Natural Environment Research Council
Institute of Geological Sciences

# Mineral Reconnaissance Programme Report

*A report prepared for the Department of Industry*

This report relates to work carried out by the Institute of Geological Sciences on behalf of the Department of Industry. The information contained herein must not be published without reference to the Director, Institute of Geological Sciences

D. Ostle
Programme Manager
Institute of Geological Sciences
Keyworth,
Nottingham NG12 5GG

# No. 58

# Investigations of small intrusions in southern Scotland

INSTITUTE OF GEOLOGICAL SCIENCES

Natural Environment Research Council

Mineral Reconnaissance Programme

Report No. 58

# Investigations of small intrusions in southern Scotland

*Geochemistry*
D. C. Cooper, BSc, PhD

*Geophysics*
M. E. Parker, BA

*Geology*
P. M. Allen, BSc, PhD



London 1982

*A report prepared for the Department of Industry*

**Mineral Reconnaissance Programme Reports**




The Institute of Geological Sciences was formed by the incorporation of the Geological Survey of Great Britain and the Geological Museum with Overseas Geological Surveys and is a constituent body of the Natural Environment Research Council

*Bibliographical reference*
Copper, D. C. and others. 1982. Investigations of small intrusions in southern Scotland. *Mineral Reconnaissance Programme Rep. Inst. Geol. Sci.*, No. 58

Photocopied in England for the Institute of Geological Sciences by Four Point Printing

CONTENTS



FIGURES



TABLES

## SUMMARY

Sixteen small intrusions and one mineral occurrence were examined briefly for indications of disseminated mineralisation. Stream sediment and panned concentrate samples were collected from streams crossing some of the intrusions to supplement existing coverage, and geophysical surveys were conducted over Priestlaw, Cockburn Law and Lamberton Moor. Rock samples collected at some of the localities were analysed for major and trace elements.

The intrusive rocks range in composition from granite to diorite and in grain size from hypabyssal to plutonic types. The larger intrusions at Portencorkrie, Priestlaw and Cockburn Law are zoned. Hydrothermal alteration, in places with associated pyrite, was recorded at Mains of Dhuloch, Mochrum, Priesthope, Lamberton Moor, Broad Law, Glenluce, Priestlaw, Cockburn Law and Mull of Galloway, and significant copper enrichment was recorded at the last four of these. It is concluded, however, that in no case is there a likelihood of there being porphyry copper style mineralisation at or near surface. An old copper mine at Tonderghie (Burrow Head) worked a vein system along a fault within Silurian sedimentary rocks.


## INTRODUCTION

Following the recognition of porphyry-style disseminated copper mineralisation at Black Stockarton Moor (Brown, M. J. and others, 1979) a desk study was made of information on small intrusions in Southern Scotland to try to identify similar occurrences. The most likely targets were considered to be intrusions or intrusive complexes mapped as granodiorite, diorite, or porphyrite associated with minor aeromagnetic anomalies. However, other intrusives, mostly mapped as granite and felsite, were also considered, particularly those having some record of alteration or sulphide mineralisation.

Reconnaissance geochemical survey data were available across parts of the area but limited weight was placed on this evidence because in most places the surface exposure of the target was small when compared with the sampling density. Available data covered the following areas:

i Loch Doon and Glenkens (Dawson and others, 1977).
ii Criffel–Dalbeattie granodiorite complex and its environs (Leake and others, 1978a).
iii Cairnsmore of Fleet granite and its environs (Leake and others, 1978b).
iv Leadhills (Gallagher and others, 1971).
v Peebles (Dr J. S. Coats, pers. comm.).
vi North-east Borders and Cheviot (Haslam, 1973, 1975; Mr R. T. Smith, pers. comm.).

The majority of the targets identified by the desk study were investigated briefly on the ground for signs of the alteration and mineralisation typically associated with porphyry style copper deposits. The localities studied are shown on Figure 1 and their positions with respect to aeromagnetic anomalies (Institute of Geological Sciences, 1972) illustrated on Figure 2. Some rock samples and panned concentrates were taken for chemical analysis and reconnaissance geophysical surveys were carried out across the intrusions at Cockburn Law, Priestlaw and Lamberton Moor. The results of these investigations are presented in this report. More detailed work was subsequently carried out across two of the intrusions (at Cairngarroch and Culvennan) and these form the subjects of separate reports (Allen and others, 1981; Parker and others, 1981). In addition to the small intrusions a copper occurrence near Burrow Head, known as Tonderghie, was also examined briefly, and the results are included below.

## MAINS OF DHULOCH [NW 995 665]

This intrusion is depicted as porphyrite on the Geological Survey of Scotland (Stranraer) sheet number 3. It has an elongate form and crops for a length of about 1.5 km parallel to the strike of vertical or steeply dipping cleaved greywacke and grey siltstone of Ordovician age. Exposure is moderately good over the intrusion, but the area in general is covered by thick drumlinoid drift. In most outcrops the rock is deeply weathered.

The rock (S64450)* is pink, porphyritic quartz-microdiorite and is heavily altered. Phenocrysts of plagioclase are albitised and altered to muscovite; biotite is replaced by calcite and muscovite and chlorite/muscovite. Quartz

*These numbers refer to specimens held in the collection of Petrology Unit, IGS.

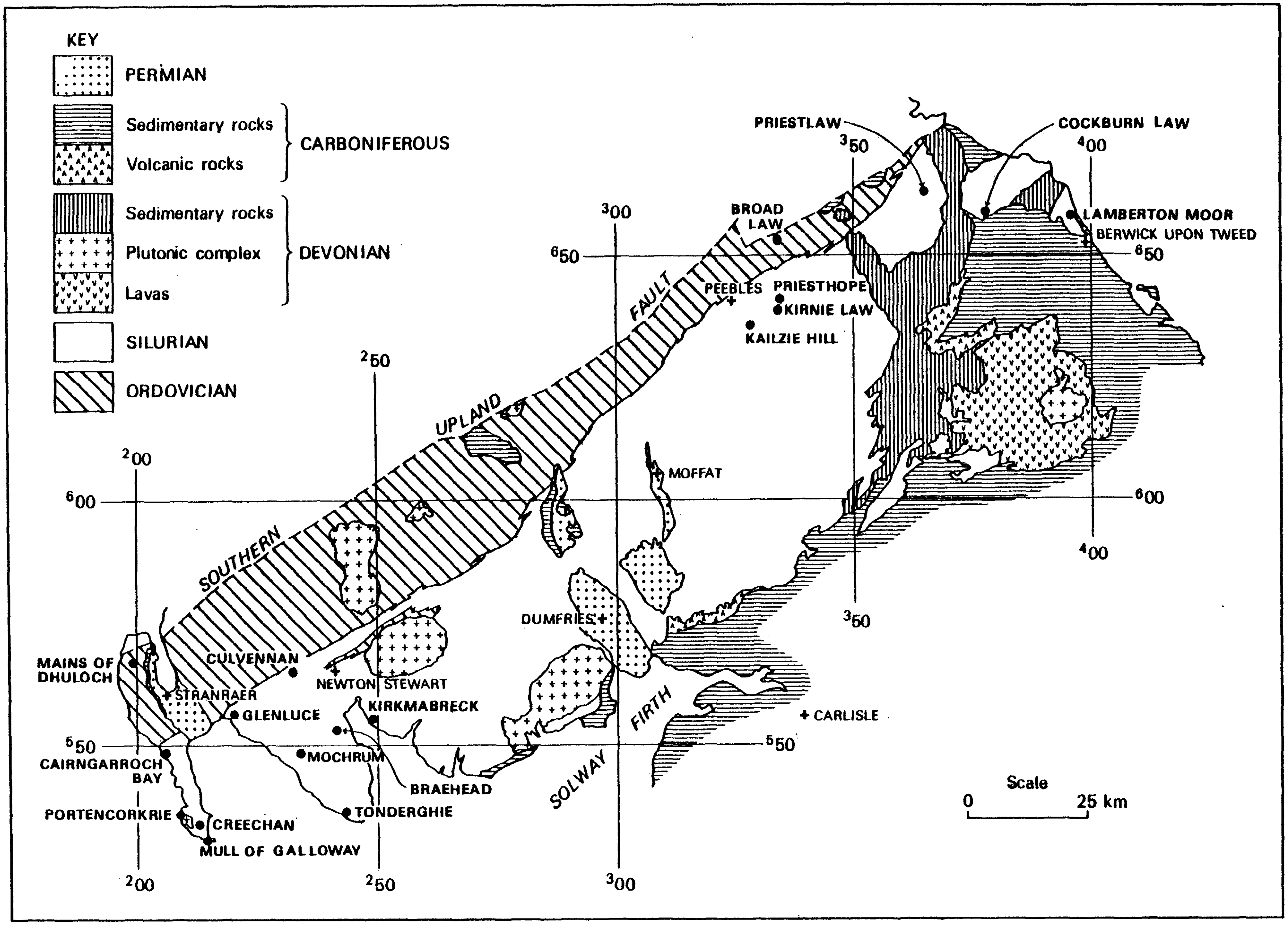



Figure 1: Locality of small intrusions and other localities investigated

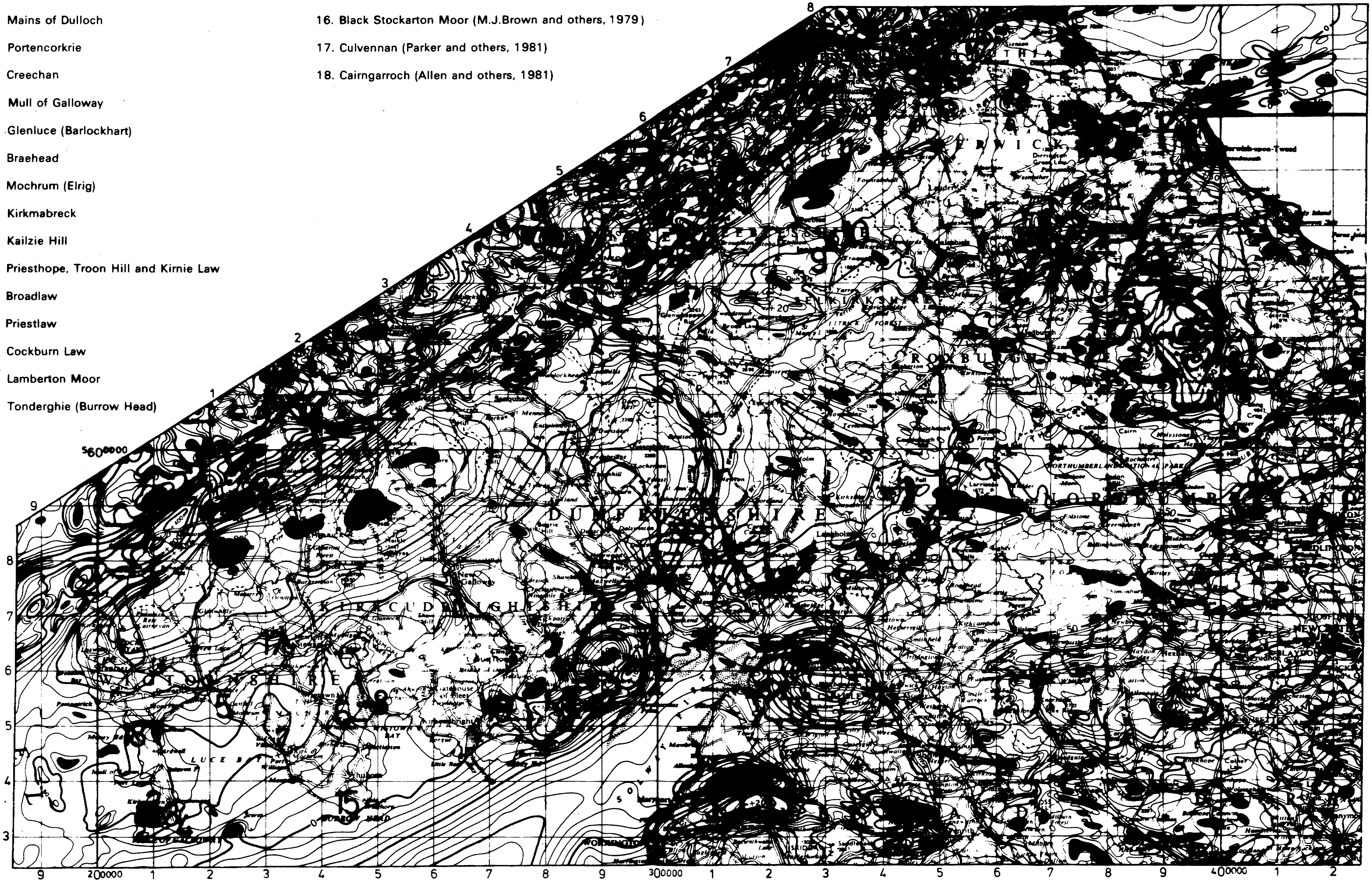
Figure 2: Aeromagnetic map of Southern Scotland showing the localities mentioned in the text.

Localities covered in this report.

1. Mains of Dulloch
2. Portencorkrie
3. Creechan
4. Mull of Galloway
5. Glenluce (Barlockhart)
6. Braehead
7. Mochrum (Elrig)
8. Kirkmabreck
9. Kailzie Hill
10. Priesthope, Troon Hill and Kirnie Law
11. Broadlaw
12. Priestlaw
13. Cockburn Law
14. Lamberton Moor
15. Tonderghie (Burrow Head)

Other localities reported elsewhere

16. Black Stockarton Moor (M.J.Brown and others, 1979)
17. Culvennan (Parker and others, 1981)
18. Cairngarroch (Allen and others, 1981)



phenocrysts are rare. The groundmass of stubby plagioclase, quartz and ?potash feldspar is patchily altered to calcite and muscovite with traces of chlorite. There is a small amount of pyrite in the rock. Its colour is probably attributable to goethite and hematite.

## PORTENCORKRIE [NX 100 350]

This area is largely drift-covered but exposure is excellent along the coast. A full description of the complex, which is zoned and consists of an outer diorite zone and an inner, younger body of adamellite, is provided by Holgate (1943). A strong aeromagnetic anomaly, oval in shape, measuring about 5 km X 4 km, elongated east-west and reaching a maximum of 110 nT is located over the intrusion.

A brief examination of parts of the complex revealed no sign of pervasive hydrothermal alteration and minimal megascopically visible pyrite in the rocks. There are minor quartz veins throughout. Near Laggantalluch Head, close to the northern contact, a vein system can be traced along a north-south strike for about 400 m. The vein system, which slickensiding suggests follows a fault zone, is about 60 m wide and consists of quartz with chalcedony, calcite, epidote and sparsely disseminated sulphides which include pyrite, chalcopyrite and galena. Two samples of the vein analysed for Cu, Pb, Zn and Ag yielded maxima of 1.1% Cu and 0.07% Pb. Minor enrichment of pyrite in the wall rock was noticed but no other signs of mineralisation were recognised.

## CREECHAN [NX 130 341]

A small intrusion mapped as porphyrite is poorly exposed in a roadside quarry. A sample (Table 1, No. 1) showed only slight alteration and contained phenocrysts of labradorite and augite, marginally altered to hornblende, in a ground mass of andesine, quartz, orthoclase, biotite, chlorite, hornblende, magnetite and ilmenite. No sulphides were seen. The chemistry of the sample shows no outstanding features.

## MULL OF GALLOWAY [NX 143 309]

An intrusion mapped as porphyrite emplaced within greywacke is exposed in East and West Tarbet bays. The igneous rocks, perhaps consisting of more than one discordant intrusion, are intensely altered, iron-stained, and sheared, so that the original lithologies are difficult to determine. The intrusives are probably microdiorite or quartz-microdiorite but little plagioclase survives, the rock consisting mainly of quartz, carbonate, sericite and chlorite with accessory apatite. Disseminated pyrite is common and, rarely, is accompanied by chalcopyrite. Locally, green copper secondaries are visible on outcrop. Quartz, carbonate, and, rarely, baryte and pyrite occur in veinlets and fracture fillings. Occasional wider (c. 20 cm) veins of quartz with copper secondary minerals, galena and ?sphalerite are also present. The greywacke sequence is also iron-stained in the West Bay and samples taken marginal to the intrusions are similarly intensely altered and veined, consisting of quartz, carbonate, sericite and chlorite. On the north side of the West Bay the sedimentary rocks are highly contorted.

An analysed sample of a small baryte vein showed, in addition to Ba, elevated levels of Sr, Cu and Mo (Table 2, No. 7). Trace element analyses of altered intrusives (Table 2, Nos. 3–6) indicate a patchy enrichment in Cu, As and Ba, a phenomenon found associated with other small intrusives in the area, for instance Cairngarroch Bay (Allen and others, 1981). Major element analyses (Table 1, Nos. 7–9) suggest a relatively basic composition and reflect the intense alteration suffered by these rocks, with low Si and Al and high P being particular features when compared with average values for diorites, tonalites and less altered intrusives from Southern Scotland. A Rb v Ba v Sr plot (following El Bouseily and El Sokkary, 1976) suggests that Ba is enriched in some of the intrusive rocks as has been found elsewhere in Southern Scotland (e.g. Allen and others, 1981). Two features not found in other small intrusions sampled are the relatively high $P_2O_5$ levels and low K/Rb ratios (130–220). Both may be the product of alteration and, if so, suggest a slightly different style or more intense form of alteration here. The greywacke analyses (Table 2, Nos. 1–2) are broadly similar to those of Culvennan (Parker and others, 1981) and Cairngarroch (Allen and others, 1981) except for a high Ca content, again reflecting veining and alteration. No substantial enrichment in chalcophile elements is evident.

## GLENLUCE (BARLOCKHART) [NX 204 560]

An L-shaped outcrop of mainly dioritic rocks of Lower Old Red Sandstone age emplaced within folded Silurian sedimentary rocks is shown south of Glenluce on the Geological Survey of Scotland Sheet 4W. The aeromagnetic map (Figure 2) suggests that a weak anomaly of about 10 nT and covering about 4 km$^2$ may coincide with the intrusion. The latter is apparently conformable with bedding at the western end but in general it is poorly exposed, and field study suggests that the L-shaped form is based on topographic

**Table 1** Analyses of rocks from small intermediate intrusions in south-west Scotland

| *No. & rock type* | *Grid reference* | *$SiO_2$* | *$Al_2O_3$* | *$TiO_2$* | *$Fe_2O_3$ (total)* | *MgO* | *CaO* | *$Na_2O$* | *$K_2O$* | *$P_2O_5$* |
|---|---|---|---|---|---|---|---|---|---|---|
| Creechan | | | | | | | | | | |
| 1 Porph. microtonalite | NX 130 341 | 57.14 | 16.43 | 0.64 | 6.03 | 4.22 | 4.62 | 4.33 | 2.43 | 0.22 |
| Braehead | | | | | | | | | | |
| 2 Quartz-microdiorite* | NX 417 526 | 60.13 | 14.97 | 0.75 | 6.01 | 4.70 | 5.01 | 4.18 | 2.13 | 0.22 |
| Glenluce | | | | | | | | | | |
| 3 Microdiorite† | NX 214 569 | 52.23 | 13.04 | 0.77 | 6.25 | 5.53 | 8.62 | 0.82 | 3.29 | 0.41 |
| 4 ? diorite† | NX 214 569 | 59.52 | 15.75 | 0.43 | 4.54 | 2.85 | 5.46 | 3.68 | 2.70 | 0.20 |
| 5 ? diorite† | NX 214 569 | 53.12 | 16.18 | 0.74 | 7.27 | 4.06 | 6.10 | 4.03 | 3.57 | 0.19 |
| 6 Microdiorite† | NX 214 569 | 52.35 | 12.43 | 0.59 | 5.37 | 4.61 | 10.01 | 2.77 | 2.32 | 0.35 |
| Mull of Galloway | | | | | | | | | | |
| 7 ? Microdiorite† | NX 140 308 | 50.00 | 12.54 | 0.86 | 7.77 | 6.78 | 7.43 | 3.53 | 1.34 | 0.44 |
| 8 ? Microdiorite† | NX 140 308 | 44.91 | 11.10 | 1.08 | 7.81 | 7.09 | 9.33 | 2.84 | 0.96 | 1.32 |
| 9 ? Microdiorite† | NX 140 308 | 46.15 | 11.23 | 1.08 | 8.04 | 4.93 | 10.33 | 2.23 | 1.89 | 1.31 |
| Culvennan | | | | | | | | | | |
| 10 Microtonalite | NX 313 645 | 61.64 | 14.83 | 0.59 | 5.47 | 3.87 | 3.49 | 4.59 | 2.20 | 0.14 |
| 11 Microgranodiorite | NX 315 643 | 64.69 | 15.49 | 0.56 | 4.54 | 2.45 | 3.20 | 4.63 | 2.96 | 0.14 |
| 12 Microgranodiorite | NX 316 642 | 65.02 | 15.71 | 0.64 | 5.34 | 2.34 | 3.18 | 4.55 | 2.54 | 0.16 |
| 13 Microtonalite | NX 312 649 | 62.36 | 15.49 | 0.66 | 5.44 | 3.52 | 3.84 | 4.34 | 2.60 | 0.16 |
| 14 Microtonalite | NX 311 649 | 61.31 | 15.31 | 0.63 | 5.34 | 3.31 | 3.89 | 4.21 | 2.86 | 0.16 |
| 15 Microgranodiorite | NX 310 651 | 61.22 | 14.77 | 0.58 | 5.09 | 3.36 | 4.21 | 4.20 | 2.66 | 0.15 |
| 16 Diorite | NX 328 655 | 55.32 | 16.38 | 1.03 | 7.39 | 4.71 | 6.23 | 4.25 | 2.43 | 0.23 |
| Cairngarroch | | | | | | | | | | |
| 17 Quartz-microdiorite | NX 051 492 | 53.76 | 15.18 | 0.93 | 7.82 | 5.57 | 6.46 | 3.88 | 1.39 | 0.20 |
| 18 Quartz-microdiorite | NX 052 493 | 57.04 | 17.30 | 0.93 | 6.95 | 3.62 | 5.21 | 4.44 | 1.98 | 0.22 |
| 19 Microtonalite | NX 044 496 | 57.51 | 16.78 | 0.81 | 6.57 | 3.30 | 5.51 | 4.02 | 2.12 | 0.19 |
| 20 Microtonalite | NX 044 495 | 57.55 | 17.83 | 0.78 | 6.84 | 2.99 | 2.58 | 4.47 | 1.86 | 0.18 |
| 21 Microtonalite | NX 044 495 | 58.98 | 17.15 | 0.81 | 5.61 | 2.68 | 5.28 | 4.53 | 1.87 | 0.21 |
| 22 Granodiorite | NX 044 495 | 59.54 | 15.84 | 0.74 | 5.91 | 3.06 | 3.30 | 4.11 | 2.73 | 0.19 |
| 23 Granodiorite | NX 045 495 | 61.33 | 15.53 | 0.67 | 4.89 | 2.55 | 4.21 | 4.06 | 2.98 | 0.17 |
| 24 Granodiorite | NX 045 494 | 60.32 | 15.45 | 0.68 | 4.68 | 2.57 | 4.30 | 4.21 | 3.37 | 0.17 |
| 25 Granodiorite | NX 045 494 | 61.17 | 15.52 | 0.64 | 4.49 | 2.60 | 4.22 | 4.05 | 3.33 | 0.17 |

| *No.* | *Ni* | *Mn* | *Cu* | *Pb* | *Zn* | *As* | *Mo* | *Ba* | *Rb* | *Sr* | *Y* | *Ce* | *Zr* | *Th* | *U* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 37 | 670 | 14 | <13 | 57 | 3 | <2 | 873 | 65 | 935 | 18 | 36 | 170 | 6 | <4 |
| 2 | 104 | 500 | <6 | <13 | 60 | 8 | 3 | 663 | 63 | 465 | 17 | 30 | 202 | 8 | <4 |
| 3 | 60 | 900 | 135 | <13 | 59 | 1019 | <2 | 682 | 110 | 673 | 19 | 92 | 243 | 9 | <4 |
| 4 | 21 | 570 | 27 | 19 | 55 | 44 | <2 | 954 | 72 | 1039 | 14 | 32 | 178 | 5 | <4 |
| 5 | 9 | 710 | 14 | <13 | 75 | 7 | <2 | 920 | 109 | 776 | 18 | 26 | 132 | <4 | <4 |
| 6 | 53 | 790 | 12 | 35 | 64 | 37 | 2 | 737 | 74 | 1750 | 14 | 67 | 230 | 7 | <4 |
| 7 | 126 | 860 | 29 | <13 | 64 | 9 | <2 | 904 | 48 | 273 | 20 | 57 | 202 | 9 | <4 |
| 8 | 138 | 1130 | 287 | 14 | 61 | 49 | <2 | 1330 | 39 | 764 | 21 | 30 | 186 | 10 | 4 |
| 9 | 134 | 1150 | <6 | 18 | 20 | 24 | <2 | 2790 | 117 | 319 | 19 | <21 | 173 | 9 | 5 |
| 10 | 72 | 580 | <6 | <13 | 48 | 15 | <2 | 679 | 63 | 388 | 16 | <21 | 163 | 8 | <4 |
| 11 | 22 | 400 | 30 | <13 | 33 | 12 | <2 | 978 | 90 | 489 | 22 | 44 | 245 | 16 | 6 |
| 12 | 24 | 390 | 60 | <13 | 39 | 6 | <2 | 876 | 94 | 537 | 24 | 44 | 275 | 16 | 6 |
| 13 | 18 | 690 | 26 | <13 | 49 | 13 | <2 | 641 | 95 | 484 | 20 | 52 | 190 | 13 | 6 |
| 14 | 25 | 670 | <6 | <13 | 55 | 9 | 5 | 701 | 106 | 450 | 21 | 38 | 202 | 15 | 5 |
| 15 | 49 | 530 | 9 | 13 | 57 | 7 | <2 | 603 | 94 | 432 | 19 | 41 | 208 | 15 | 5 |
| 16 | 58 | 820 | 93 | 17 | 79 | 6 | <2 | 805 | 50 | 697 | 24 | 31 | 182 | 7 | <4 |
| 17 | 77 | 720 | 26 | 19 | 76 | 6 | 2 | 413 | 50 | 590 | 21 | 30 | 158 | 4 | <4 |
| 18 | 12 | 620 | 54 | <13 | 63 | 5 | 4 | 763 | 60 | 676 | 20 | 25 | 122 | 5 | <4 |
| 19 | 11 | 580 | 110 | <13 | 47 | 89 | 8 | 672 | 82 | 869 | 18 | 34 | 152 | 5 | <4 |
| 20 | 12 | 460 | 150 | <13 | 49 | 49 | 9 | 945 | 65 | 656 | 18 | 35 | 153 | 6 | <4 |
| 21 | 10 | 570 | 42 | 14 | 67 | 21 | 3 | 625 | 62 | 717 | 17 | 41 | 145 | 7 | <4 |
| 22 | 24 | 280 | 144 | <13 | 27 | 20 | 4 | 810 | 98 | 543 | 19 | 52 | 217 | 12 | <4 |
| 23 | 21 | 200 | 241 | <13 | 25 | 7 | 23 | 824 | 112 | 576 | 16 | 49 | 205 | 11 | <4 |
| 24 | 25 | 250 | 201 | <13 | 24 | 8 | <2 | 947 | 101 | 601 | 19 | 63 | 232 | 12 | <4 |
| 25 | 23 | 310 | 38 | <13 | 26 | 9 | 3 | 860 | 79 | 666 | 19 | 40 | 219 | 14 | <4 |

Major elements in per cent, trace elements in ppm.

* Moderate alteration

† Intense alteration

Major element analyses by Betaprobe, trace elements by XRF, following methods described elsewhere (e.g. Allen and others, 1981).

**Table 2** Partial analyses of rock samples from the Mull of Galloway

| *No.* | *Rock type* | *Grid reference* | *Ti* | *Ni* | *Mn* | *Fe* | *Cu* | *Pb* | *Zn* | *As* | *Mo* | *Ba* | *Sr* | *Ca* | *Zr* | *Th* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Veined, altered | NX 140 309 | 4080 | 44 | 530 | 43200 | 30 | <13 | 51 | 20 | <2 | 841 | 206 | 50800 | 271 | 9 |
| 2 | ?greywacke | NX 145 309 | 3540 | 42 | 530 | 39700 | 95 | 14 | 46 | 10 | <2 | 605 | 401 | 38800 | 183 | 9 |
| 3 | Intensely altered rock, ?micro-diorite | NX 140 308 | 5490 | 135 | 930 | 44100 | 202 | <13 | 36 | 12 | 3 | 325 | 358 | 57800 | 123 | 4 |
| 4 | Intensely altered | NX 140 308 | 5950 | 126 | 860 | 62800 | 29 | <13 | 64 | 9 | <2 | 904 | 273 | 40000 | 202 | 9 |
| 5 | intrusive, ?micro- | NX 140 308 | 6910 | 138 | 1130 | 60600 | 287 | 14 | 61 | 49 | <2 | 1330 | 764 | 52200 | 186 | 10 |
| 6 | diorite | NX 140 308 | 6410 | 134 | 1150 | 59400 | <6 | 18 | 20 | 24 | <2 | 2790 | 319 | 57100 | 173 | 9 |
| 7 | Baryte vein | NX 140 308 | 1110 | 12 | 100 | 720 | 330 | <13 | <3 | <3 | 14 | 390000 | 5200 | 170 | 151 | 7 |

All results in ppm. U was also determined, but all results were ≤5 ppm.

Analyses by XRF, described in detail elsewhere (e.g. Parker and others, 1981).

**Table 3** Analyses of panned concentrates collected during the survey from streams crossing small intrusions in southern Scotland

| *Sample site* | *Intrusion* | *Ti* | *Ni* | *Mn* | *Fe* | *Cu* | *Pb* | *Zn* | *Sb* | *Sn* | *Ba* | *Ca* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NX 334 473 | Mochrum | 8250 | 19 | 300 | 27200 | 35 | 17 | 64 | <11 | <9 | 193 | 1160 |
| NX 337 478 | Mochrum | 9130 | 22 | 370 | 37500 | 34 | 202 | 78 | <11 | 35 | 194 | 1210 |
| NX 493 568 | Kirkmabreck | 3440 | 23 | 2200 | 29000 | <6 | 20 | 61 | <11 | <9 | 293 | 3610 |
| NX 498 571 | Kirkmabreck | 3030 | 13 | 1690 | 19800 | <6 | 19 | 89 | <11 | <9 | 193 | 2130 |
| NX 491 550 | Carsluith | 4350 | 21 | 6340 | 37200 | 11 | 60 | 96 | <11 | 32 | 245 | 3880 |
| NT 644 626 | Priestlaw | 7480 | 48 | 560 | 69400 | 10 | 29 | 149 | 13 | <9 | 7540 | 970 |
| NT 645 631 | Priestlaw | 7090 | 50 | 480 | 103400 | 9 | 34 | 101 | <11 | <9 | 4670 | 1540 |
| NT 778 593 | Cockburnlaw | 28800 | 93 | 2840 | 285900 | <6 | 177 | 204 | 45 | 50 | 3960 | 2250 |
| NT 772 589 | Cockburnlaw | 15200 | 86 | 1910 | 293900 | – | 155 | 142 | 207 | 89 | 3820 | 1960 |
| NT 951 572 | Lamberton Moor | 31900 | 34 | 760 | 124000 | 29 | 52 | 144 | <11 | <9 | 482 | 2700 |

Analyses by XRF. Sample collection, preparation and analysis described in detail elsewhere (e.g. Leake and others, 1978a).

**Table 4** Partial analyses of rocks from Tonderghie, Burrow Head

| *No.* | *Rock type* | *Grid reference* | *Ti* | *Ni* | *Mn* | *Fe* | *Cu* | *Zn* | *As* | *Mo* | *Ba* | *Sr* | *Ca* | *Zr* | *Th* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Altered greywacke | NX 441 346 | 4110 | 33 | 650 | 45100 | 13 | 39 | 368 | <2 | 381 | 79 | 45500 | 229 | 10 |
| 2 | Altered, veined (60°) greywacke | NX 441 346 | 2340 | 15 | 1630 | 41600 | 20 | 15 | <3 | <2 | 100 | 52 | 97500 | 71 | 5 |
| 3 | Altered, veined (60°) greywacke | NX 441 346 | 2120 | 19 | 1170 | 32100 | 92 | 29 | <3 | <2 | 79 | 65 | 80200 | 128 | 6 |
| 4 | Altered siltstone in fault breccia (120°) | NX 441 346 | 4410 | 18 | 1000 | 36500 | 60 | 19 | 3 | 3 | 136 | 58 | 53100 | 216 | 9 |
| 5 | Quartz vein (120°) | NX 441 346 | 1660 | 6 | 400 | 14900 | 295 | 3 | 6 | <2 | 2810 | 233 | 27500 | 63 | <4 |
| 6 | Quartz vein (120°) with minor sulphides | NX 441 346 | 330 | <5 | 150 | 7900 | 1080 | <3 | 3 | <2 | 8780 | 584 | 1800 | 21 | <4 |
| 7 | Mine tip sample | NX 438 348 | 1080 | 169 | 340 | 38800 | >10000 | – | 581 | 3 | 182 | 39 | 5400 | 46 | 10 |

All results in ppm. U and Pb were also determined, but all results were ≤4 ppm and ≤13 ppm respectively.

Analyses by XRF, following methods described elsewhere (e.g. Parker and others, 1981).

features. It is a complex intrusion. A sample from NX 2045 5590 contains olivine phenocrysts with a reaction rim of pyroxene which in turn appears to be rimmed by biotite. Another sample from NX 1984 5588 (S64453) is a hornblende-diorite. Neither sample is altered or mineralised.

Adjacent to the large mapped aureole of the intrusion a roadside quarry [NX 214 569] exposes an unmapped intrusion in greywacke which may represent an offshoot of the main body. The rock here is highly altered, consisting mainly of sericite, chlorite, carbonate and a little quartz. Some of the chlorite is after biotite and remnant sodic plagioclase can be recognised. Sparsely disseminated pyrite is common, arsenopyrite and chalcopyrite rare. Quartz-carbonate veins and pyritic veinlets are also present. The greywacke and shale sequence is disrupted by small faults with quartz and carbonate veins which carry minor disseminated pyrite and a trace of chalcopyrite. Partial trace element analyses (Cu, Pb, Zn) of four veined sedimentary rocks showed Cu enrichment (145 and 335 ppm Cu) in two of them. Analyses of the intrusive rocks (Table 1, Nos. 3–6) reflect the intense alteration, with low $SiO_2$ and $Al_2O_3$ and high CaO, $K_2O$ and MgO in some samples compared with average diorites and tonalites. Trace element chemistry also reflects the alteration and patchy mineralisation, with one sample containing high Cu and As levels and another high Sr; but otherwise trace element contents are similar to less altered intermediate rocks.

## BRAEHEAD [NX 418 526]

A small area around a road junction between the A714 and A746 is shown on the Geological Survey of Scotland sheet 4E, to comprise porphyrite. There is very little exposure. One specimen from a roadside outcrop at the road junction consists of non-porphyritic microtonalite, which is fresh and free from signs of secondary alteration and mineralisation. A second sample of quartz-microdiorite is somewhat altered with primary ferromagnesian minerals replaced by secondary amphibole. Some of the pseudomorphs are rimmed with biotite. The analysis of this rock (Table 1, No. 2) shows no unusual features.

## MOCHRUM (ELRIG) [NX 335 478]

Centred nearly 2 km north-west of Mochrum an irregular area of approximately 0.75 $km^2$ is shown on the Geological Survey of Scotland sheet 4W to consist of porphyrite. There is little exposure in the area, and the outcrops of intrusive rocks may be interpreted as a series of dykes and not a single mass. The few exposures are deeply weathered. A dyke to the south [NX 3400 4726] consists of porphyritic microtonalite (S64457) which weathers pink, shows minor alteration to calcite, and contains some pyrite. With the exception of some barren quartz veins in the sedimentary rocks, no signs of mineralisation were observed. Two panned concentrates were collected from the stream crossing the centre of the area at NX 334 473 and NX 337 478 (Table 3). The latter sample contains appreciable Pb (202 ppm) but the presence of 35 ppm Sn in the sample suggests that it may be caused by contamination, perhaps by dumping from the road upstream. No sulphides were seen in the pan.

## KIRKMABRECK GRANITE [NX 485 566]

This intrusion, consisting of a large dyke-like body of granodiorite, trends ENE parallel to the regional strike and has been extensively quarried. The rock is typically a grey, medium to coarse-grained granodiorite, but at the northern contact it becomes porphyritic and finer grained. Blyth (1955) described the joint system in detail and recorded a joint fracture filled with quartz and traces of copper mineralisation as well as an adit used to gain access to a second copper-bearing vein, but during the present survey no such clear evidence of mineralisation was found. Where seen, the granodiorite is fresh and unaltered, and the quartz veining in country rocks is barren.

The outcrops of granite around Carsluith, to the south of Kirkmabreck, are of identical rock and it is probable that both these dyke-like bodies are from the same magma source.

A reconnaissance geochemical drainage survey (Leake and others, 1978b) across the area yielded no significant metal anomalies in the vicinity of these intrusions. Two panned concentrates taken from streams draining the eastern part of the Kirkmabreck mass at NX 493 568 and NX 498 571 during this survey failed to give any significant metalliferous concentrations (Table 3). A third, collected in Carsluith Burn, at NX 491 550 contained appreciably higher Fe, Mn, Sn and Pb (Table 3) but contamination had been noted in the stream, and the relatively small increases were not considered significant in terms of sulphide mineralisation.

The old Pb working at Englishmans Burn [NX 482 588] about 2 km north of the granite outcrop, as well as other mineral occurrences at greater distances such as Lauchentyre [NX 557 576] and Kings Laggan [NX 562 578], may be related to this intrusion. The majority of these occurrences are fracture-controlled vein-type deposits but, interpreting the poor descriptions availabe, Kings Laggan may be of different style.

## KAILZIE HILL [NT 280 360]

Kailzie Hill is shown on the Geological Survey of Scotland Peebles sheet 24E to be composed mainly of granite. There is very little exposure on the steep, heather-covered flanks of the hill and on the top there are only boulders, mostly of granodiorite (S64492) which is mildly altered but which shows no evidence of mineralisation. Near the hilltop [NT 2814 3604] a small outcrop of highly sericitised quartz-feldspar-porphyry (S64491) occurs near some small trial diggings, presumably in quartz veins. The porphyry, which contains a little pyrite, possibly represents a dyke cutting the granodiorite. A recent geochemical drainage survey covers the area but the intrusion is not effectively cut by any stream and no anomalous results, except for some weakly elevated levels of Ni in stream sediment, were recorded in the area (Dr J. S. Coats, pers. comm.).

## PRIESTHOPE, TROON HILL AND KIRNIE LAW [NT 345 395]

The area consists of deeply disected hills, covered in short heather on head. Two tiny areas mapped as granite are shown on the Geological Survey of Scotland Pebbles sheet 24E at Kirnie Law. An east-west aeromagnetic anomaly can be seen as a deflection of the contours here, but it is most likely to be related to a Permo–Carboniferous dyke. On Priesthope Hill a large body of quartz-porphyry is shown and about 1 km to the west, on Troon Hill, there are three small intrusions of porphyrite. There is no outcrop on Kirnie Law and rubble is concealed by the heather except near the reservoir where there are piles of boulders near excavations. The boulders are mostly granodioritic (S64493) in composition and the rock is fresh; there are no signs of mineralisation. The only exposures on Priesthope Hill are in two small excavations on the summit. Rubble of deeply weathered and sericitised porphyry, with phenocrysts of feldspar and pseudomorphs after amphibole, occurs in one, and hornfelsed, laminated, sandy siltstone in the other.

The porphyrite body on Troon Hill (S64494), and several others nearby, are poorly exposed but appear to be dykes of sericitised feldspar porphyry with little or no associated pyrite.

Anomalous levels of As in stream sediment were recorded in a stream draining the western side of this area, but the regional pattern suggests that this is related to a sedimentary horizon and not to the intrusives. Weakly anomalous levels of Cu, Pb and Sn in sediment in another stream are interpreted as being caused by contamination. Anomalous levels of Pb in sediment and panned concentrates were recorded to the north-east, in the upper reaches of Walker Burn (Dr J. S. Coats, pers. comm.).

## BROAD LAW [NT 344 539]

A small, elongate body of granodiorite on Broad Law has been worked in a series of now disused road-metal quarries. An elongated 20 nT aeromagnetic anomaly covering about 8 km$^2$ is located mainly to the north and east of the exposed granodiorite. The intrusion is porphyritic and pink, and contains small basic xenoliths. Locally it is kaolinised and there is patchy alteration to sericite and calcite. Pyrite is rare. Quartz veins are uncommon and usually less than 1 cm wide, but one 8 cm vein contains abundant pyrite and arsenopyrite. No drainage anomalies were recorded in streams draining the ridge where the granodiorite outcrops, except for high levels of Fe, Mn and Zn in one sediment sample which is interpreted as a secondary concentration. However, minuteman power-augering in the depression to the north of Broad Law, to investigate the faulted Silurian–Carboniferous junction, found weak indications of pyrite-arsenopyrite mineralisation of unknown affinity (Dr J. S. Coats, pers. comm.).

## PRIESTLAW [NT 650 632]

The intrusion is composed mainly of medium-grained, pink, hornblende-biotite-granodiorite. Hybridisation at the margin gives the rock a dioritic composition. It was described briefly by Walker (1928). Alteration, particularly chloritisation of mafic minerals, is common at the margins, but generally the main mass of the granite shows little alteration. Close to the contact on Faseny Water there are old mineral workings in hornfelsed siltstones, sandstones, and greywackes cut by granitic veins. The sedimentary rocks are near-vertical, and the granite veins are both concordant and cross-cutting to the bedding. The sedimentary rocks are brecciated and veined by quartz and baryte, but no evidence of sulphide mineralisation was seen.

### *GEOCHEMISTRY*

A stream sediment survey (Haslam, 1973) yielded no anomalies in the vicinity of the intrusion, but coverage of the mapped outcrop of the intrusion was poor. A subsequent panned concentrate survey only provided partial cover of the intrusion (R. T. Smith, pers. comm.); samples were collected from tributaries entering Whiteadder reservoir from the north-east and from Killmade Burn. No significant anomalies were recorded in the samples from these streams, and in the general area the only anomalous site [NT 673 630] was in a stream draining Cranshaws Hill where high levels of Sb, Pb, As and Fe are related to a regional Sb–As enrichment in the vicinity of the basal Devonian unconformity. Two panned concentrates taken in Faseny Water over the intrusion at NT 644 626 and NT 645 631 during the present survey contained high levels of Ba and moderately high levels of Fe (Table 3). No sulphides were recorded in the pans and therefore the high Fe levels are attributed to mafic minerals and iron oxides. The high Ba content suggests the presence of baryte derived from the known veins.

Partial trace element analysis (Cu, Pb, Zn) of a quartz-baryte vein and a granodiorite sample from Faseny Water failed to show any enrichment in base metals.

*GEOPHYSICS*

An aeromagnetic anomaly of about 100 nT is centred just south of the outcropping intrusion. Bennett (1969) modelled this anomaly after making additional measurements on the ground. Assuming vertical prisms extending infinitely to depth, he found that the shape of the top of the source is as shown on Figure 3. To the north and east of the outcropping part the margins of the intrusion are steep, but to the south and west the top of the intrusion is quite close to the surface for 2 km away from the exposed margins, causing an apparent offset of the peak of the anomaly away from the intrusion. Dykes occur in the low ground immediately above this shallowly buried part of the intrusion.

In view of the observed alteration, indications of mineralisation, and poor geochemical coverage, two induced polarisation (IP) traverses were made to investigate the intrusion and the sedimentary rocks above it. The expanding dipole-dipole array was used with 60 m dipole length. Magnetic field measurements were also made along these lines, and along a third east-west line to investigate the airborne anomaly (Figure 4). Parts of two lines were covered by Very Low Frequency Electromagnetic measurements (VLF–EM). All results are presented in Figures 5–7.

Chargeability values are higher over the intrusion than over the sedimentary rocks (10–16 ms and 3–8 ms respectively) although the boundary is gradational with maximum values occurring near the intrusive margin, presumably due to the contact metamorphism. Similarly resistivities over the intrusion are generally higher than those over the sedimentary rocks, although this is less easy to quantify.

The magnetic profiles broadly confirm the shape and position of the aeromagnetic anomaly and that the intrusion is slightly magnetic in parts. The absence of clear steps on the magnetic profiles over the intrusive margins, however, and the substantial offset of the peak from the intrusion at outcrop, suggest that the source may not be as simple as earlier thought.

Several VLF crossovers occur, and most can be also recognised as low resistivity features on the pseudosections. The two major crossovers coinciding with steep gradients on the south sides of magnetic anomalies are suggestive of faulting with downthrow to the south, giving low resistivities in the fault zone and a magnetic high over the south edge of the upfaulted blocks of intrusive rock. The crossover at 1440S on the baseline also coincides with a small gully. These features have been marked on Figure 4.

These geophysical data give no indication of porphyry-style copper mineralisation at Priestlaw. The increase in chargeability over the intrusion is too small to suggest the presence of disseminated sulphide mineralisation in any quantity.

## COCKBURN LAW [NT 772 593]

This intrusion, a poorly exposed steep-sided boss emplaced into Silurian sedimentary rocks, is described by Midgeley (1946). A hornblende-adamellite core passes outward through granite and microgranite into a hybrid diorite containing xenoliths of basic igneous and sedimentary rocks. Alteration is recorded along joints in the adamellite with quartz, baryte and, rarely, topaz and limonite in veins. Tourmaline occurs locally. Stevenson (1849) records galena and chalcopyrite on Stoneshiel Hill and poorly documented evidence for several ancient trial workings for copper are mentioned. One old working was found on the banks of Whiteadder Water at approximately NT 788 602, and in a quarry about NT 777 593 disseminated sulphide (pyrite with minor chalcopyrite) occurs in veins and host rock. Several old levels, presumably cut to exploit copper ore, lie along a fracture zone about 1.5 km north-east of the intrusion. Several dykes, principally of lamprophyre and quartz-porphyry of different ages, cross the area, and the southern part of the granite is cut by a dolerite bearing disseminated pyrite.

*GEOCHEMISTRY*

No samples were collected in the vicinity of this intrusion during the stream sediment survey (Haslam, 1973). Also, because of the absence of tributary drainage, only one sample was collected over the intrusion during the subsequent panned concentrate survey (R. T. Smith, pers. comm.). This sample did not yield any anomalous results, but in the general area anomalous levels of Sb and As were recorded in a sample from the Otter Burn, above its confluence with the Whiteadder, and very highly anomalous Ba with weakly anomalous Sb was found in a sample collected about 1 km west of the granite margin [NT 755

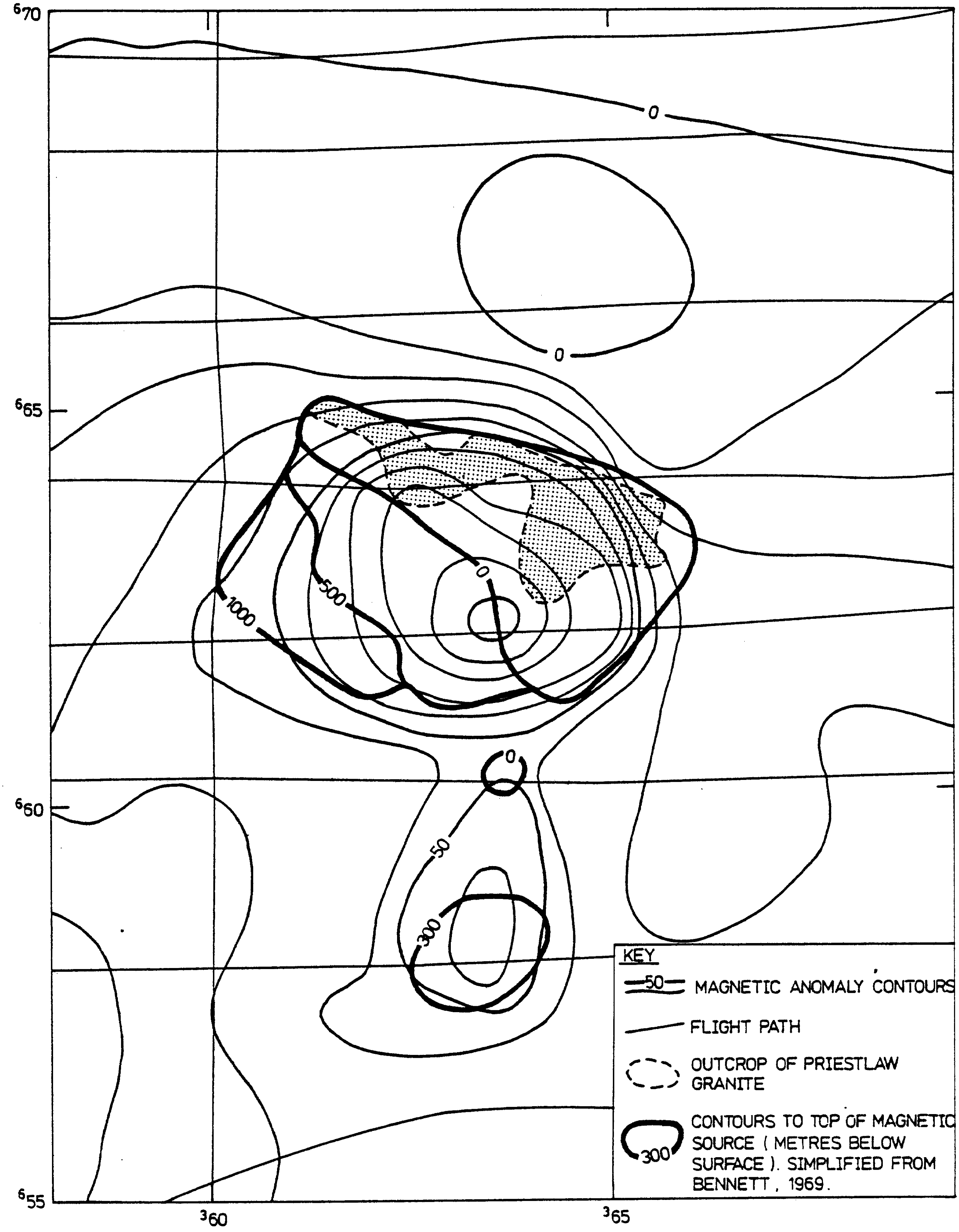



**FIG 3. PRIESTLAW AEROMAGNETIC ANOMALY & CONTOURS TO TOP OF SOURCE**

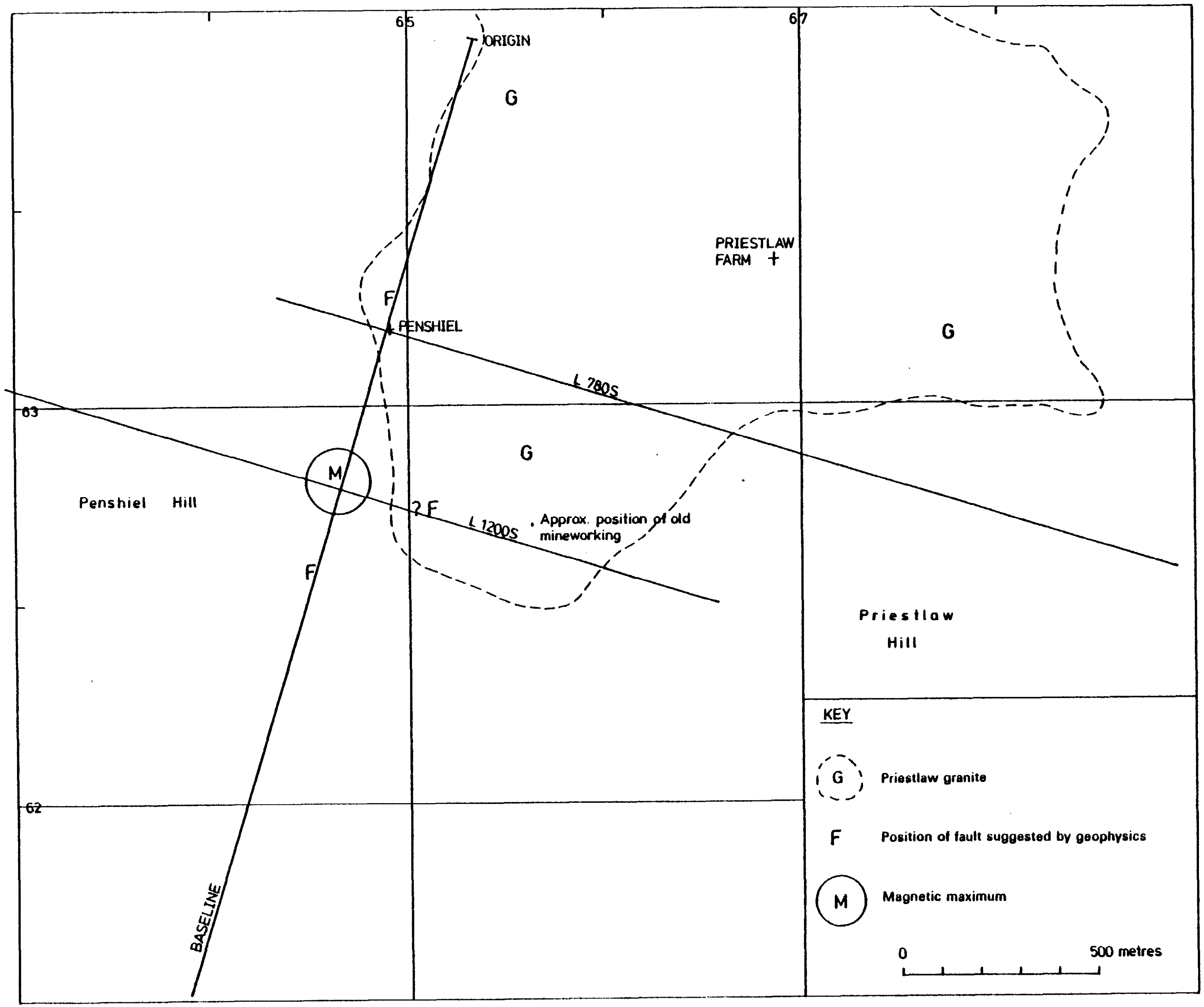



Figure 4: Priestlaw: outline geology, positions of traverse lines and main geophysical features.

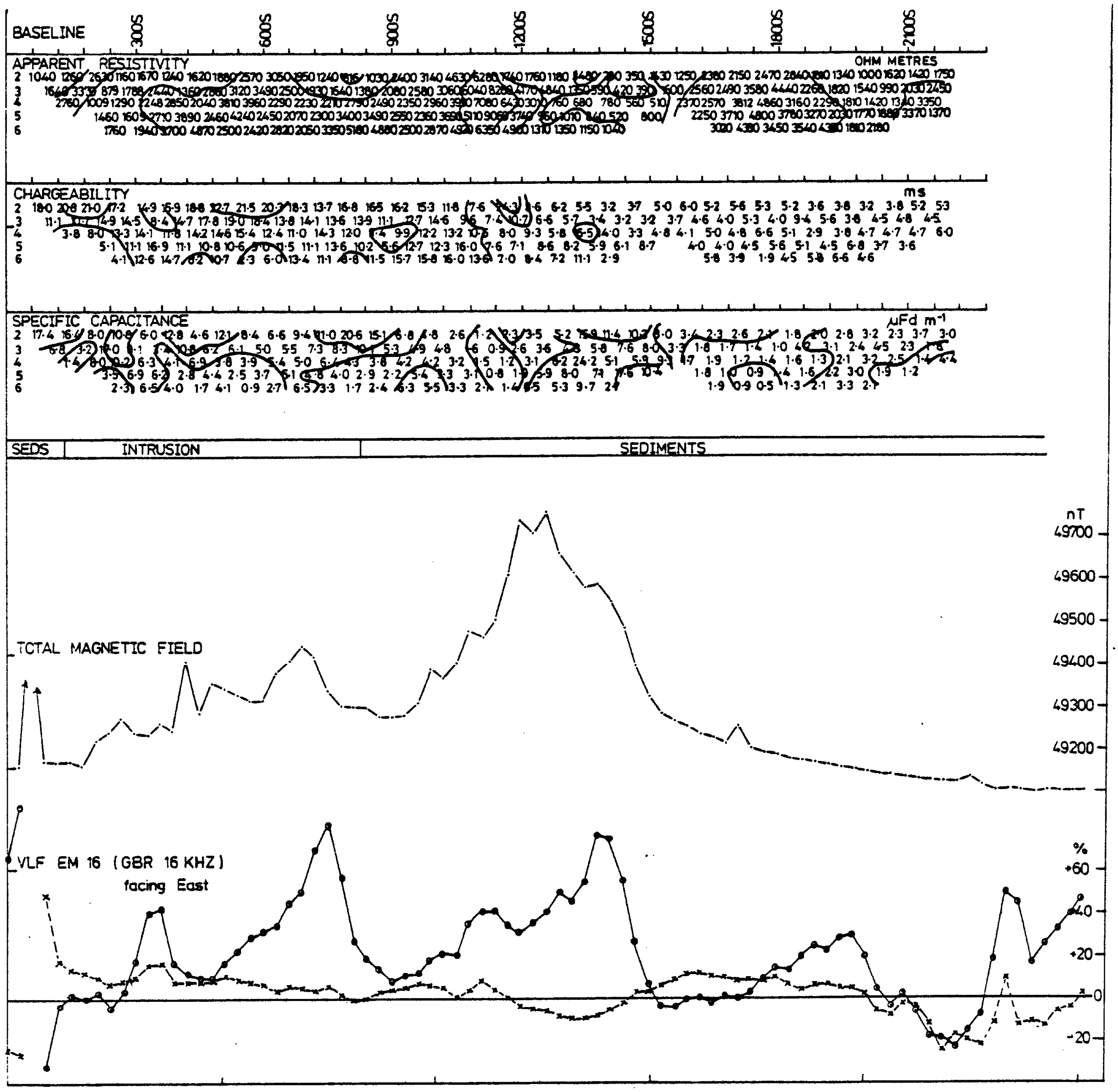



Figure 5: Preistlaw: geophysical results for baseline

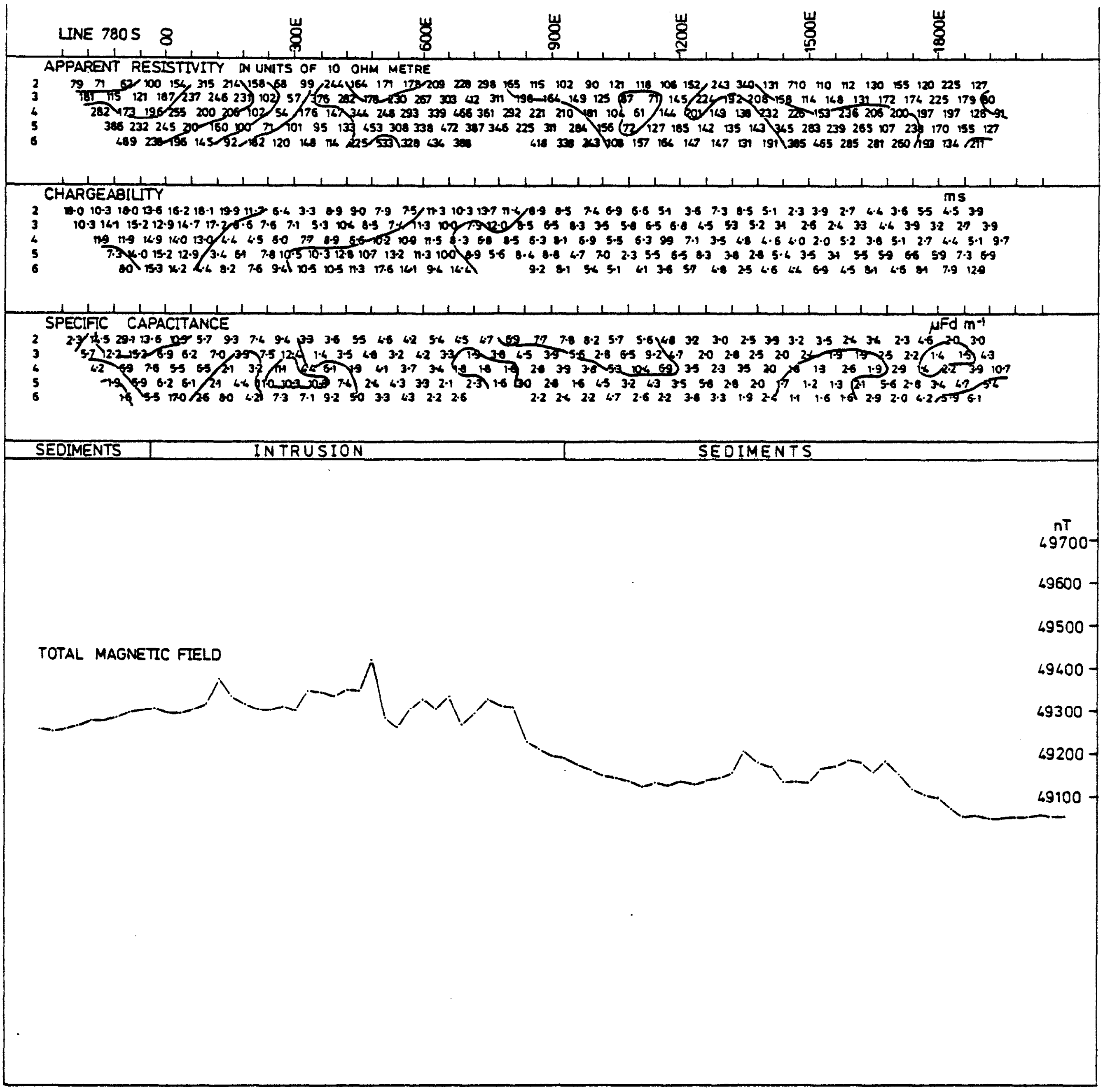



Figure 6: Preistlaw: geophysical results for traverse line 780S

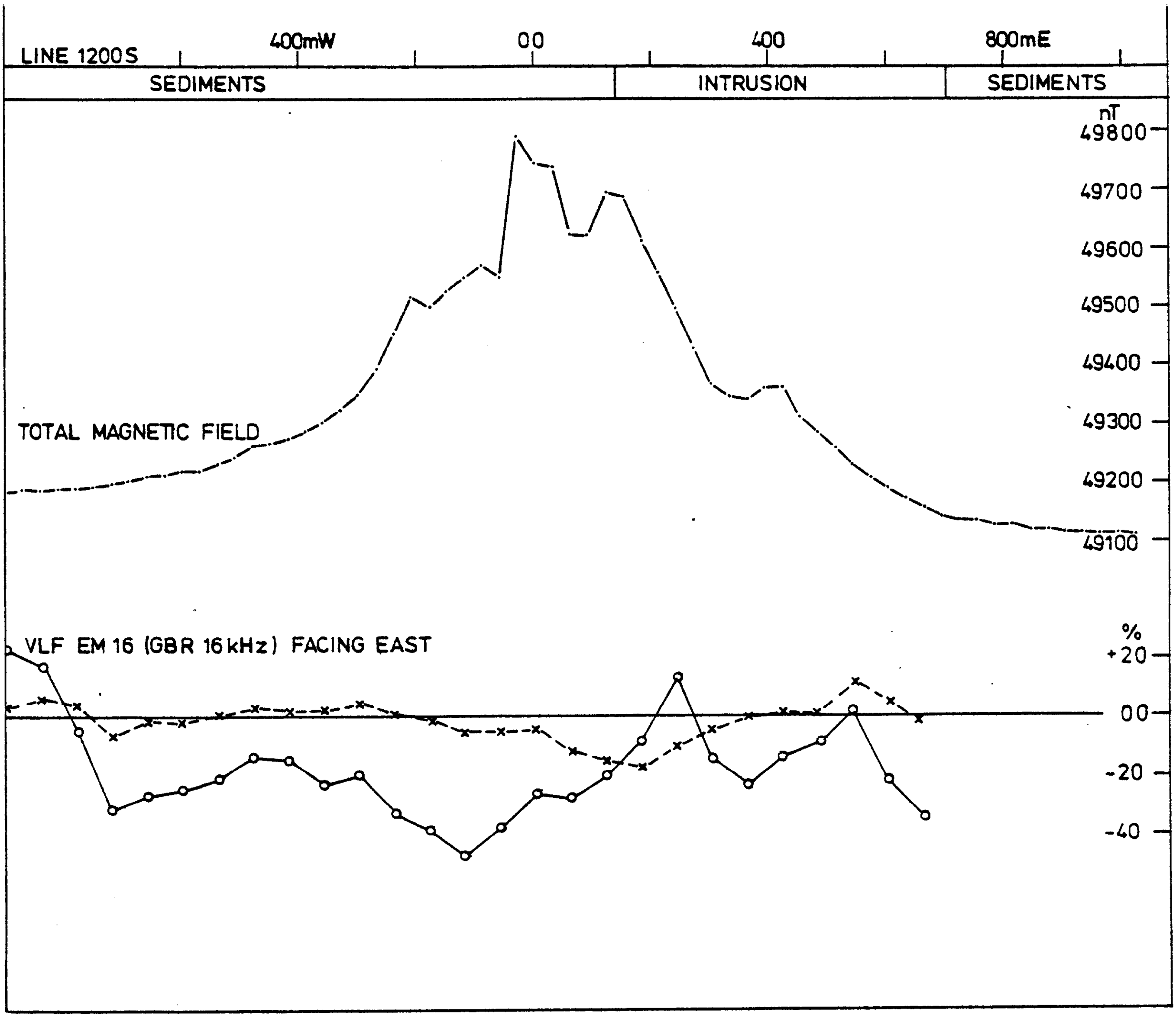



Figure 7: Preistlaw: geophysical results for traverse line 1200S

590]. On a regional scale it appears that both anomalies are related to metalliferous enrichments associated with the basal Devonian unconformity. Two panned concentrates collected in the Whiteadder during the present survey, at NT 778 593 and NT 772 589 contained high concentrations of Ba, Sb and Fe, and moderate but still probably anomalous levels of Sn, Pb, Zn and Ti (Table 3). A trace of sulphide was noted in the latter sample and the high levels are attributed to a combination of iron oxides, contamination and sulphide mineralisation. It is not certain whether the latter is entirely related to the regional Sb–As enrichment or whether a component is related to or enhanced by the granite. A rock sample from a hematised shear zone exposed at the Otter Burn–Whiteadder Water intersection was analysed for a range of elements and contained weakly elevated levels of Cu (106 ppm) and Sb (14 ppm, R. T. Smith, pers. comm.).

*GEOPHYSICS*

A large aeromagnetic anomaly (about 7 X 2 km) crossing the area is associated with a dolerite dyke but broadens slightly over the intermediate intrusion (Figure 2).

In view of the recorded mineralisation and inconclusive geochemical data, four north-south traverses were surveyed with the IP and magnetic methods. Locally steep topography, dense plantations, farm buildings and the Whiteadder Water placed constraints on the positions of the traverse lines (Figure 8). Results are shown on Figures 9–12.

Except for the continuous strong magnetic anomaly and minor chargeability high due to the dyke, no patterns can be discerned. The main intrusion cannot be differentiated geophysically from the surrounding sedimentary rocks and there is no evidence of an IP halo of the classic porphyry-copper type. However, a minor resistivity low at ~00 on line 1680E may be related to the fracture zones exploited for copper and a VLF–EM survey could be carried out to investigate it further, although high voltage power lines in the area would be a problem.

## LAMBERTON MOOR [NT 953 580]

This intrusion is very poorly exposed but where seen it is quartz-diorite (feldspar-porphyry) containing a high percentage of feldspar phenocrysts. A quarry at the northern end of the intrusion shows the porphyry to be brecciated, chloritised and veined by calcite. Minor sulphides have also been noted. Country rocks consist of flat-lying Old Red Sandstone beds.

*GEOCHEMISTRY*

A stream sediment sample from the stream rising over the intrusion gave no anomalous results (Haslam, 1973). The panned concentrate survey yielded no anomalies that could be related to mineralisation in this area, though coverage was poor because of inadequate drainage density and results were difficult to interpret because of extensive contamination (R. T. Smith, pers. comm.). A panned concentrate collected above Mordington Farm [NT 951 572] during this survey contained large amounts of Fe and Ti (Table 3) which could be related to the large amount of iron oxides noted in the pan.

*GEOPHYSICS*

Because of the poor exposure, observed alteration, and lack of geochemical drainage data, IP measurements were made along three NNW–SSE traverses and magnetic measurements were taken along these traverses and the baseline (Figure 13). Strong interference, thought to be due to a TV broadcasting mast to the north-west, was encountered during the IP survey, and in areas of low resistivity readings were difficult or impossible to obtain.

The results (Figures 14 and 15) are generally uninteresting. Resistivities varied between 100 and 1000 Ωm, chargeability rarely exceeded 8 ms, and the magnetic field profiles show little variation, except for sharp local anomalies of up to 100 nT, which could well be artificial in origin. The single feature of interest lies at 300 N on line 960W, where coincident resistivity, chargeability and magnetic anomalies occur. The shape of the anomalies indicates a very local source, probably at or near the surface. No geophysical indications of porphyry-style or other significant mineralisation were found and hence no further work could be justified.

## TONDERGHIE (BURROW HEAD) [NX 439 348]

On the coast about 2.5 km north-west of Burrow Head are the remains of the Tonderghie copper mine, which exploited a vein system trending a few degrees north of west and heading north at 70°. Chalcopyrite and pyrite were noted in a gangue of quartz and bartye (Wilson and Flett, 1921). The remains of two shafts, a tip, an open-cut, and an adit may be discerned but the shafts are now infilled, the adit collapsed and the tip partly washed away. The open working which is still accessible is up to 2 m wide and trends 300°.

The country rock consists of thinly inter-bedded greenish-grey siltstone and greywacke with some thin beds of light grey limestone, all of Silurian age. Bedding generally strikes 060° and dips 80° to south-east, but there are minor undula-

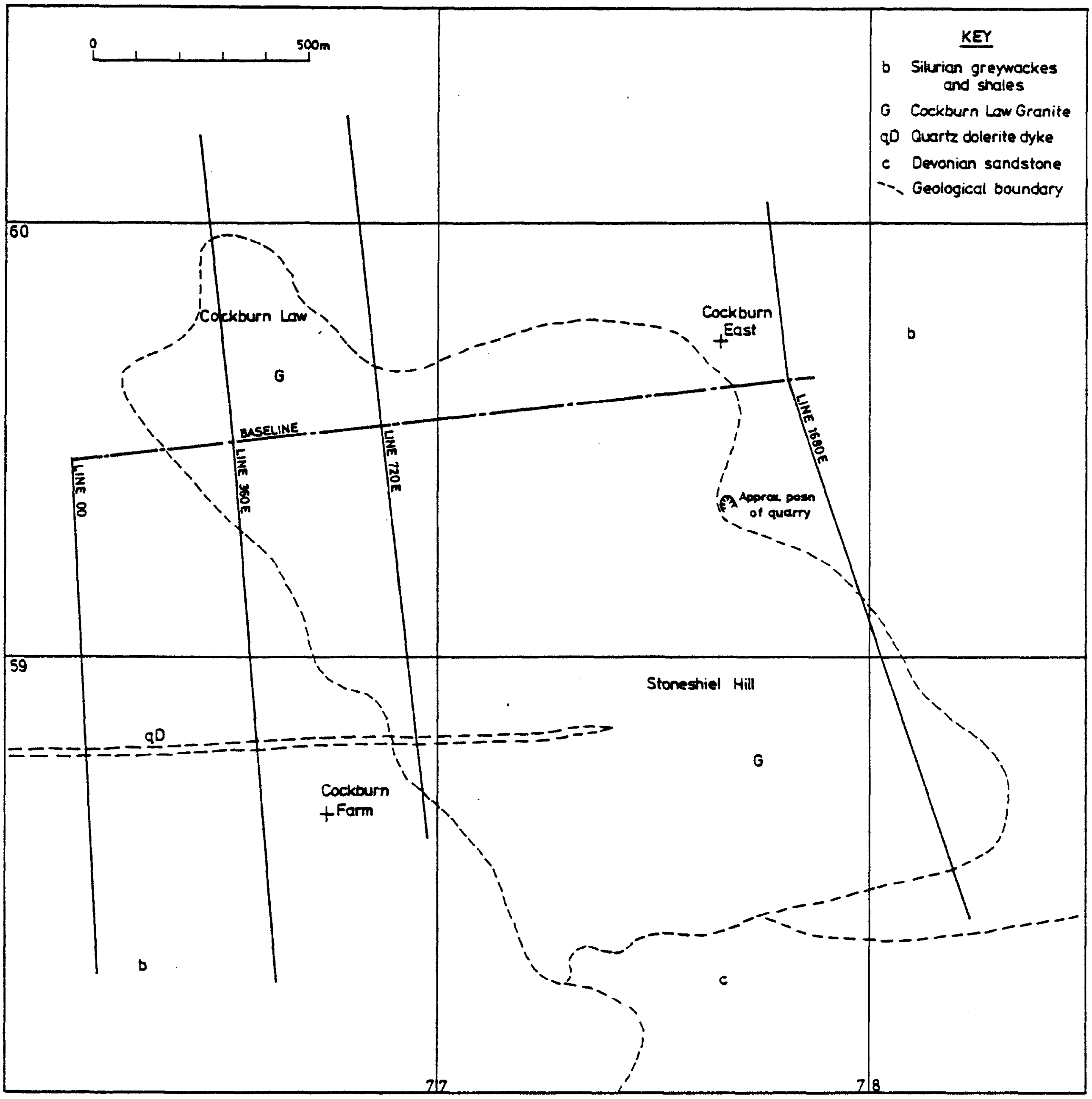



Figure 8: Cockburn Law: outline geology and position of traverse lines

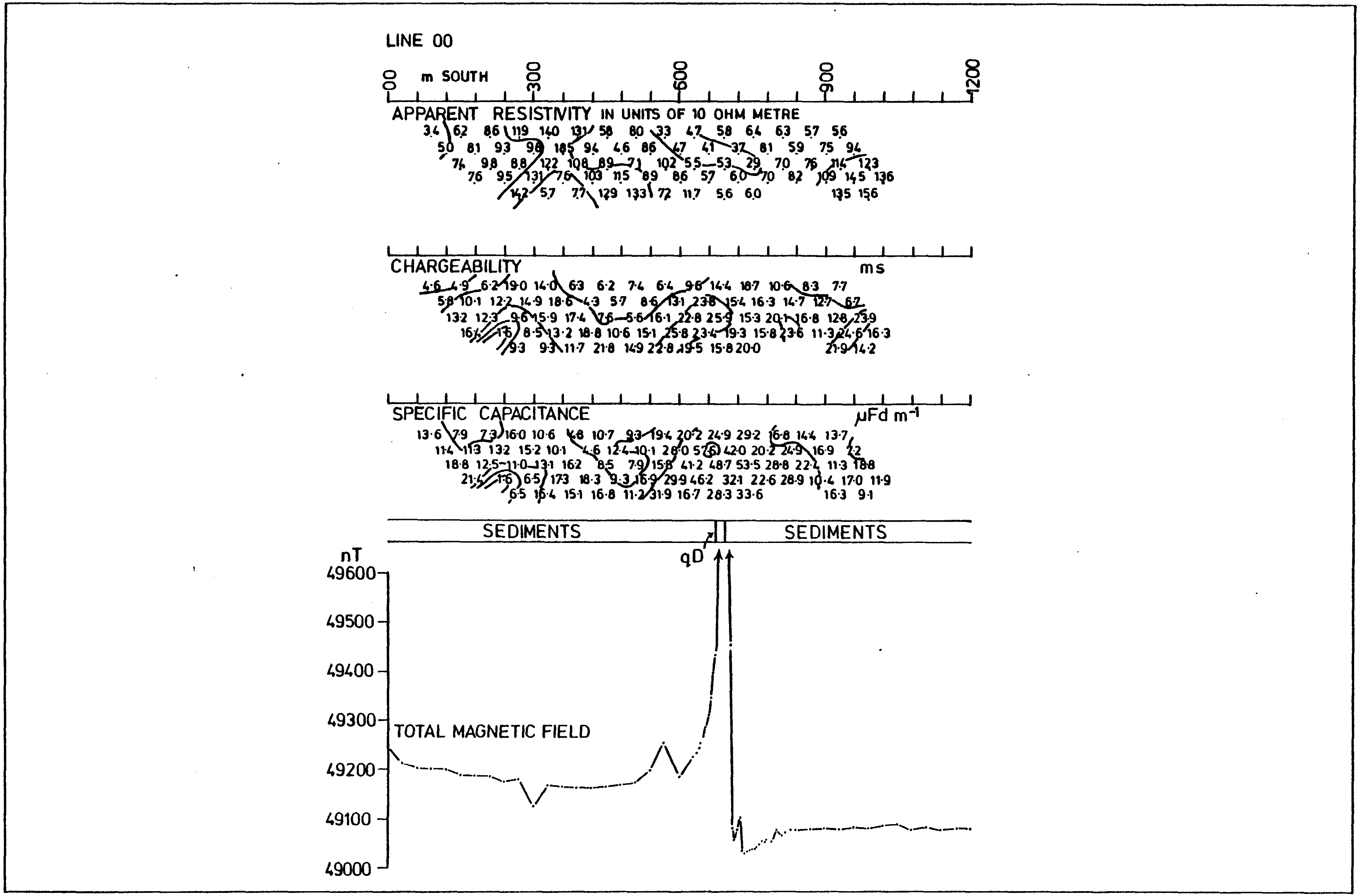



Figure 9: Cockburn Law: geophysical results for traverse line 00

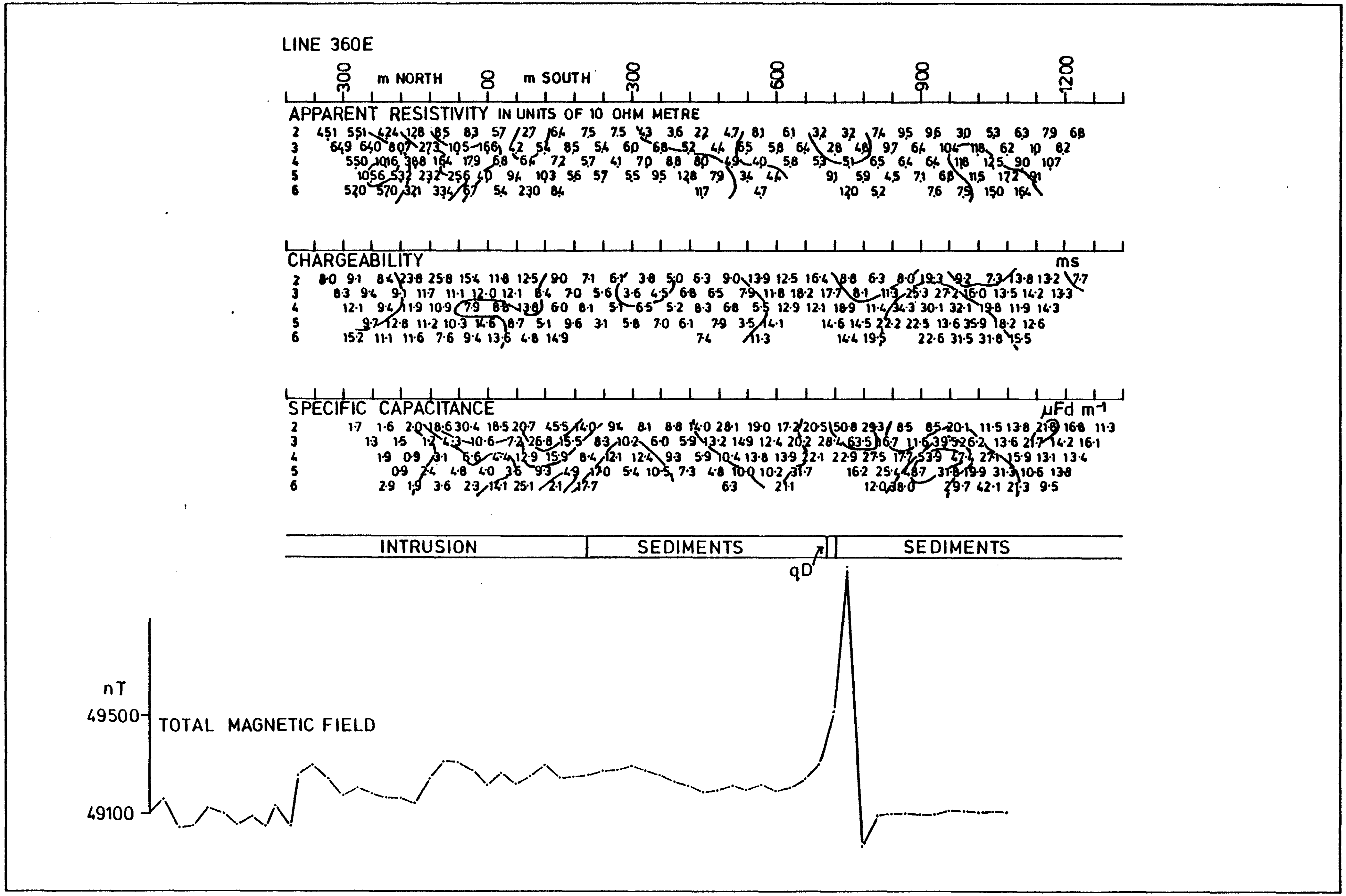



Figure 10: Cockburn Law: geophysical results for traverse line 360E

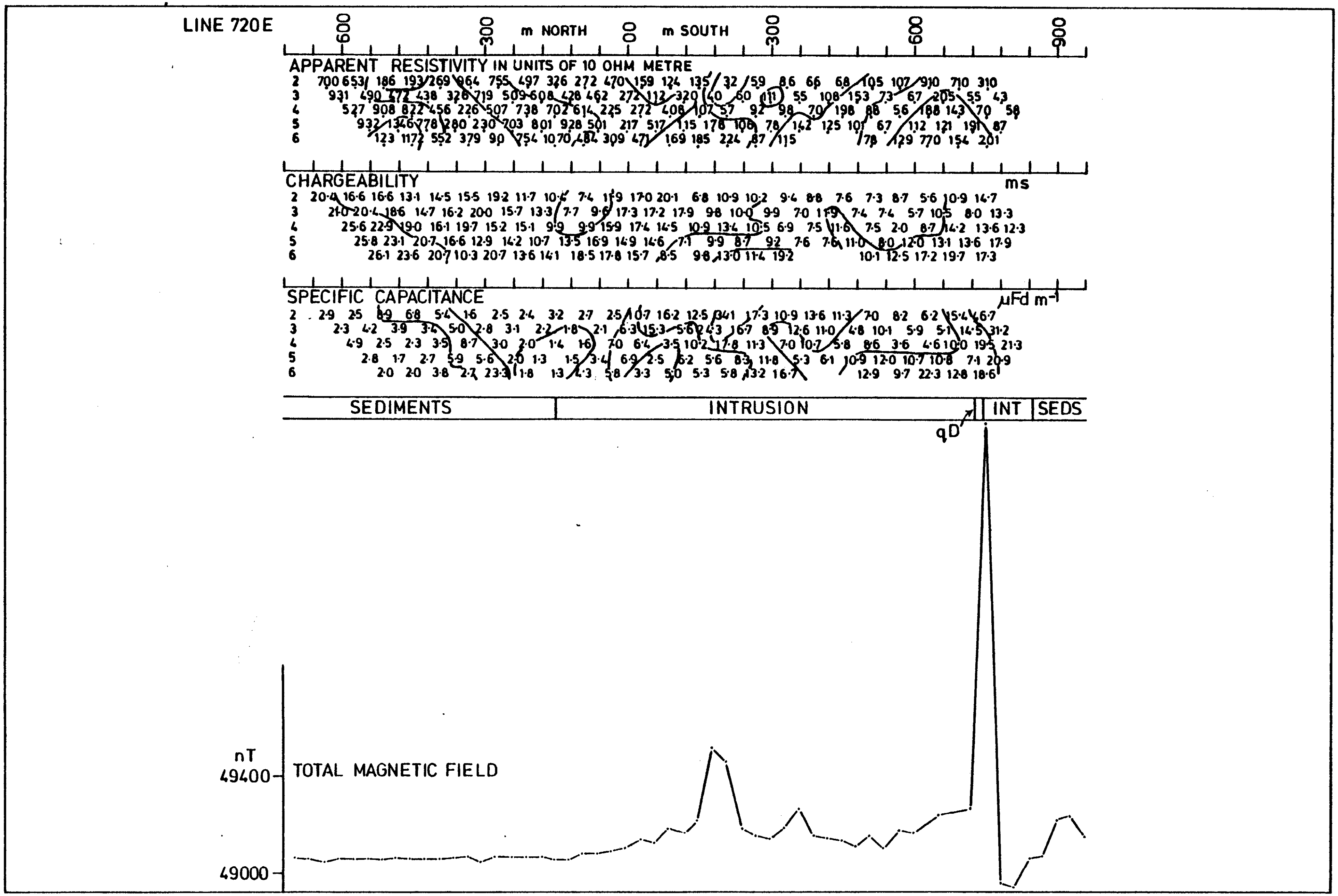



Figure 11: Cockburn Law: geophysical results for traverse line 720E

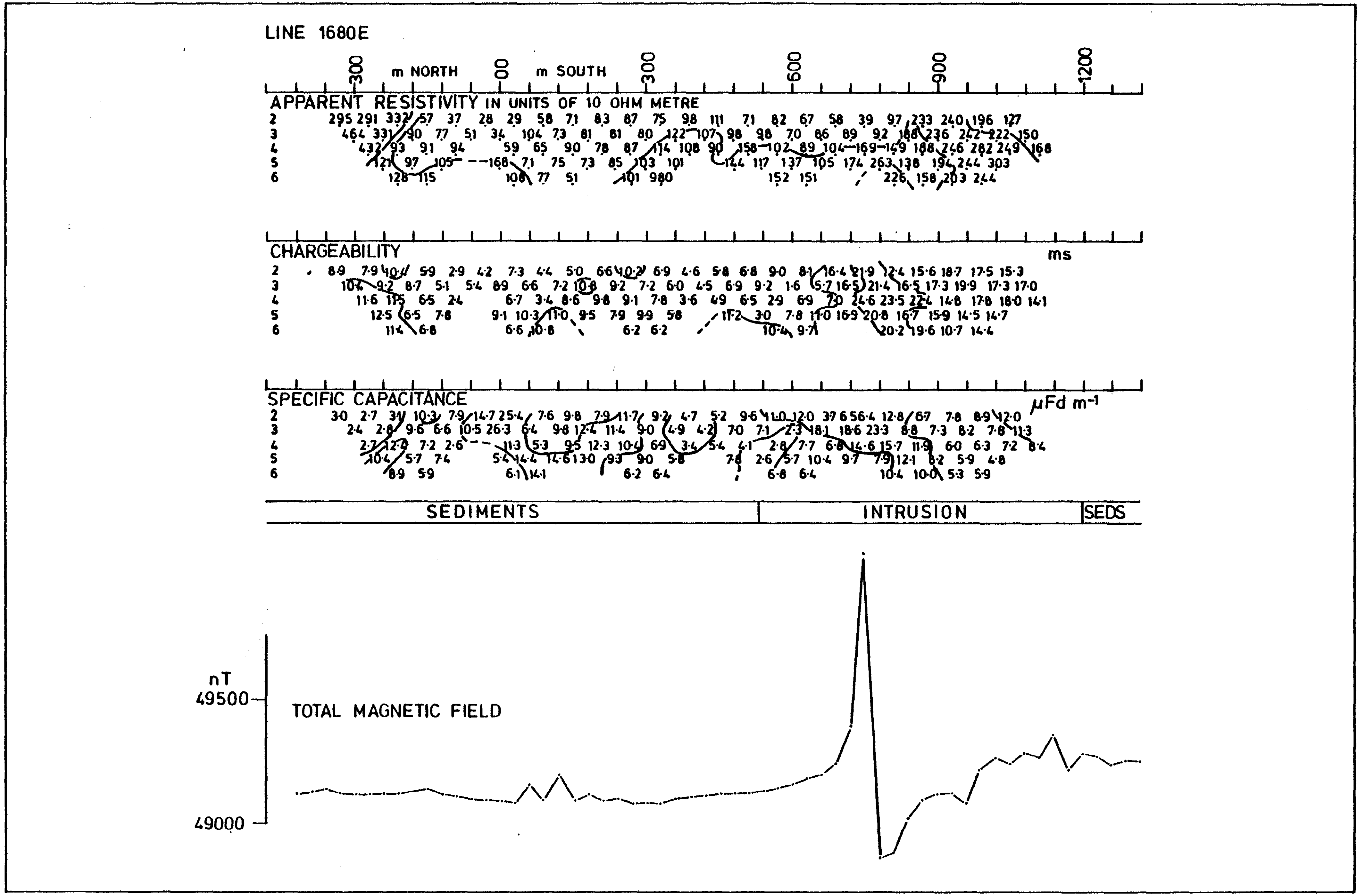



Figure 12: Cockburn Law: geophysical results for traverse line 1680E

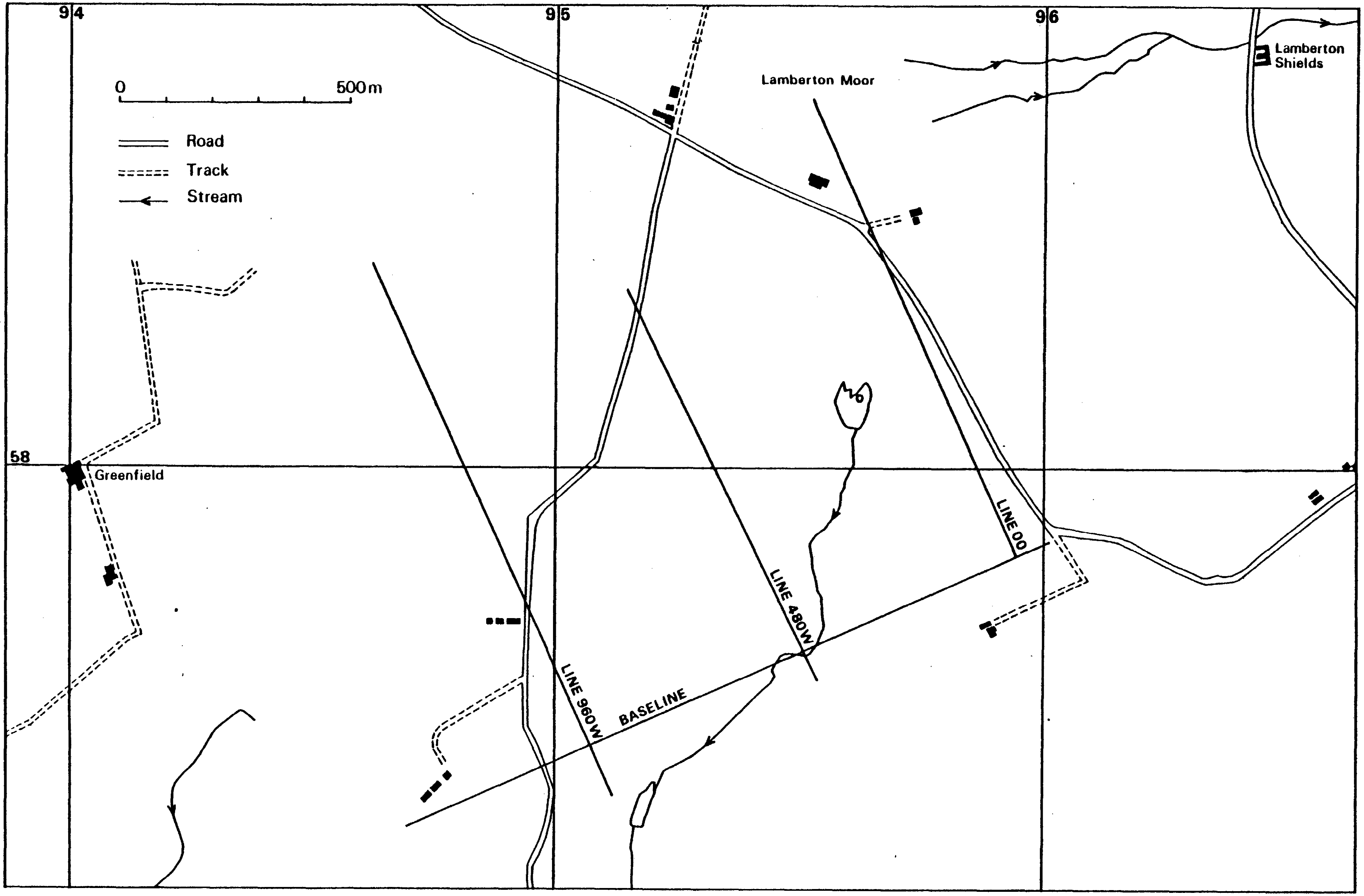



Figure 13. Lamberton Moor: position of traverse lines

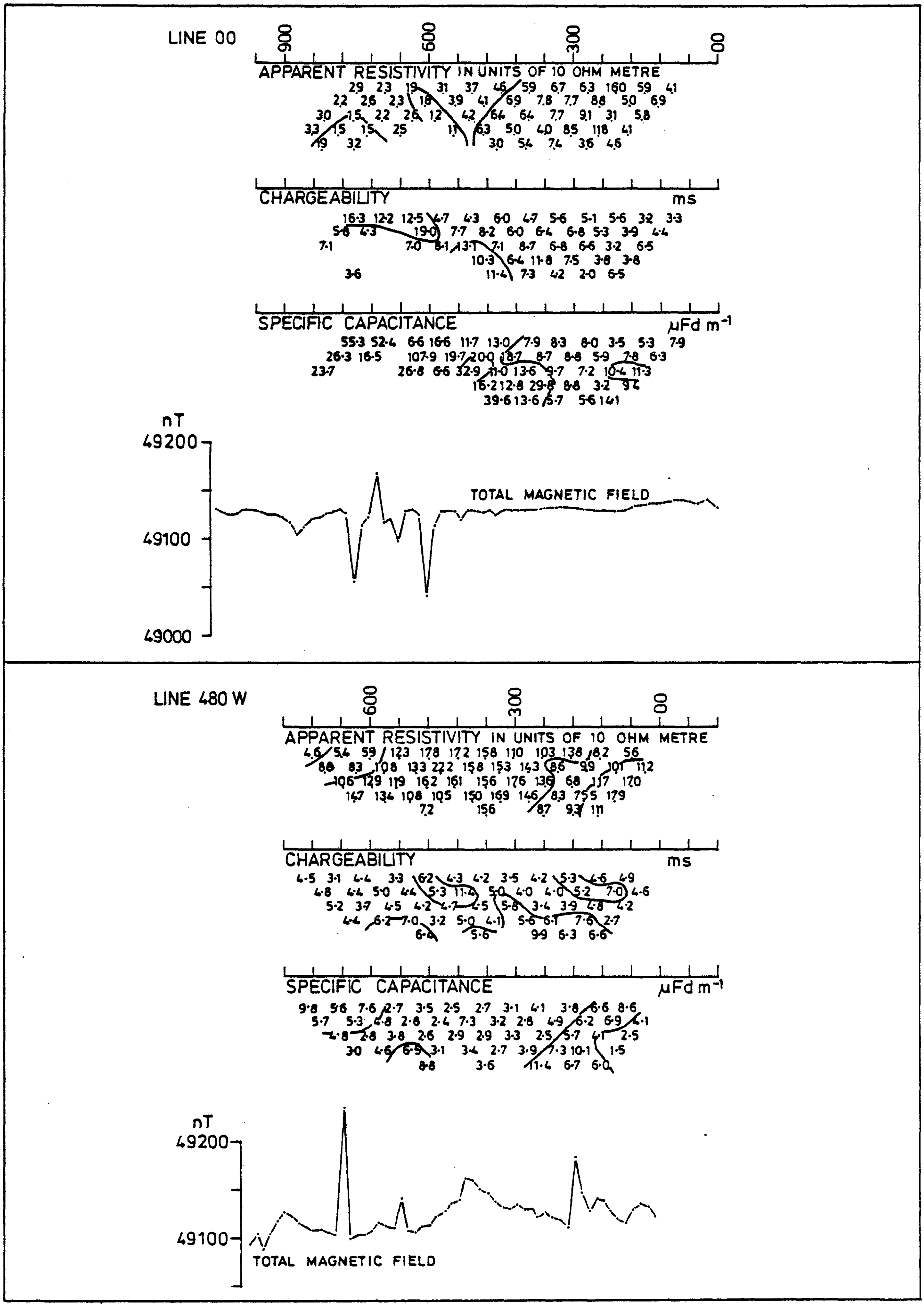
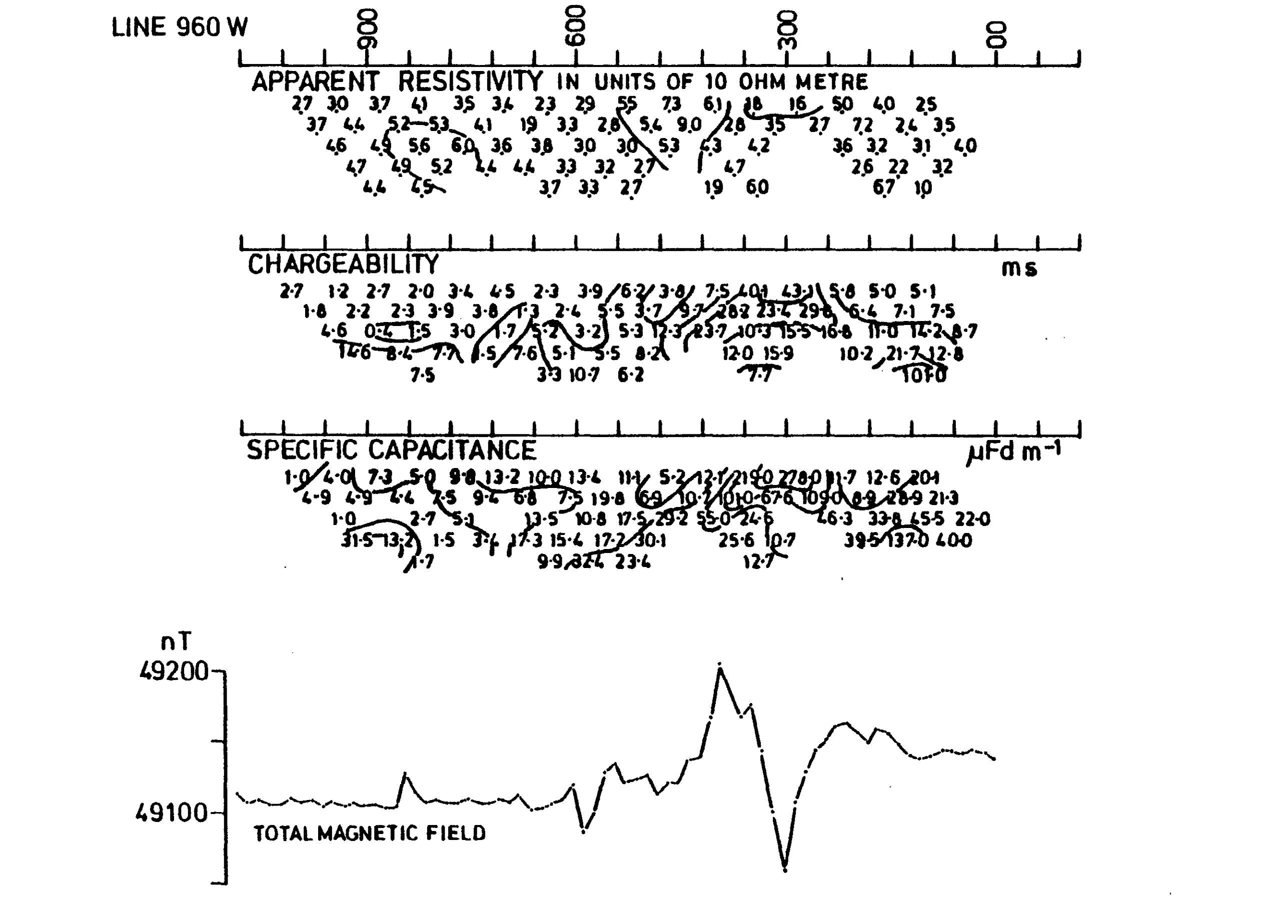



Figure 14: Lamberton Moor: geophysical results for traverse lines 00 and 480W



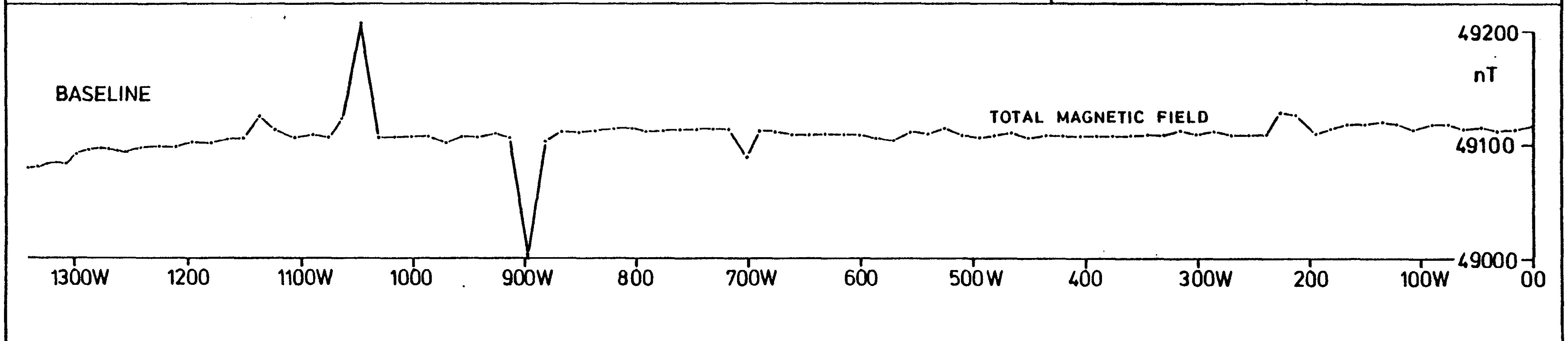




Figure 15: Lamberton Moor: geophysical results for baseline and traverse line 960W

tions. There are profuse small veins, pods and patches of quartz parallel to the bedding and in several other directions. Calcite veinlets are common. Adjacent to the old working the quartz veins are most commonly parallel and at right angles to it. Two samples of greywackes containing quartz-calcite veinlets parallel to the strike and one free of veinlets were analysed for a range of elements (Table 4, Nos. 1–3). The two veined samples showed predictably high Ca contents, but, except for a weakly enhanced Cu result, the only significant mineralisation was detected in the vein-free samples which shows appreciable As enrichment, perhaps present as arsenopyrite, although only pyrite was recognised in hand specimen.

The breccia vein system was examined in and around the opencut. The breccia fragments, mostly less than 3 cm long, consist of strongly foliated sericitised mudstone, quartzwacke siltstone and, less commonly, greywacke. Fragments are rounded and angular. They are heavily veined and impregnated by iron-stained calcite and baryte. The matrix is composed of fine-grained crystalline quartz with some sericite and calcite. The quartz matrix itself is locally brecciated and recemented.

Sulphides, including pyrite and chalcopyrite, occur within the breccia fragments and the quartz matrix. Malachite staining is not uncommon. In places there appears to be a phase of calcite with pyrite veining after the quartz.

A mineralised sample from the remains of a small tip near the opencut and old shaft was analysed for a range of elements (Table 4, No. 7). Besides the high level of Cu, present as chalcopyrite, the sample also showed enhanced levels of Ni and As. The amount of Ni suggests that it may be accommodated in pyrite and chalcopyrite, but arsenopyrite may be present as a separate phase. Three other samples from the south-eastern part of the 120°-trending breccia vein system (Table 4, Nos. 4–6) show less intense Cu mineralisation and no As or Ni enrichment, but two do contain appreciable Ba and associated weak increases in Sr.

Minor faults near the working contain breccia with a calcite cement and there is a suggestion in the workings that the breccia is confined to zones elongated parallel to the length of the working. After the formation of the breccia, the voids were filled with calcite cement and the whole rock was rebrecciated and recemented, mainly by quartz, at least once. Whether or not the breccia was formed as a result of faulting, or emplaced afterwards along the faults as intrusion breccia dykes, is not known for certain, but the history of movement after its initial formation suggests that the breccia is most likely to be genetically related to the faulting. The sulphides appear to be associated with the quartz and the late calcite formation.

## DISCUSSION

There are few published analyses of intrusive rocks in the Southern Uplands. MacGregor (1937) gives some major element analyses of the Criffel–Dalbeattie mass, and Phillips and others (1981) give a summary of Stephens' (1972) unpublished work. Average major element analyses for the main components of the Loch Doon complex are given by G. C. Brown and others (1979). Earlier analyses of the same complex are listed by Higazy (1954) who adds semi-quantitative trace element data. Six major-element analyses of samples from the small intrusions of Priestlaw, Cockburn Law and Spango are given by Walker (1928) but the sum of the published data, particularly for trace elements and the small intrusions, is too limited to allow compositional variations to be studied in detail within and between intrusions. This deficiency has been partly overcome by a combination of petrographic and isotope studies of the main intrusions (e.g. Stephens and Halliday, 1980).

Major and trace element analyses of samples collected during this study from four small intermediate intrusions are shown in Table 1, together with analyses of the least altered rocks from small intrusions at Culvennan and Cairngarroch already reported elsewhere (Parker and others, 1981; Allen and others, 1981). All the samples from the four small intrusions, with the exception of the Creechan microtonalite, are moderately or intensely altered, a fact which, coupled with the small number of samples and lack of comparative data, prevented a detailed chemical study. Some general points and tentative suggestions can however be made.

The Mull of Galloway and Glenluce samples both show distinctive features when compared with the other intrusives, notably low Si, Al and K/Rb and high Fe, Mg, Cu, P, Mn, Ni and Ba in the Mull rocks, and high Ca, Sr, Mg and P and low Si and Al in the Glenluce samples. All these features may be attributed to the highly altered nature of these rocks, the elements commonly regarded as stable during alteration processes (Ce, Zr, Y, Ti) indicating no obvious differences from the other intrusions. The major element analyses from Cockburn Law, Priestlaw and Spango given by Walker (1928) are similar to each other and to those quoted here with the exception of $Al_2O_3$ which is apparently higher in the south-east Scotland rocks. This may represent a geologically significant change but is more likely to be the result of analytical bias.

Differences in $K_2O/Na_2O$, Rb/Sr and K/Rb ratios between our results and those quoted by Brown (1979) for the south-west Scotland plutonic bodies are apparent with higher Rb/Sr and $K_2O/Na_2O$ and lower K/Rb ratios in the plutons. This difference may be the product of biased sampling, for only intermediate intrusions were considered in this study, and examination of the analyses quoted by Higazy (1954) for Loch Doon and MacGregor (1937) for Criffel suggests no clear differences in $K_2O$ at equal silica percentages. The trace element data given by Higazy (1954) for intermediate members of the Loch Doon complex show distinct differences from the results listed in Table 1, with apparently much higher levels of Mn, Ni, Sr and Y in the Loch Doon rocks. However, the Loch Doon data are only semi-quantitative and it is suspected that at least some of the differences are caused by analytical bias.

All of the small intrusives sampled show whole rock compositions similar to tonalites; they are generally richer in Na and Si and poorer in Fe and Ca compared with averages quoted for diorite. Trace element levels are similar, for comparable elements, to those of Antarctic tonalites quoted by Saunders and others (1980), except for lower Y and perhaps marginally higher Ba-Rb-Sr in the Scottish rocks. Compared with Harlech Dome microtonalites (Allen and others, 1976) there are several relatively small but distinct differences, the Scottish rocks containing higher levels of $K_2O$ and Ba, marginally larger amounts of $TiO_2$, P, Zr and As, and lower Zn. The Harlech Dome rocks are believed to have been emplaced in an island arc environment and the Antarctic rocks to be typical of a continental margin magmatic arc (Saunders and others, 1980) and therefore it may be suggested that the southern Scotland intrusives were emplaced in a broadly similar geological environment, but with a suggestion of more crustal involvement than in the Harlech Dome.

Because of the unknown age of the intrusions, it is difficult to reach conclusions concerning metallogenesis in the area. Some features are apparent, notably a patchy Ba-As-Cu enrichment in some intrusions in the south-west of the area. Metal enrichments are generally associated with alteration, but at Cairngarroch some of the least altered rocks contain higher metal levels than highly altered lithologies, and here at least there is some evidence for a copper-rich magma. In the south-west, appreciable Pb-Zn-Sb mineralisation appears to be restricted to massive sulphide lenses in (?later) veins. For lack of data it is uncertain whether these associations and distinctions apply in the north-east of the region. Tourmaline is the dominant feature of the alteration at Foreburn where it is closely linked with the sulphide mineralisation. It is also recorded at Cockburn Law and very sparsely at Black Stockarton Moor but not at the other mineralised localities examined. The significance of this distribution, if any, is uncertain. Other styles of alteration associated with recorded mineralisation do not form a clear pattern except at Black Stockarton Moor, the only place where a typical porphyry style alteration pattern has been recorded. Significant sulphide mineralisation in association with intrusions in southern Scotland so far examined (at Foreburn, Cairngarroch and Black Stockarton Moor) suggests a link with small intermediate intrusions which the tenuous available evidence indicates may have been emplaced at a relatively early stage in the Caledonian magmatic cycle of the region. It is also interesting to note that the authors of two of these studies concluded that the mineralisation at Black Stockarton Moor and Foreburn was most similar in type to descriptions of porphyry copper deposits in the Canadian Cordillera, and it may be worth examining further occurrences in this light.

## CONCLUSIONS

1 The survey suggests that no extensive porphyry-style disseminated copper mineralisation is associated with any of the intrusions examined at or near the surface.

2 The incomplete and brief nature of these investigations means that small expressions of more concentrated or deeply buried mineralisation may have escaped detection.

3 It is not possible on the small amount of data available to draw firm conclusions on local or regional patterns of mineralisation, or on the petrogenesis of the intrusions. Modern geochemical and geological studies of the intrusions, both large and small, in southern Scotland are required as a prerequisite to an overall understanding of mineralisation in the region. Recent isotopic studies have provided some useful information but there is a lack of published chemical data.

## RECOMMENDATIONS

1 Some of the intrusions merit investigation for other styles of mineralisation. The clearest example is Cockburn Law, where fracture-controlled copper mineralisation is recorded and high levels of Ba, Sb, As, Pb and Zn in drainage samples require explanation. Some of these anomalies appear on a regional scale to be related to stratigraphic controls, but the presence of a heat and fluid source in the form of the intrusion may have caused redistribution and upgrading of any metalliferous concentrations. The environs of Priestlaw should be examined for similar reasons.

2 A few intrusions with some mineral potential were not examined. The most notable of these is considered to be Spango (NS 8020) over which two weak copper anomalies in stream sediment were recorded by Gallagher and others (1971). Walker (1928) records that the intrusion is poorly exposed but, where seen, it consists of 'basic hornblende-biotite-granodiorite' or quartz diorite. The twin intrusions of Poleshill (NS 6612) and the Knipe (NS 6610) are two others which should be examined briefly. The latter contains an old

working in a quartz-stibnite vein whilst the former is said by Walker to be lithologically very similar to Cockburn Law.


## ACKNOWLEDGEMENTS

Some of the material in this report was extracted from an unpublished report by H. Colley. Geochemical analyses were the work of T. K. Smith, A. E. Davis and their colleagues in the Analytical Chemistry Unit of IGS. Some mineralogical examinations were carried out by G. D. Easterbrook.


## REFERENCES


**Allen, P. M. and others.** 1976. Geochemistry and relationships to mineralisation of some igneous rocks from the Harlech Dome, Wales. *Trans. Inst. Mining Metall. Sect. B.*, Vol. 85, pp. 100–108.

— 1981. Copper mineralisation at Cairngarroch Bay, south-west Scotland. *Mineral Reconnaissance Programme Rep. Inst. Geol. Sci.*, No. 39.

**Bennett, J. R. P.** 1969. Results of geophysical surveys in the Haddington area. *Inst. Geol. Sci. Appl. Geophysics Unit* [Unpublished Report].

**Blyth, F. G. H.** 1955. The Kirkmabreck granodiorite near Creetown, South Galloway. *Geol. Mag.*, Vol. 92, pp. 321–328.

**Brown, G. C.** 1979. Geochemical and geophysical constraints on the origin and evolution of Caledonian granites. *In* The Caledonides of the British Isles reviewed. *Spec. Pub. Geol. Soc. London*, No. 8, pp. 645–652.

— **and others.** 1979. The Loch Doon granite: an example of granite petrogenesis in the British Caledonides. *J. Geol. Soc. London*, Vol. 136, pp. 745–753.

**Brown, M. J. and others.** 1979., Porphyry style copper mineralisation at Black Stockarton Moor, south-west Scotland. *Mineral Reconnaissance Programme Rep. Inst. Geol. Sci.*, No. 30.

**Dawson, J. and others.** 1977. A mineral reconnaissance survey of the Doon–Glenkens area south-west Scotland. *Mineral Reconnaissance Programme Rep. Inst. Geol. Sci.*, No. 18.

**El Bouseily, A. M. and El Sokkary, A.** 1976. The relation between Rb, Ba and Sr in granitic rocks. *J. Geol. Min. Metall. Soc. India*, Vol. 47, pp. 103–116.

**Gallagher, M. J. and others.** 1971. New evidence of uranium and other mineralisation in Scotland. *Trans. Inst. Min. Metall. Sect. B.*, Vol. 80, pp. 150–173.

**Haslam, H. W.** 1973. Geochemical reconnaissance of the north-east Scottish borders. *Inst. Geol. Sci., Unpub. R.M. M.U. Report.*

— 1975. Geochemical survey of stream waters and stream sediments from the Cheviot area. *Inst. Geol. Sci.*, Rep. No. 75/6.

**Higazy, R. A.** 1954. The trace elements of the plutonic complex of Loch Doon and their petrogenetic significance. *J. Geol.*, Vol. 62, pp. 172–181.

**Holgate, N.** 1943. The Portencorkrie complex of Wigtownshire. *Geol. Mag.*, Vol. 80, pp. 171–195.

**Institute of Geological Sciences.** 1972. *Aeromagnetic map of Great Britain, Sheet 2.* First edition (Southampton, Ordnance Survey).

**Leake, R. C. and others.** 1978a. A reconnaissance geochemical drainage survey of the Criffel–Dalbeattie granodiorite complex and its environs. *Mineral. Reconnaissance Programme Rep. Inst. Geol. Sci.*, No. 19.

— 1978b. A geochemical drainage survey of the Fleet granitic complex and its environs. *Mineral Reconnaissance Programme Rep. Inst. Geol. Sci.*, No. 21.

**MacGregor, M.** 1937. The western part of the Criffel–Dalbeattie igneous complex. *Q. J. Geol. Soc. London*, Vol. 93, pp. 457–484.

**Midgeley, H. G.** 1946. The geology and petrology of the Cockburn Law intrusion, Berwickshire. *Geol. Mag.*, Vol. 83, pp. 49–66.

**Parker, M. E. and others.** 1981. Mineral exploration in the area around Culvennan Fell, Kirkcowan, south-western Scotland. *Mineral Reconnaissance Programme Rep. Inst. Geol. Sci.*, No. 42.

**Phillips, W. J., Fuge, R. and Phillips, N.** 1981. Convection and crystallisation in the Criffel–Dalbeattie pluton. *J. Geol. Soc. London*, Vol. 138, pp. 351–366.

**Saunders, A. D., Tarney, J. and Weaver, S. D.** 1980. Transverse geochemical variations across the Antarctic Peninsula: implications for the genesis of calc-alkaline magmas. *Earth Planet. Sci. Letter*, Vol. 46, pp. 344–380.

**Stephens, W. E.** 1972. The geochemistry of the Dalbeattie granodiorite complex and associated rocks. Ph.D. Thesis, U.C.W., Aberystwyth, [Unpublished].

— **and Halliday, A. N.** 1980. Compositional variation in the Galloway plutons. *In* **Atherton, M. P. and Tarney, J.** (editors) *Origin of granite batholiths: geochemical evidence.* (Shiva Publishing Ltd.), pp. 9–17.

**Stevenson, W.** 1849. The geology of Cockburn Law and adjoining district in Berwickshire. *Trans. Roy. Soc. Edinburgh*, Vol. 16, pp. 33.

**Walker, F.** 1928. The plutonic intrusions of the Southern Uplands east of the Nith Valley. *Geol. Mag.*, Vol. 65, pp. 153–162.

**Wilson, G. F. and Flett, J. S.** 1921. The lead, zinc, copper and nickel ores of Scotland. *Special Report Mineral Resources GB*, Vol. 17.