programme was accordingly designed to clarify the structure of the body as well as to investigate its mineralisation.

Boreholes 1 and 2

Borehole 1 was sited on the basis of a shallow to moderate dip into the hillside towards the south-east. It was drilled from the south side of the pyroxenite towards the north-north-west inclined at an angle of 70° from horizontal.

The bulk of the section recovered in this borehole comprises various types of gabbro-amphibolite, with only two thin pyroxenites (Figure 20). The amphibolites are generally gabbroic, but often very heterogeneous in grain size, modal composition and degree of deformation. Other common variants include a fine-grained, mafic, strongly foliated variety and a very streaky mylonitic type developed in zones up to about 3 m thick. Local faulting is manifested by late quartz and/or carbonate veining, sometimes accompanied by brecciation of the sheared amphibolite. This faulting is most evident below 50 m and led to severe drilling problems below that depth. Accordingly the hole was terminated at 61.7 m and relocated a further 10 m to the north-north-east. This hole (2) was drilled at an inclination of 60° with the same azimuth as the first borehole.

The section in this borehole (Figure 21) includes the same two thin pyroxenite layers which were present in borehole 1, local relatively minor zones of veining and brecciation and a sequence of heterogeneous gabbro-amphibolites comparable with the first borehole. Below 93 m pyroxenite becomes increasingly important, with subordinate olivine pyroxenite. From 117 m to the bottom of the hole at 162 m the core comprises a sequence of intercalated olivine pyroxenite. pyroxenite and minor thin dunites. There is considerable modal variation (on a scale of a few cm) within the olivine-pyroxene lithologies, with variation from pyroxenite through wehrlite to dunite. Shear zone fabrics are commonly developed within all the ultramafic rocks, but are especially conspicuous in the olivine-rich types. Most contacts are similarly deformed but in some cases apparently undeformed transitions between contrasting types are preserved. These are generally at a high angle to the core axis and are interpreted as original magmatic phase and modal layers. The other type with deformed contacts is also inferred to represent former magmatic variation. Occasional zones of highly sheared and deformed mylonitic pyroxenite are also present.

The shear zone fabrics in both boreholes 1 and 2 are in accord with those present in outcrop and indicate a steep dip (70 - 80°) towards the south-south-east. The attitude of the magmatic layering,

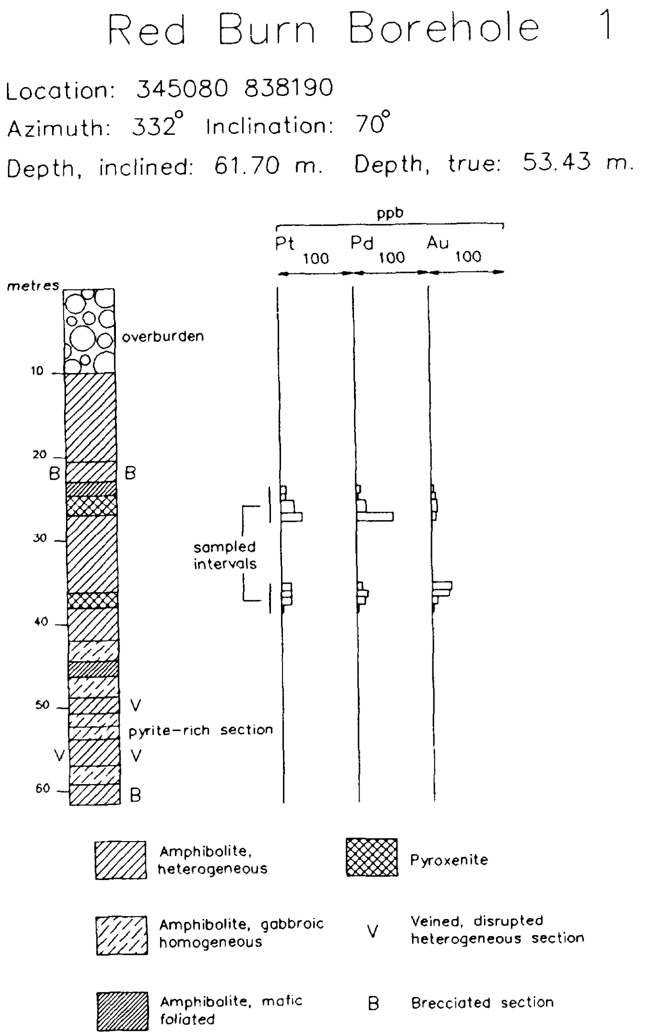

Figure 20 Summary lithological and chemical log for Red Burn borehole 1

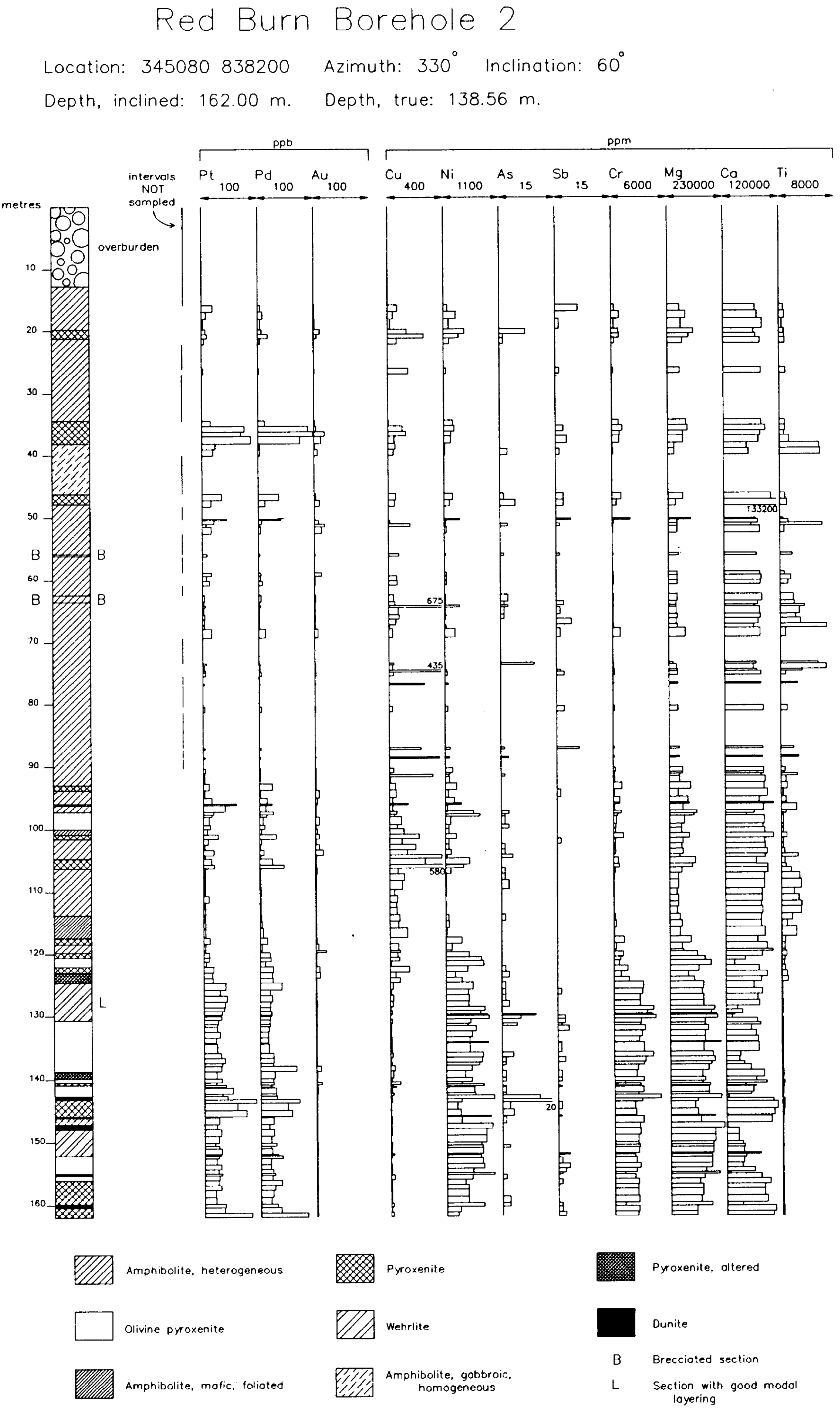

Figure 21 Summary lithological and chemical log for Red Burn borehole 2

derived from the depths of the intersections of the two shallow pyroxenites and from the intersection angles of the layering in the lower part of borehole 2 are also consistent with outcrop measurements and suggest a dip of about 30° into the hillside. In order to reconcile this structural data with the intersection of the main pyroxenite below 90 m in borehole 2, it is necessary to postulate that the main pyroxenite is downfaulted to the south-east from its outcrop position in a prominent scarp only some 30 m from the site of borehole 2. Evidence for cross-faulting of this type is present not only in the boreholes, but also from aerial photographs and from close examination of the magnetic profiles.

Borehole 3

A third borehole was drilled from the north side of the main pyroxenite at an angle of 60° towards the south-south-east (Figure 22). The section comprises mainly ultramafic lithologies, with only three thin sections of amphibolite present. Olivine pyroxenite is the predominant lithology, displaying the same features of layering and late shearing as borehole 2. Sporadic zones of altered and mylonitic pyroxenite are present, especially below 125 m.

Borehole 4

This borehole was located to provide a section through the main pyroxenite near its northernmost exposure. It was collared on the track some 200 m from borehole 3 and was drilled at an inclination of 60° in a southerly direction towards conspicuous craggy outcrops of olivine pyroxenite (around 525E 1900N). The ground between the track and the outcrops is covered with very large boulders of pyroxenite which were interpreted as sub-outcrop. The borehole section however (Figure 23) proves that this is not so as most of the core comprises amphibolite of various types. There are a few thin pyroxenite bands (up to 1.5 m thick) present between 33 and 56 m. Olivine pyroxenite is only encountered in the basal 2.5 m of the hole in a sheared, altered section in faulted contact with the overlying amphibolite. The intersection angles of the shear fabrics within the amphibolite indicate that they are near vertical or steeply-dipping into the hillside. Evidence of minor brittle faulting is present at several points in the section below 60 m.

Petrology

The mafic and ultramafic rock types show parallel histories of deformation and hydration. Their heterogeneous development allows recognition of the original nature of the lithologies and the alteration patterns superimposed on them. This heterogeneity is probably related to the shear zones that bound and cut through the intrusion and which have been the sites for deformation and fluid movement.

Ultramafic rocks. The ultramafic rocks are dominated by the presence of olivine and clinopyroxene with minor amounts of chrome-spinel. The proportions of olivine and clinopyroxene vary from dunite to clinopyroxenite, with olivine clinopyroxenites being an important rock type and wehrlites, with subequal olivine and pyroxene less common. The fresher samples show that these were coarse-grained rocks with crystals up to several millimetres in size.

The dunites are the most altered lithologies and are now extensively serpentinised with very little olivine remaining. A good dunitic texture is often preserved in the serpentinite, but, where there has been significant deformation or intense hydration, serpentine recrystallises and talc is often

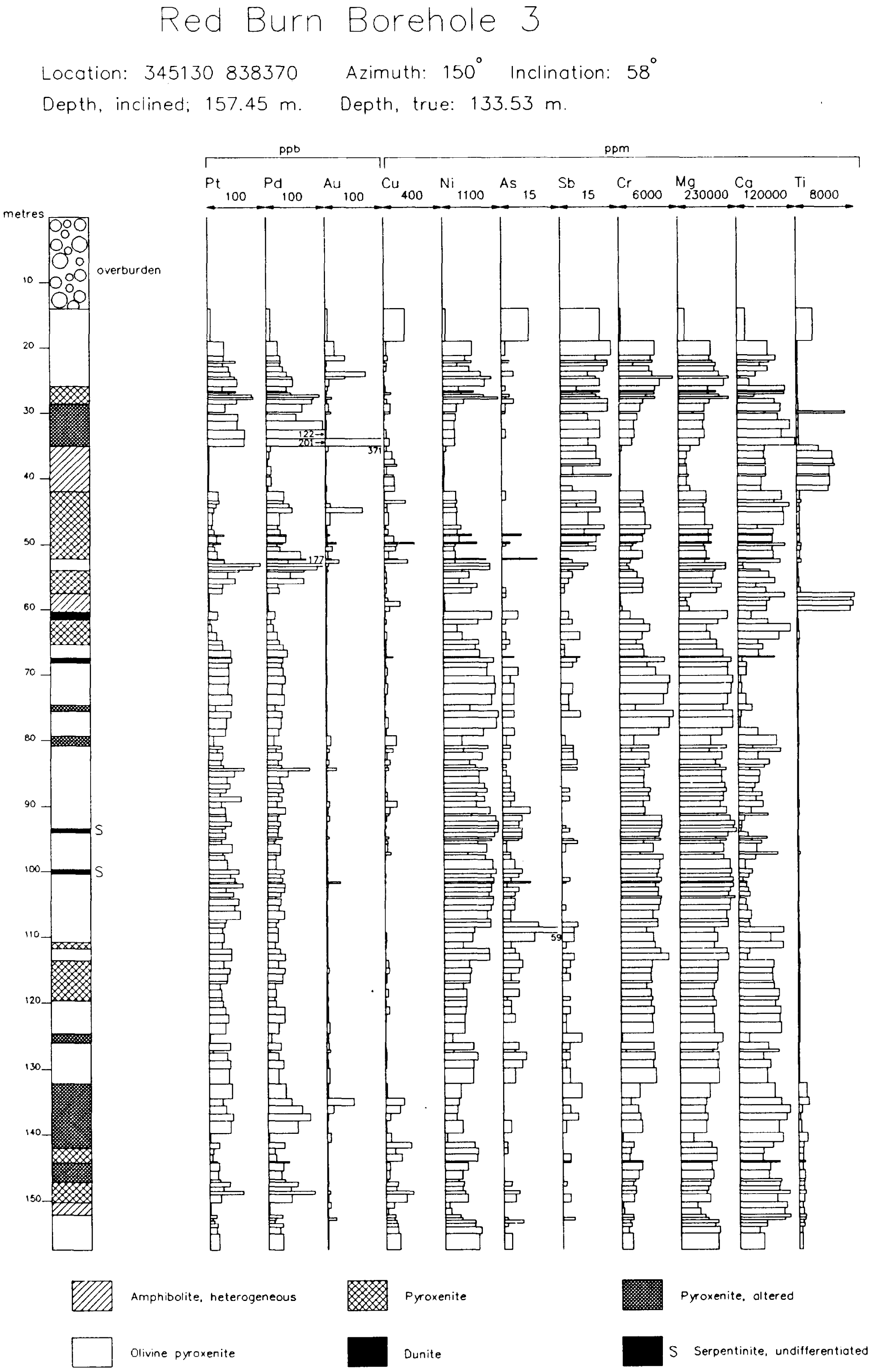

Figure 22 Summary lithological and chemical log for Red Burn borehole 3

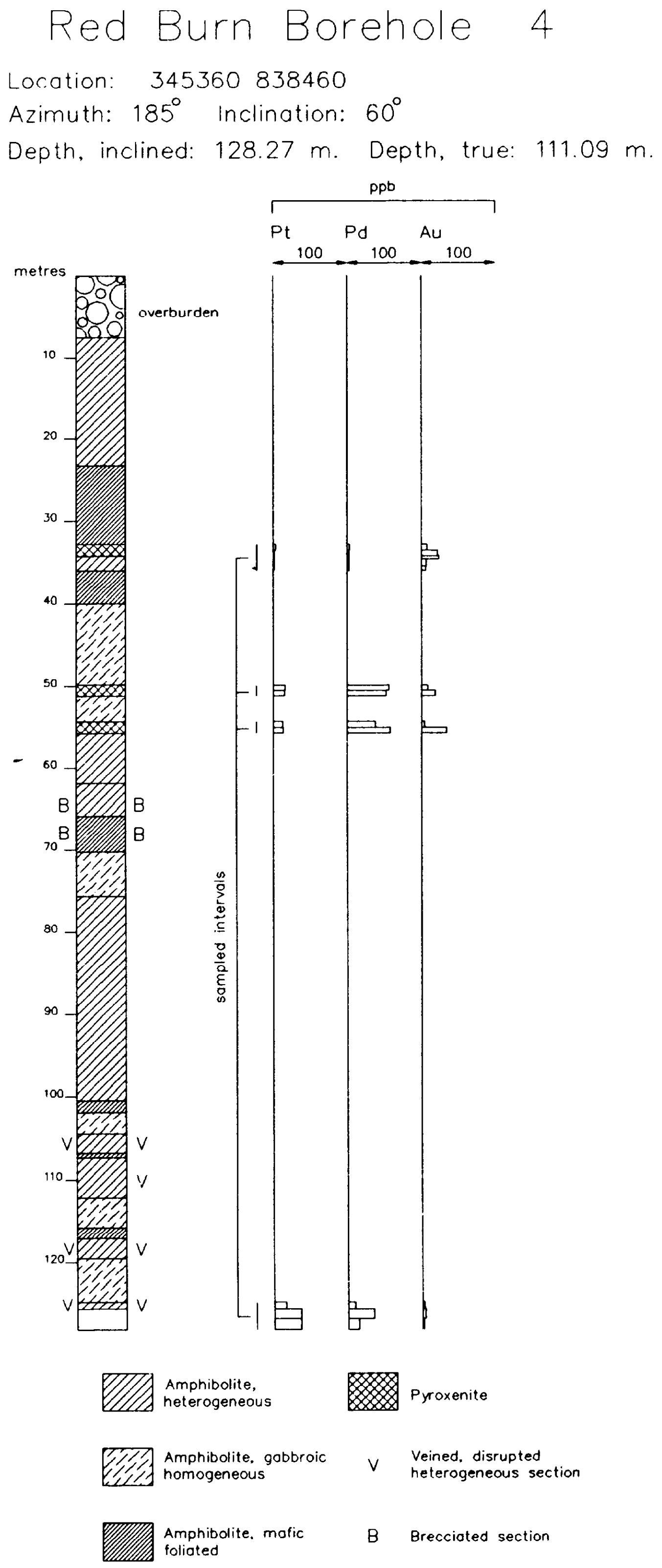

Figure 23 Summary lithological and chemical log for Red Burn borehole 4

formed due to the addition of silica. In the most altered sections substantial alteration to carbonate occurs and sheared talc-carbonate rocks result.

The pyroxene-rich rocks are mostly altered extensively to Mg-hornblende, a colourless clinoamphibole. This forms large plates and produces a coarse interlocking texture similar to the original pyroxenite. With deformation this undergoes recrystallisation to finer grains and develops a schistose fabric. In many of these rocks olivine is a stable metamorphic mineral and recrystallises from its original coarse grain size into many fine grains. Increasing hydration at lower temperatures alters the olivine to serpentine and amphibole to chlorite. Carbonate alteration also affects these rocks in the vicinity of shear zones.

Mafic rocks. The mafic rocks exhibit alteration patterns generally similar to the ultramafic rocks, although with obvious differences in the minerals affected and the end products. The freshest mafic rocks have a coarse gabbroic, sub-ophitic texture with large plagioclases partially enclosed by large plates of green hornblende. This hornblende replaces clinopyroxene which is only preserved in one sample but, as this is an essentially static hydration, almost perfect textural integrity is retained. Opaque minerals are rare or absent from most of the metagabbros and only in one suite of samples from Tods Hill and Evron Hill is magnetite present. Here it is quite abundant, and is accompanied by minor pyrite and chalcopyrite. The pyrite may show alteration to goethite.

The deformation causes the gabbroic-textured amphibolites to undergo recrystallisation, varying from granulation along thin shear zones to total recrystallisation and development of a strong preferred orientation. This gives rise to the relatively fine grained foliated amphibolite developed quite commonly in the boreholes with loss of all original textures. A gradation through all these stages of alteration can be seen.

The addition of further fluids at lower temperatures than the amphibolite facies described above results in a series of further changes. The green hornblendes are altered to a pale actinolitic amphibole or chlorite. Increased hydrothermal alteration changes the plagioclase and some of the amphibole to epidote and may be accompanied by carbonate. Epidote and quartz-epidote veins are also produced. At the lowest temperatures the feldspars suffer intense saussuritisation. As in the ultramafic rocks all these effects are variably developed but are most intense in the vicinity of the shear zones.

Sulphides. Several of the samples contain minor amounts of sulphides. These occur mostly as small grains and are often associated with small shears and veins. The minerals identified are dominantly pyrite with less chalcopyrite and pyrrhotite, and a little pentlandite in ultramafic rocks.

A summary of the alteration events and products in both mafic and ultramafic rocks is presented in Table 1.

Chemistry of boreholes

The analysis of the borehole samples confirmed the results of the outcrop sampling in verifying the enrichment in Pt and Pd in the pyroxene-bearing ultramafic rocks and also the uniformly low levels present in the gabbro-amphibolites. Mean concentrations of Pt and Pd are around 30 ppb in the ultramafics compared with only 5 ppb in the mafic rocks. This distinction is clearly demonstrated in

Table 1 Mineralogy and alteration of rocks in the Succoth - Brown Hill Intrusion

Event	**Mineralogy / Texture** *Ultramafic*	 *Gabbros*
1. Magmatic	ol + cpx (coarse)	cpx + plag (coarse)
2. High T (a) static hydration	ol + Mg-amphibole + secondary cpx (?) (coarse)	hbl + plag
(b) shearing	grain size reduction and regrowth of amphibole with schistose fabric	variable - from localised shears to complete recrystallisation with development of schistose fabric
3. Low T (? further shearing?)	serpentine + chlorite	actinolite + plag
4. Hydrothermal	talc + carbonate	epidote
5. Low T - static	saponite (Mg - clay)	saussuritisation of plag

Abbreviations: ol - olivine; plag - plagioclase; hbl - hornblende; cpx - clinopyroxene

the scatter plot of Pt v Pd (Figure 24). Summary statistics for these two rock groups are presented separately in Tables 10 and 11.

Although the distinction between mafic and ultramafic rock types is clear in terms of their PGE contents, the controls on their distribution within the ultramafic group itself is not clear. Figure 24 shows that the olivine pyroxenites cluster fairly closely and are slightly enriched in Pt relative to Pd. The pyroxenites on the other hand scatter more widely, in both their PGE contents and Pt/Pd values. The graphic logs (Figures 21 and 22) clearly show the variations within the ultramafic rocks of Mg, Ca, Cr and Ni as the modal proportions of olivine and clinopyroxene vary. The very low PGE concentrations in the amphibolites are clearly evident, as are the enhanced background levels of Pt and Pd in the ultramafic rocks.

Significant PGE enrichment is present in two intervals in borehole 3. The first occurs between 27 and 35 m in a zone of fairly marked small-scale modal variation, including a thin amphibolite, olivine pyroxenite and dunite. The lower part is highly sheared and altered and mainly pyroxenitic. In this section the Pt/Pd ratio is less than 1, decreasing to around 0.5 or less in the lower 2.5 m of altered core. Au enrichment up to 371 ppb accompanies this Pd enrichment in the basal sample of this interval. Immediately below is a dark foliated amphibolite with very low precious metal values. The high PGE, low Pt/Pd altered samples are accompanied by marked depletion in Cr and Ni and an increase in Ca. Cu, As and Sb show no significant variation through this section. Automated scanning of three samples on the electron microprobe did not detect any PGE-bearing minerals in

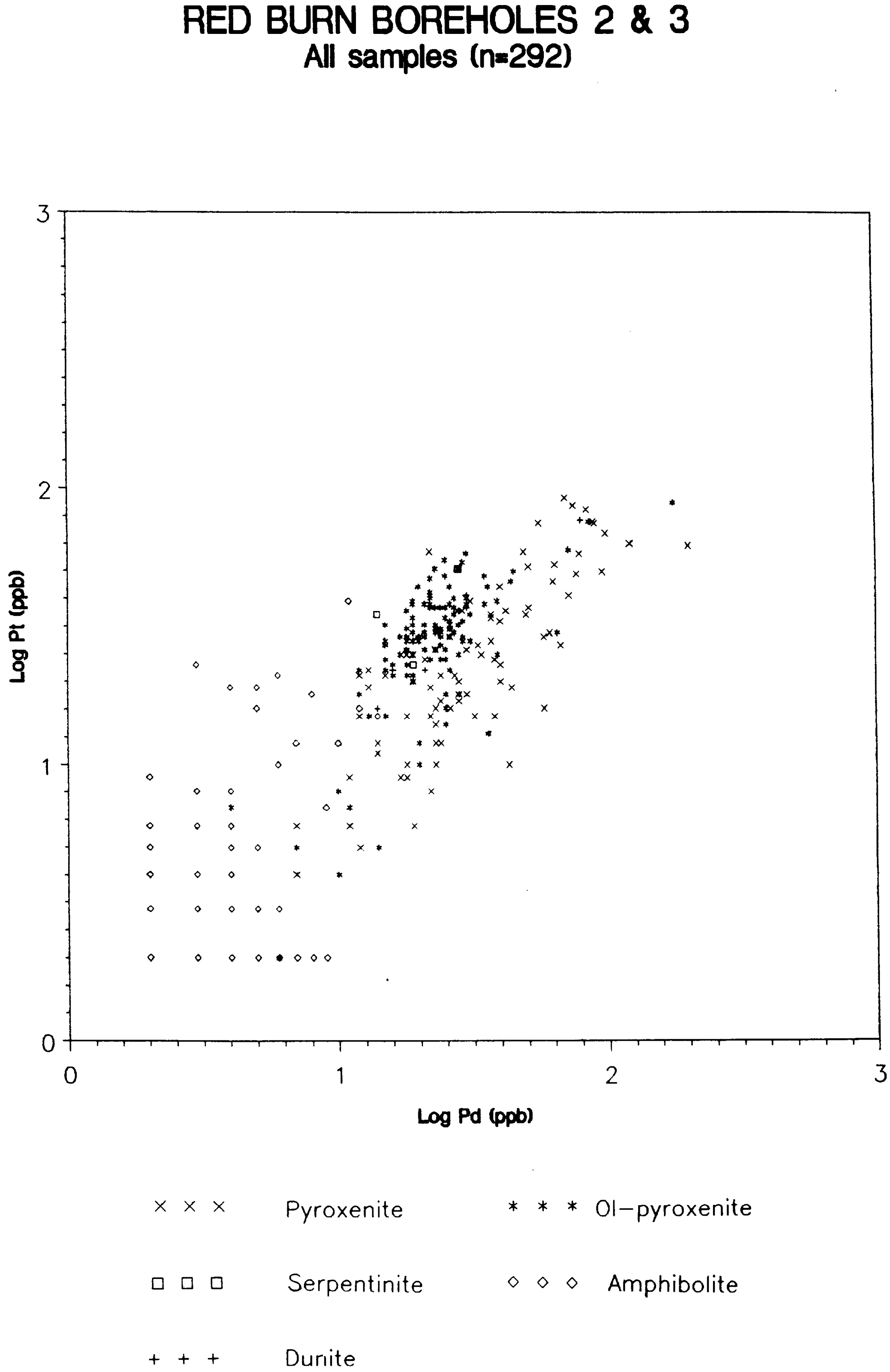

Figure 24 Relationship between Pt and Pd in samples from Red Burn boreholes 2 and 3

this interval, but did reveal a number of small gold grains (1 - 10 microns) occurring in cracks in clinopyroxene or tremolitic amphibole or included within amphibole in association with chalcopyrite and pyrite. These findings highlight the significance of the 'nugget effect' in searching for rare phases in thin sections. It would be necessary to scan many samples of this size in order to assess accurately the relative abundances, and controls on the distributions, of the phases of interest.

The second PGE-enriched interval occurs between 51 and 56 m. This section comprises pyroxenite and olivine pyroxenite with similar marked variation in modal mineralogy. It is also sheared and altered to greater or lesser degrees. In this section Pt/Pd is always less than 1, and in the most enriched sample (Pd 177 ppb, Pt 89 ppb) it is 0.5. Au, however, is not significantly enriched in this interval. The highest values of Pt and Pd are found within a highly sheared and serpentinised wehrlite containing minor pyrite and chalcopyrite. As with the other PGE-enriched section Cr levels are very low, but in contrast Ni and Mg remain at high 'magmatic' concentrations. Scanning on the microprobe of a section cut from the most PGE-rich sample revealed three small complex Pt-bearing grains, similar to those found in the Kelman Hill serpentinite. They comprise Pt-Cu alloy overgrowths on NiAs cores, one of which is enclosed within chalcopyrite. They are situated within a vein through serpentine in the wehrlite host rock. The mineral paragenesis, comparable to that found at Kelman Hill, suggests an origin related to processes of serpentinisation for the Pt-Cu assemblage. No Pd-bearing phases were located, again reflecting the importance of the 'nugget effect' at these low concentrations.

In borehole 2 only limited sampling of the amphibolites was undertaken, restricted to sections with enhanced sulphide or to zones immediately adjacent to ultramafic lithologies. The PGE distribution in this borehole is similar in many respects to that in borehole 3. The ultramafic rocks are generally enriched to around 30 ppb Pt with the same level of Pd. Some sections of pyroxenite have concentrations of 2 - 3 times this level. Pt/Pd remains close to 1, even in the most PGE-enriched intervals. In contrast to borehole 3 the most altered sections of pyroxenite are not especially enriched in PGE. The highest concentrations (up to 170 ppb Pt+Pd) are found in three intervals of fresh or amphibolitised pyroxenite, only locally sheared and with little late, low temperature alteration. Scanning on the microprobe revealed four small Pd-Sb minerals, with variable Pd/Sb, in one thin section from a depth of 36 m. Two of these grains are enclosed within amphibole, while the others are situated in cracks in amphibole. The setting of these grains and the minor low temperature alteration of the host rocks indicate that the Pd-Sb assemblage may be the product of higher temperature processes than those envisaged for the Pt-Cu mineralisation.

Analysis of volatile chalcophile trace elements (As, Sb, Bi, Se, Te and Ge) was carried out on a suite of ultramafic rocks, including the PGE-enriched samples, by hydride generation and ICP. This method (only partial for Ge) has detection limits of 200 ppb or better for the six elements determined. However no significant enrichments in any were reported and no correlation with the PGE is present. The elevated As concentrations found in the PGE-bearing fresh pyroxenite from around 143.5 m in borehole 2 were confirmed.

The sampling in boreholes 1 and 4 was restricted to the sections of pyroxenite and adjacent wallrocks encountered in these boreholes. In most cases the pyroxenites have similar enhanced backgound PGE levels, but no enrichments as high as those in borehole 3 were reported.

Discussion

A clear distinction between the mafic and ultramafic rocks in terms of their PGE contents has been established. Regardless of the primary proportions of olivine and clinopyroxene the mean levels of Pt and Pd are about 30 ppb with Pt/Pd near to 1 (Table 10). The higher Pt+Pd zones in little-altered clinopyroxenite in borehole 2 may represent an extreme manifestation of a primary magmatic enrichment or a high temperature remobilisation related to shearing..

Superimposed on this are the effects of later alteration and deformation events which have given rise to elevated PGE concentrations, commonly with an increased proportion of Pd relative to Pt. This is accompanied locally by associated enrichment in Au. These processes have taken place in rocks of widely varying olivine content, but have been especially important in the pyroxene-rich types. This accounts for the observed high PGE levels in the ultramafic types with relatively low Cr and Ni. Study of the PGE distribution at these concentrations is very difficult due to sub-sampling problems and to the difficulty of recognising PGM grains in thin section. The 'Turboscan' searching has greatly facilitated these studies, however, and the limited scanning undertaken has shown that secondary processes have been important in remobilising the PGE in some of the pyroxenites. Further detailed chemical and mineralogical studies are required to elucidate these processes and to separate original magmatic variation in the PGE from the effects of secondary processes.

CONCLUSIONS

These investigations have highlighted many of the problems inherent in PGE exploration. Commercial interest in these commodities is already at a high level and is likely to increase. The metallogenic models and exploration methodologies are lagging behind, however, and do not allow the definition and use of rigid criteria for the recognition of favourable targets. Important advances have nevertheless been made recently in the field of analytical technology which have led to the availability of high quality PGE analyses at reasonable cost.

The recent EGP mapping has been very useful in guiding exploration in the Upper Deveron Belt. The use of ground magnetic surveys has been valuable not only in the definition of favourable units on a regional scale, but also, in the Succoth - Brown Hill intrusion, in the selection of individual zones of high prospectivity.

The limitations of drainage and overburden sampling in locating sources of PGE or associated elements in this terrain have been demonstrated. Further orientation surveys are required to evaluate the application of these techniques in such environments.

The surveys described in this report have been successful in demonstrating enrichments in Pt and Pd in ultramafic intrusive rocks in two zones. Near Kelman Hill enhanced PGE levels are found in Cr-rich serpentinised dunites and peridotites. In the Red Burn area of the Succoth - Brown Hill intrusion clinopyroxene-bearing ultramafic rocks have been discovered with similarly high concentrations of Pt and Pd. In both areas a component of hydrothermal activity has been significant, but the mechanisms of such processes are poorly understood and further research is required.

There are major difficulties in studying PGE distributions at these low concentrations, due not only to the scarcity of discrete PGM grains but also due to the difficulty of recognising them in thin section. A new automated technique for scanning and analysing rare phases has been successfully employed in the study of the drillcore obtained in the course of these investigations. This represents a major advance in the technology available to study PGE distributions in rocks. It will be of considerable value in scientific studies relating to PGE mobility and concentration and will therefore contribute to improved exploration models for the PGE.

The surveys described in this report were not intended to be a complete and exhaustive assessment of the PGE potential of the Upper Deveron Belt. Rather they have focused on certain zones in the Belt where some favourability was indicated at an early stage. The potential of the ultramafic intrusive rocks in this Belt for the occurrence of PGE-bearing mineralisation has been demonstrated. Favourable targets meriting further attention are the marginal shear zones which bound many of the intrusive bodies. Particular attention should be directed towards the clinopyroxene-bearing varieties. Studies of the mafic-ultramafic volcanics of the Blackwater Formation however have not produced encouraging results. These units are not now regarded as favourable targets for the occurrence of PGE or Au mineralisation.

The PGE investigations have also provided much useful geological data regarding the mafic and ultramafic igneous rocks of this Belt. In particular, the investigations in the Red Burn area have yielded chemical, mineralogical and petrographic data which will assist in unravelling the petrogenesis and structural history of the Succoth - Brown Hill intrusion. Similarly the borehole sections through the volcanic rocks of the Blackwater Formation will promote our understanding of their genesis.

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APPENDIX: Summary tables of chemical data

Table 2 Summary statistics for panned drainage concentrates from the Upper Deveron Belt

Element		No Samples	Mean	Standard Deviation	Minimum	Maximum
Pt	(ppb)	21	3	2	1	10
Pd	(ppb)	21	1	1	1	5
Si	(ppm)	29	220054	30616	142715	270767
Al	(ppm)	29	46869	11689	30100	79879
Ti	(ppm)	29	24472	23178	3837	130151
Fe	(ppm)	29	126478	30272	76514	198210
Mg	(ppm)	29	36300	12019	12484	77619
Mn	(ppm)	29	4158	2061	1767	11610
Ca	(ppm)	29	40755	18816	10792	85907
P	(ppm)	27	550	424	87	2095
As	(ppm)	29	4	5	0	23
Ba	(ppm)	27	159	82	36	292
Cr	(ppm)	29	32187	36101	446	152415
Cu	(ppm)	29	32	8	17	46
Ni	(ppm)	29	423	358	47	1170
Pb	(ppm)	29	20	28	0	140
S	(ppm)	29	169	94	41	377
V	(ppm)	29	452	207	186	968
Zn	(ppm)	29	541	460	93	2218
Zr	(ppm)	29	304	187	133	1006

Table 3 Summary statistics for ultramafic intrusive rocks from the Upper Deveron Belt

Element		No Samples	Mean	Standard Deviation	Minimum	Maximum
Pt	(ppb)	45	20	26	1	127
Pd	(ppb)	45	15	20	1	65
Rh	(ppb)	17	4	3	2	12
Au	(ppb)	17	11	24	1	93
Si	(ppm)	45	212466	14344	186613	245409
Al	(ppm)	45	8484	8836	1587	45917
Ti	(ppm)	51	332	1127	0	7614
Fe	(ppm)	51	64523	14879	35949	96237
Mg	(ppm)	45	227268	54350	53133	293107
Na	(ppm)	43	314	848	0	5335
K	(ppm)	43	122	494	0	3237
Ca	(ppm)	51	24563	36506	0	146585
As	(ppm)	51	5	7	0	31
Ba	(ppm)	37	14	15	0	61
Cr	(ppm)	51	2387	836	48	4295
Cu	(ppm)	51	18	47	0	307
Ni	(ppm)	51	1760	1064	41	4249
Pb	(ppm)	51	4	3	0	17
S	(ppm)	45	500	483	67	1857
V	(ppm)	51	57	62	10	370
Zn	(ppm)	51	33	18	9	115
Zr	(ppm)	51	13	15	0	91
Sr	(ppm)	27	13	43	0	226

Table 4 Summary statistics for volcanic rocks and associated sills from the Upper Deveron Belt

Element		No Samples	Mean	Standard Deviation	Minimum	Maximum
Pt	(ppb)	10	2	3	1	10
Pd	(ppb)	10	3	3	2	10
Rh	(ppb)	9	2	0	2	2
Au	(ppb)	9	3	3	1	8
Si	(ppm)	8	217879	8024	204546	231025
Al	(ppm)	8	34180	9278	23593	50890
Ti	(ppm)	10	9631	5627	4976	20263
Fe	(ppm)	10	84587	8349	64275	97000
Mg	(ppm)	8	139286	47615	57596	197756
Na	(ppm)	8	3751	6347	0	18599
K	(ppm)	8	540	718	0	1992
Ca	(ppm)	10	53078	25420	18368	91767
As	(ppm)	10	2	2	0	4
Sb	(ppm)	10	7	20	0	64
Ba	(ppm)	10	80	74	0	210
Cr	(ppm)	10	1206	421	557	2146
Cu	(ppm)	10	56	17	32	84
Ni	(ppm)	10	986	360	290	1474
Pb	(ppm)	10	11	19	0	65
S	(ppm)	8	133	97	56	341
V	(ppm)	10	163	58	99	283
Zn	(ppm)	10	89	6	78	99
Zr	(ppm)	10	118	33	59	172
Sr	(ppm)	7	214	149	14	436

Table 5 Summary statistics for panned basal overburden samples from the Bridgend area

Element	No Samples	Mean	Standard Deviation	Minimum	Maximum
Pt (ppb)	91	8	10	2	60
Pd (ppb)	91	4	5	1	25
Si (ppm)	151	257966	29118	147152	318728
Al (ppm)	151	43881	9499	12696	68241
Ti (ppm)	151	21792	9933	2698	68403
Fe (ppm)	151	111753	27674	67072	213597
Mg (ppm)	151	43212	21979	19179	161209
Ca (ppm)	151	26133	8762	3073	69540
K (ppm)	97	7450	2853	2324	16519
Mn (ppm)	151	1652	564	820	4859
As (ppm)	151	7	6	0	49
Co (ppm)	151	106	50	33	284
Cr (ppm)	151	27926	18285	687	115297
Cu (ppm)	151	28	13	6	133
Ni (ppm)	151	668	477	60	3536
S (ppm)	151	141	124	49	1027
V (ppm)	151	302	112	138	853
Zr (ppm)	151	707	396	80	1898
Pt/Pd	91	4.92	6.81	0.08	35.00

Table 6 Summary statistics for ultramafic intrusive rocks from the Bridgend area

Element	No Samples	Mean	Standard Deviation	Minimum	Maximum
Pt (ppb)	9	9	5	2	15
Pd (ppb)	9	3	2	1	6
Rh (ppb)	4	2	0	2	2
Au (ppb)	4	13	19	1	41
Si (ppm)	13	213103	5533	203846	222152
Al (ppm)	13	7117	11732	2010	45917
Ti (ppm)	13	673	2090	0	7614
Fe (ppm)	13	65722	16168	36369	93300
Mg (ppm)	13	244780	59551	53133	290875
Na (ppm)	13	177	421	0	1556
K (ppm)	13	70	101	0	332
Ca (ppm)	13	12755	40246	643	146585
As (ppm)	13	7	6	0	20
Ba (ppm)	13	18	18	0	61
Cr (ppm)	13	1627	571	48	2605
Cu (ppm)	13	13	26	0	99
Ni (ppm)	13	2732	1068	41	4249
Pb (ppm)	13	5	2	3	11
S (ppm)	13	338	483	75	1498
V (ppm)	13	55	95	23	370
Zn (ppm)	13	32	10	9	49
Zr (ppm)	13	19	22	0	91
Sr (ppm)	11	23	67	0	226

Table 7 Summary statistics for Kelman Hill borehole 1 - all samples excluding lamprophyre

Element	No Samples	Mean	Standard Deviation	Minimum	Maximum
Pt (ppb)	153	2	1	1	11
Pd (ppb)	153	2	1	2	10
Rh (ppb)	153	2	0	2	5
Au (ppb)	153	7	17	1	150
Ti (ppm)	153	13572	3297	400	22610
Fe (ppm)	153	76041	14237	10200	103400
Ca (ppm)	153	69891	37171	3900	230800
Mn (ppm)	153	1204	277	100	1790
As (ppm)	153	0	1	0	9
Sb (ppm)	153	0	1	0	3
Ba (ppm)	153	110	46	9	234
Co (ppm)	153	51	14	5	112
Cr (ppm)	153	446	235	73	1700
Cu (ppm)	153	67	62	4	733
Ni (ppm)	153	215	142	10	1019
Pb (ppm)	153	6	6	0	38
V (ppm)	153	181	54	16	262
Zn (ppm)	153	94	27	3	325
Rb (ppm)	153	18	15	0	73
Sr (ppm)	153	253	122	5	696
Y (ppm)	153	17	4	1	33
Ag (ppm)	153	2	1	0	6
Zr (ppm)	153	170	40	1	270
La (ppm)	153	17	6	2	38
Ce (ppm)	153	19	12	0	71
Pt/Pd	153	0.77	0.41	0.33	2.00

Table 8 Summary statistics for Kelman Hill borehole 5

Element		No Samples	Mean	Standard Deviation	Minimum	Maximum
Ti	(ppm)	77	14249	3612	3420	22890
Fe	(ppm)	77	80471	16955	42500	163300
Ca	(ppm)	77	60478	34598	5700	194600
Mn	(ppm)	77	1337	272	850	2410
As	(ppm)	77	1	2	0	6
Sb	(ppm)	77	1	1	0	3
Ba	(ppm)	77	112	80	21	464
Co	(ppm)	77	55	18	14	107
Cr	(ppm)	77	476	323	63	1349
Cu	(ppm)	77	50	27	2	155
Ni	(ppm)	77	258	176	39	874
Pb	(ppm)	77	18	62	1	544
V	(ppm)	77	201	50	52	331
Zn	(ppm)	77	91	16	37	141
Rb	(ppm)	77	17	27	0	169
Sr	(ppm)	77	333	207	64	971
Y	(ppm)	77	18	3	8	23
Ag	(ppm)	77	2	1	0	4
Zr	(ppm)	77	183	39	45	253
La	(ppm)	77	17	6	5	35
Ce	(ppm)	77	18	9	0	36

Table 9 Summary statistics for serpentinites from Kelman Hill boreholes 2 and 3

Element	No Samples	Mean	Standard Deviation	Minimum	Maximum
Pt (ppb)	81	17	23	1	136
Pd (ppb)	81	17	24	2	140
Rh (ppb)	81	3	1	2	8
Au (ppb)	81	8	12	1	70
Ti (ppm)	81	185	790	0	6240
Fe (ppm)	81	67480	7642	42400	90800
Ca (ppm)	81	3991	9158	0	53200
Mn (ppm)	81	1452	513	630	4530
As (ppm)	81	0	1	0	4
Sb (ppm)	81	1	1	0	3
Ba (ppm)	81	13	26	0	196
Co (ppm)	81	139	25	17	162
Cr (ppm)	81	3712	1618	457	7736
Cu (ppm)	81	7	12	0	64
Ni (ppm)	81	1584	365	100	1980
Pb (ppm)	81	4	7	0	43
V (ppm)	81	29	50	8	308
Zn (ppm)	81	30	10	20	92
Rb (ppm)	81	1	4	0	26
Sr (ppm)	81	14	46	1	320
Y (ppm)	81	1	3	0	17
Ag (ppm)	81	0	1	0	3
Zr (ppm)	81	3	13	0	67
La (ppm)	81	1	3	0	18
Ce (ppm)	75	1	3	0	18
Pt/Pd	81	1.27	0.68	0.25	4.00

Table 10 Summary statistics for ultramafic rocks from Red Burn boreholes 2 and 3

Element	No Samples	Mean	Standard Deviation	Minimum	Maximum
Pt (ppb)	219	30	17	2	93
Pd (ppb)	219	31	24	4	201
Rh (ppb)	219	2	1	2	7
Au (ppb)	219	6	26	1	371
Ti (ppm)	219	271	289	30	2220
Fe (ppm)	219	70526	20049	36800	145000
Mg (ppm)	219	144519	37321	25244	220885
Ca (ppm)	219	55266	29395	1100	117000
Mn (ppm)	219	1266	238	850	2080
As (ppm)	219	2	5	0	59
Sb (ppm)	219	2	3	0	13
Ba (ppm)	219	33	109	4	1330
Co (ppm)	219	99	38	43	187
Cr (ppm)	219	2513	1135	92	5406
Cu (ppm)	219	32	59	0	580
Ni (ppm)	219	549	246	54	1034
Pb (ppm)	219	2	2	0	8
V (ppm)	219	120	60	44	522
Zn (ppm)	219	36	9	18	74
Rb (ppm)	219	1	3	0	46
Sr (ppm)	219	19	25	3	190
Y (ppm)	219	1	2	0	6
Ag (ppm)	219	3	2	0	8
Zr (ppm)	219	1	1	0	8
Ni/Mg(*)	219	3.64	0.94	0.93	6.75
Pt/Pd	219	1.12	0.48	0.23	2.68

Note: * = x 1000

Table 11 Summary statistics for amphibolites from Red Burn boreholes 2 and 3

Element	No Samples	Mean	Standard Deviation	Minimum	Maximum
Pt (ppb)	73	6	7	2	39
Pd (ppb)	73	4	3	2	14
Rh (ppb)	73	2	0	2	2
Au (ppb)	73	3	4	1	19
Ti (ppm)	73	2535	2161	260	7770
Fe (ppm)	73	79800	20633	42000	122100
Mg (ppm)	73	43572	12497	18933	75732
Ca (ppm)	73	75367	14216	47300	133200
Mn (ppm)	73	1237	247	750	1990
As (ppm)	73	1	1	0	9
Sb (ppm)	73	1	3	0	13
Ba (ppm)	73	151	155	28	941
Co (ppm)	73	47	10	33	84
Cr (ppm)	73	165	159	23	842
Cu (ppm)	73	86	111	0	675
Ni (ppm)	73	56	55	0	295
Pb (ppm)	73	2	2	0	8
V (ppm)	73	315	201	109	1018
Zn (ppm)	73	59	19	26	112
Rb (ppm)	73	2	4	0	27
Sr (ppm)	73	223	80	44	413
Y (ppm)	73	7	10	0	32
Ag (ppm)	73	3	2	0	6
Zr (ppm)	73	15	25	0	82
Ni/Mg(*)	73	1.19	1.21	0.00	9.35
Pt/Pd	73	1.43	1.20	0.22	7.67

Note: * = x 1000