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Mineral Reconnaissance Programme

The potential for gold mineralisation in the British Permian and Triassic red beds and their contacts with underlying rocks

Department of Trade and Industry

MRP Report 144

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R C Leake, D G Cameron, D J Bland,
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BRITISH GEOLOGICAL SURVEY

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SUMMARY

A review of the potential for gold and related mineralisation in Permian and Triassic red beds and their contacts with other sequences has been carried out for the whole of Britain. This follows on from the MRP discoveries of gold in Devon and the formulation of a model to account for the association of gold-bearing mineralising solutions with red-bed basins and the sites of gold deposition with interfaces with more reduced rocks and fault zones carrying more reduced fluids. Attention has been focused on areas close to the contacts between Permian or Triassic rocks and underlying rocks, on sequences containing alkali basaltic rocks of Permian age and on areas of extensive reddening of rocks beneath the Permian land surface.

Drainage sampling in the Mauchline Basin of red sandstones, sedimentary breccias and alkali basalts of Permian age revealed that gold was widespread (present in 38 out of 76 panned concentrates collected) and locally abundant. The gold is relatively poor in silver (median 3.0% Ag) and rich in copper (26% of grains with >0.6% Cu) and there are also several grains of palladian gold (maximum 6.1% Pd). Inclusions in the gold are mostly selenides of Hg and Cu, with smaller numbers of other selenides and isolated examples of palladium telluride, cobaltite and chalcopyrite. Apart from the last two minerals, this is an inclusion assemblage very similar to that seen in the gold from the Crediton Trough in Devon. The distribution of Au in drainage sediment shows some positive correlation with that of Fe, Ba and Hg, but not As.

Limited drainage sampling was also carried out at isolated sites in the Vale of Eden, Ingleton Coalfield, Charnwood Forest, West Midlands, Malverns, Mendips, Quantocks and Brendon Hills. Gold was found in drainage sediment in Charnwood, in the Weatheroak area north of Redditch, at the south end of the Malvern Hills, south of Radstock, near Wells, to the east of Wiveliscombe and west of Tiverton. The auriferous drainage sites represent 65% of those sampled.

Limited rock sampling was carried out from carbonate horizons in the reddened coal measures of Ayrshire. These rocks are considered to be the oxidised remnants of coal seams and therefore the potential sites of metal deposition from oxidised mineralised solutions, but no evidence of Au or other metal enrichment was found by chemical analysis. Two grains of gold were extracted by panning from an exposure of soft altered alkali basalt and some of the eight analysed samples of alkali basalt, though not enriched in Au, show evidence of hydrothermal alteration. Two samples of a sandstone raft within the alkali basalt were found to be impregnated with native copper (with 0.36% Cu).

This orientation and reconnaissance exploration has demonstrated that gold is associated with the Permian red beds of Britain, especially where alkali basalts are present within the sequence, and to a lesser extent with Triassic rocks. The findings support the mineralisation model, developed from previous MRP work in Devon, which envisages that significant amounts of gold can be carried in oxidised solutions which typically circulate within red-bed basins and that deposition is favoured where these solutions are reduced by reaction with unoxidised rocks or fluids of different composition. Further exploration is recommended, particularly in the Mauchline Basin.

INTRODUCTION

The examination of the mineral potential of the Permian and Triassic rocks of Britain follows on from the discovery of a close association between gold and the Permian red-bed sediments and volcanics in Devon (Leake et al., 1991; Leake et al., 1992; Cameron et al., 1994). As a result of this work, a model has been formulated to account for an association of gold with the boundary between the red beds and underlying more reduced strata. This model envisages the leaching of gold from a dispersed large-volume source by breakdown of sulphide minerals due to the activity of saline oxidising fluids which typically circulate within a red-bed basin. Under these conditions the gold is carried as a chloride complex. If this type of solution is concentrated and focused it can form an important mineralising solution which is likely to precipitate all or most of the gold if it meets a more reduced fluid or reacts with more reduced rocks. Thus the contact zones between red beds and underlying rocks, whether unconformable or faulted, constitute the most favourable environment for gold precipitation. Gold solution chemistry indicates that precipitation of gold could occur within the stability field of hematite, where sulphate is the dominant sulphur species. This can result in the separation of gold from most other metallic elements, which remain in solution under these conditions. In Devon, the Permian sequence includes alkali basalts and unusual alkali lamprophyric lavas, and these igneous rocks may represent the ultimate source of much of the gold and, more particularly, palladium and platinum. The present study was designed to look for evidence of gold in environments considered to be geologically favourable and to establish whether the presence of alkali basalt, which, apart from Devon, occurs within the Permian sequence only in Southern Scotland, is important for the occurrence of gold and/or platinum group minerals.

The nature of the gold associated with the oxidising environment of transport and deposition is distinctive. This fact is apparent from BGS gold characterisation data, which comprise electron microprobe determinations of the internal chemistry of sectioned alluvial gold grains (Leake et al., 1995; Leake and Chapman, 1996). BGS has investigated over 8000 gold grains from many sites in Britain and from several other countries round the world. Palladium, a platinum group element, is frequently alloyed with the red-bed type of gold, in amounts up to about 6% Pd, because in the red-bed environment this element behaves in a similar way to gold. Copper may also be present alloyed with the gold or associated with the gold as the intermetallic compounds Au_3Cu and AuCu (auricupride). In some grains platinum is also present alloyed with the gold. In many grains a silver-rich gold is intergrown with the silver-poor palladium-bearing gold.

Most alluvial gold grains contain microscopic inclusions of sulphide and other minerals. A very distinctive feature of the red-bed gold is the absence of sulphide inclusions and the presence of selenide minerals and sometimes tellurides and arsenides. This character arises because selenides, tellurides and arsenides are stable under more oxidising conditions than corresponding sulphide minerals.

Permian, and especially Triassic rocks, are very widespread in Britain, from the north of Scotland to south-west England. Their main outcrops are shown in Figures 1 and 2. In Permian and Triassic times Britain was a land of considerable relief. In the Midlands and South Wales areas Triassic rocks rest directly on older rocks and Permian rocks are generally absent. In contrast, in northern England and southwest England both Permian and Triassic rocks are present.

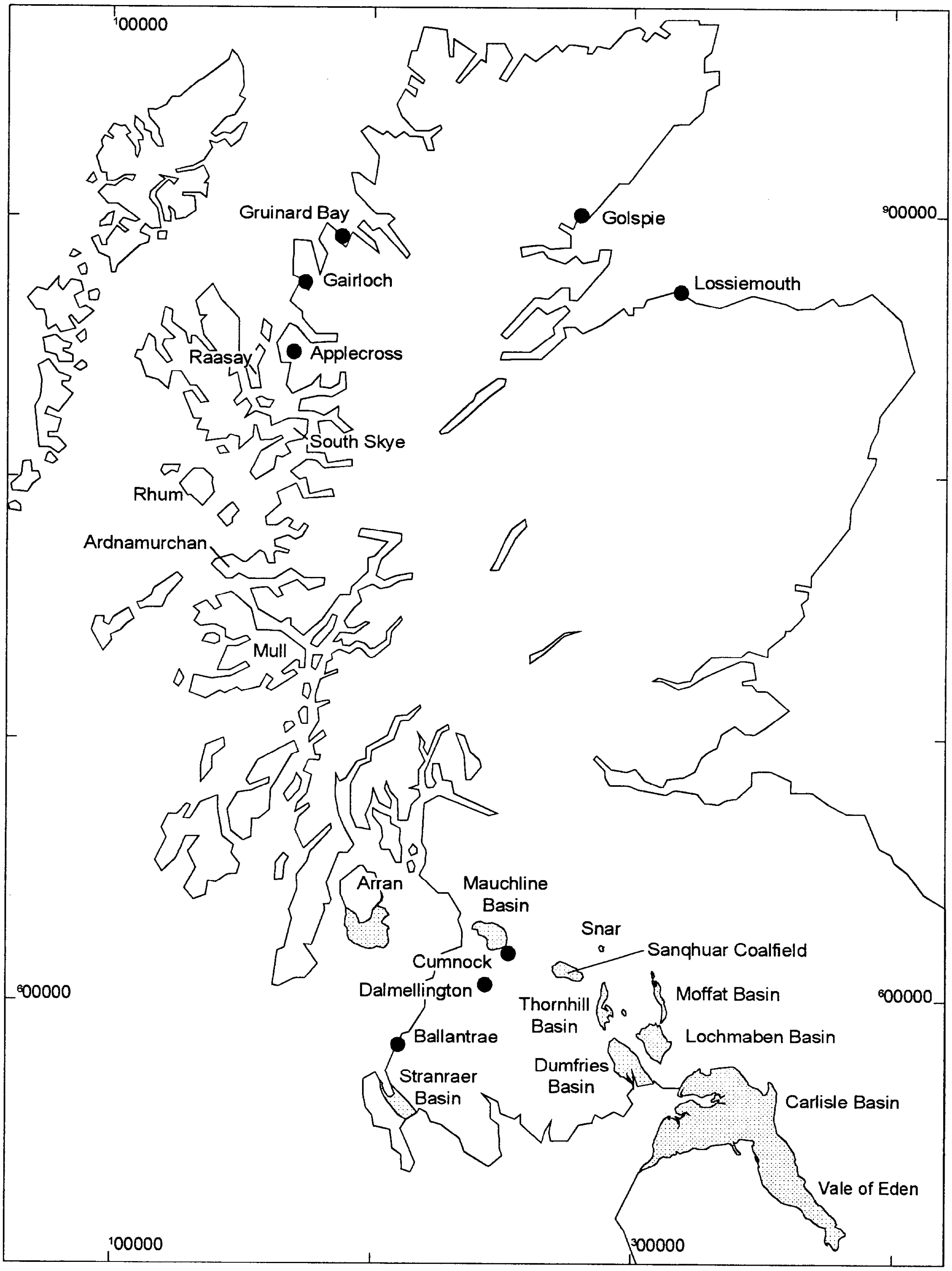

Figure 1 Simplified map of northern Britain, showing location of Permian and Triassic red beds

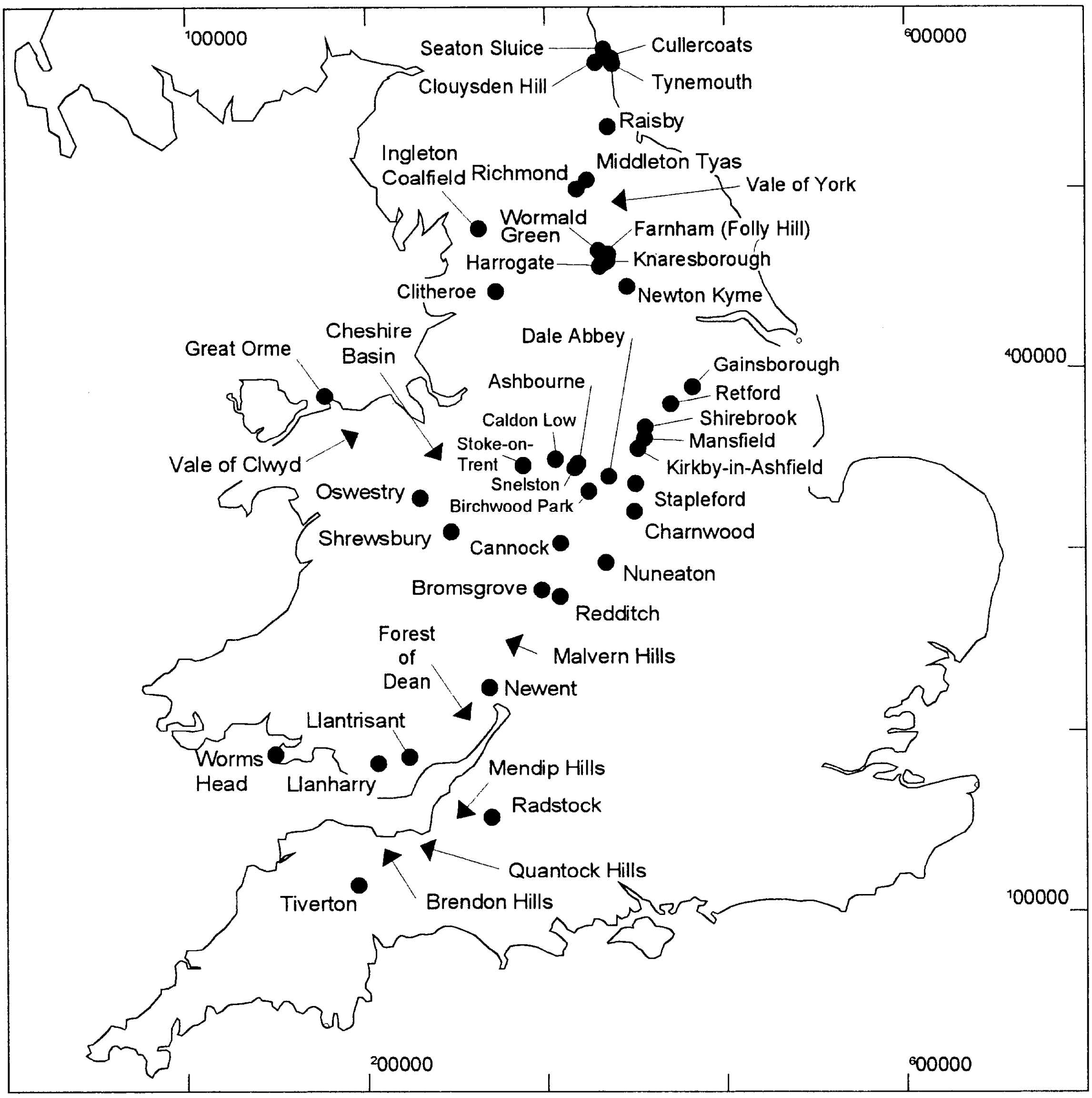

Figure 2 Simplified map of southern Britain, showing locations of areas mentioned in text

In mineral exploration, consideration has to be given to the relative values of any minerals present and the likely size of potentially economically interesting targets. Thus a potentially economic target of a high value commodity like gold can be much smaller than for less valuable metals like copper. There are many small occurrences of base-metal mineralisation within the Permian and Triassic rocks and it is necessary to establish whether any of these suggests the presence of more substantial mineralisation before exploration activity can be recommended. However, exploration for precious metals can more readily be justified.

The present project commenced with a desk study of the red Stephanian, Permian and Triassic rocks of Britain and their associated mineralisation. Consideration was also given to the nature of underlying rocks and their contacts with the overlying red beds. Particular attention was paid to evidence of significant interaction between the red-bed environment and the underlying rocks, manifest by pervasive or partial reddening. Huge variations in the degree of this interaction is evident between different parts of the country. Thus complete oxidation exists in rocks below the Permian unconformity in Ayrshire to a depth of 425 m while in north-east England similar reddening is present only to a depth of a few metres. Much, if not most, of this oxidation probably took place before deposition of Permian rocks.

Following this study, a limited amount of drainage sampling was carried out in as many different areas of Permian and Triassic rocks as possible, where these are not mantled by extensive glacial drift. Sites were generally chosen close to unconformable or faulted contacts between the Permian and Triassic red beds and underlying rocks or in areas where mineralisation was known to be present within the red-bed sequence. This was augmented by limited rock sampling, either in isolation, as in the case of cliff exposures at Tynemouth, or in conjunction with drainage sampling. Much of the survey was of an orientation nature, though more detailed drainage sampling was undertaken in the Mauchline Basin of Ayrshire because of promising discoveries at the start of the field work.

Unfortunately, from an exploration point of view, most Permian and Triassic rocks in Britain are very poorly exposed because they are relatively soft. This means that locating the source of the several new drainage occurrences of gold discovered in the course of this project is difficult. Nevertheless sufficient data were obtained to give, in conjunction with published information, some general picture of the mineral potential of these rocks. Several of the new occurrences of gold merit follow-up exploration, but because of the termination of the Mineral Reconnaissance Programme this has not been possible.

PERMIAN AND TRIASSIC ROCKS AND ASSOCIATED MINERALISATION

Northern Scotland

In Northern Scotland outcrops of Permian and Triassic rocks are generally small and scattered (Figure 1). Triassic rocks occur around Golspie on the north-west shore of the Dornoch Firth and Upper Permian and Triassic rocks occur around Lossiemouth on the south shore of the Moray Firth. Around Lossiemouth, aeolian and fluviatile sandstones overlain by a calcrete, rest with slight unconformity on sandstone with pebbly beds of fluviatile origin, calcareous sandstone and cherty limestone of either early Carboniferous or late Devonian age. Base metal mineralisation is present, particularly in the sandstones, with baryte, hematite, fluorite, calcite, galena and pyrite. The mineralisation is in the form of joint coatings, veinlets, zones with patchy cementation or nodules of fluorite or baryte and silicified zones with sporadic disseminated galena.

There are several small outcrops of Permian and Triassic rocks in north-west Scotland (Figure 1), e.g. at Gruinard Bay, Gairloch, Applecross, Raasay (Bruck et al., 1967), south Skye (Steel et al., 1975), Rhum, Ardnamurchan and Mull. The age of these rocks is usually uncertain and, accordingly, they are often referred to by the term 'New Red Sandstone' (e.g. Warrington et al., 1980). Except on Skye and Mull the 'New Red Sandstone' rests on the Torridonian sequence. Since this is also an oxidised sequence there is little potential for reduction reactions controlling deposition of mineralisation at boundaries between the two sequences. In Skye the 'New Red Sandstone' also rests on the Cambrian quartzite and limestone and in Mull it also rests on Moine rocks. However, the exposures are very small and not likely to be worth investigating for mineralisation.

The Stornoway Formation in the Outer Hebrides is thought to be late Permian to Triassic in age (Fettes et al., 1992). It consists of up to 4 km of conglomerates of Lewisian provenance and is dominated by acid gneiss which is unlikely to be a productive source of metals on oxidative weathering.

Southern Scotland

Arran

A well developed sequence of Permian and Triassic rocks is present on the Island of Arran (Tyrrell, 1928). The Permian and Triassic strata occur in an isolated exposure in the north of the island, along the east coast and in the southern half of the island (Figure 1). In the north Permian strata are in faulted contact with Dalradian strata and rest unconformably on Coal Measures from which coal was worked. On the east coast north of Brodick, they rest unconformably on Coal Measures and are also in faulted contact with Upper Devonian red-brown cross-bedded sandstone. On the west coast, Permian rocks rest unconformably on the Upper Devonian and are overlain by Triassic rocks. South and south-west of the Central Ring Complex, Permian strata rest unconformably on the Lawmuir Formation of Dinantian age, consisting of cyclic sandstone, siltstone and mudstones, and on basalt of the Clyde Plateau lavas and are also faulted against Upper Devonian.

Apart from the occurrence of basalt at the base of the Permian sequence in the small inlier in central southern part of the island, volcanics occur only in the form of abundant debris in the Brodick Breccia, suggesting near proximity to a volcano. Sedimentary rocks of Permian age comprise red aeolian sandstone (Piper, 1970) and alluvial fan breccias. These are overlain by yellow and red sandstones with thin conglomerate horizons and mudstones which are probably at least partly Triassic in age and are succeeded by Triassic fluvial sandstone and mudstone with pedogenic limestone.

Much of the Carboniferous sequence on Arran is oxidised as a result of the influence of fluids derived from the Permian (Bailey, 1926). At Corrie some 175 m of Carboniferous rocks, including shales, limestone and sandstone, are reddened. This suggests a tremendous amount of interaction between oxidising fluids and the underlying rocks, though this probably took place before deposition of the red beds. Leaching of Carboniferous shales and volcanics would be likely to release large amounts of metals into solution. However, there are no records of mineralisation in the Permian or Triassic rocks on Arran.

No field work was carried out in Arran but there are several drainage anomalies of potential interest in sieved sediment samples (British Geological Survey, 1993) and panned concentrates (Beer, 1988). Unfortunately gold has not been analysed in any of these samples. The region to the south-east of the central ring complex is marked by relatively high levels of As, Mn, V and perhaps Cu, Sb and Bi in some drainage samples and this area should be investigated further. There are also isolated anomalies for Cu and Pb in the southern part of the island which merit further work.

Mauchline Basin, Ayrshire

The Mauchline basin of Permian rocks (Eyles et al., 1949; Mykura, 1967) is located within the Ayrshire coalfield to the west of the town of Ayr (Figure 1). The area is mainly gently rolling farmland cut by the deeply incised valleys of the Water of Ayr and the Lugar Water. In the past there has been extensive coal working with some shafts cutting through the Permian rocks to reach the coal seams beneath, and these reveal complete oxidation of the rock beneath the Permian sequence to a depth of 425 m and oxidation of fractured rock down to a depth of 590 m below the base of the Permian. This is the greatest degree of oxidative weathering recorded anywhere in Britain (Mykura, 1960). In addition, there are many coal seams that have been partly or completely oxidised and converted to carbonate rocks or to hematitic material. Because of the extensive shafts and boreholes in the area it was possible to trace the gradations between coal seams and carbonate horizons (Mykura, 1960). This process is particularly interesting as coal seams could have been important precipitation barriers during the early stages of downward penetration of the oxidising fluids. It has also been suggested that the Ca and Mg which have replaced the coal were derived from the weathering of the Permian alkali basalts.

At the base of the Permian rocks in the Mauchline Basin is a sequence of alkaline basic lavas and tuffs (Figure 3), similar in composition to those found in the Crediton Trough, Devon. Overlying the basalts are mostly red, dune sandstones and around the basin are volcanic necks which were probably feeders to similar volcanic rocks which once covered all or most of the area and were subsequently removed by erosion. In addition, there are also intrusive sheets of alkali dolerite which probably represent pulses of alkali basaltic magma which did not reach the surface. The reconnaissance drainage exploration and limited rock sampling carried out in this area is described below (page 19).

Stranraer Basin

The Stranraer Basin is a half-graben structure with up to 2 km of strata preserved adjacent to the Loch Ryan Fault which forms its eastern boundary (Stone, 1995). The sequence thins westward where it rests unconformably upon Lower Palaeozoic greywackes. Thin basal sandstones and shales containing one basalt sheet of Carboniferous age are overlain by breccias with greywacke clasts in a red sandstone matrix, and red sandstones. No evidence of mineralisation is known within the basin.

Sanquhar Coalfield

There are some 240 m of Upper Coal Measures in the Sanquhar Coalfield (Simpson and Richey, 1936; Davies 1970). The lower three quarters of the sequence consists of alternating red and grey mudstones, siltstones and sandstones with some coals while above this all the strata are red. It is has been suggested that the red colour of these rocks is an original feature but it is perhaps more likely that the reddening reflects the oxidation of strata beneath the early Permian land surface or red beds which have since been removed (Davies, 1970). A small area of highly altered and decomposed basic lavas of possible Permian age occurs at east end of the coalfield (Simpson and Richey, 1936). The lavas rest on productive Coal Measures which in this area are also reddened. The presence of teschenite sills within Lower Coal Measures rocks in the area and the existence of several volcanic vents in the east of the basin also suggest that Permian rocks, including lavas, once covered the region.

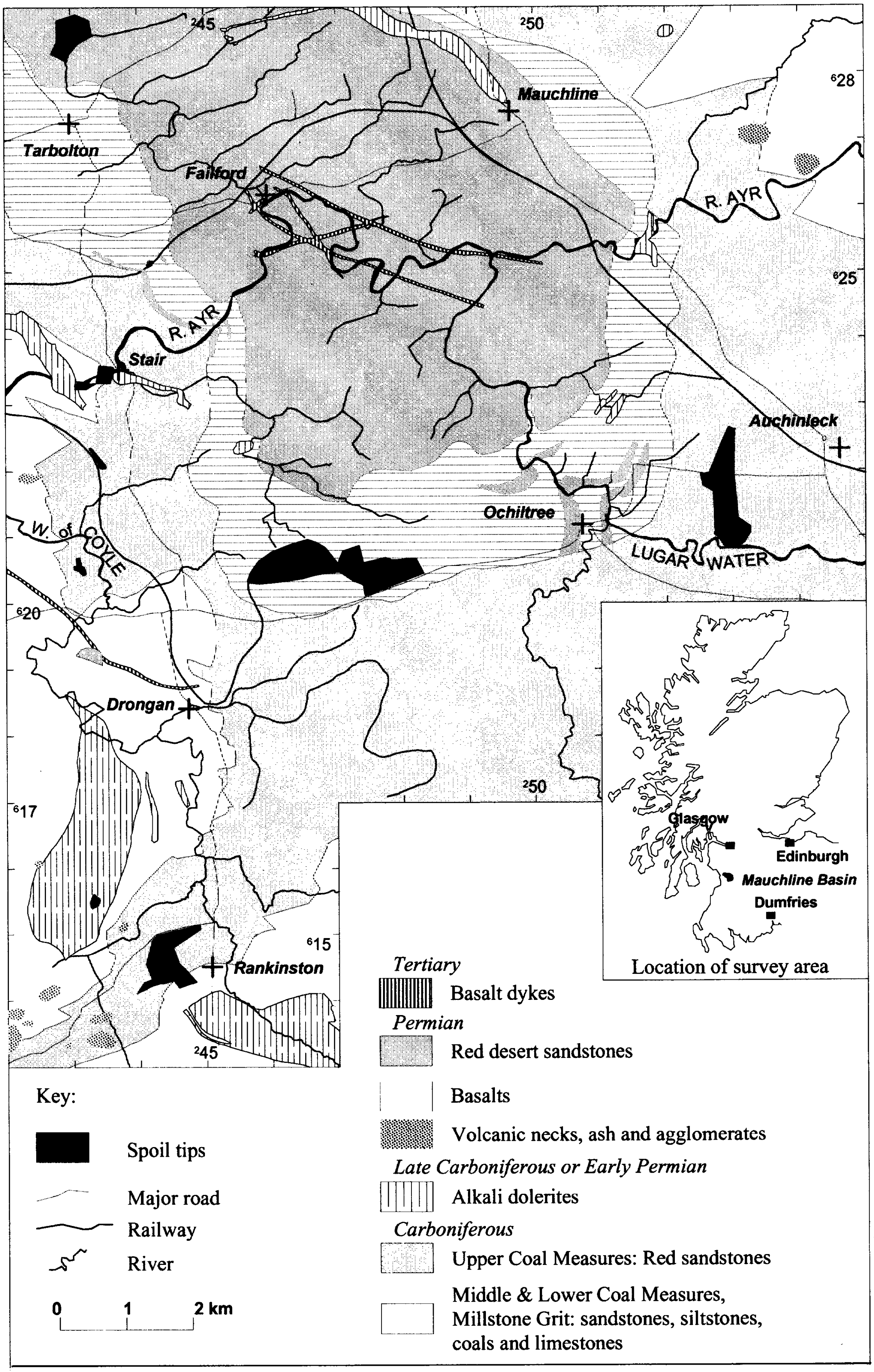

Figure 3 Simplified geological map of the Mauchline area

Thornhill Basin

The geology of the Thornhill Basin has recently been re-examined as part of the BGS Southern Uplands Regional Geological Survey (McMillan and Brand, 1995). The basin is filled with Westphalian strata which locally overlie older Carboniferous rocks and are in turn overlain by Permian basalt, red breccias and sandstones. The Westphalian strata are divided into Lower, Middle and Upper Coal Measures and comprise fine to medium grain sandstones, siltstones, mudstones and seatearths. Though coal seams may occur, none have been observed at surface or in boreholes. Most of the Westphalian strata are reddened and this is thought to reflect oxidation of the strata beneath the late Carboniferous and early Permian land surface. The Carboniferous strata are overlain unconformably either by a thin fluviatile sandstone or, particularly in the north, by streamflood breccias interbedded with alkali olivine basalt of Permian age. The basalt is much decomposed and up to 45 m thick (Simpson and Richey, 1936); it is separated into at least three flows by sandstone partings or surfaces with fissures filled with sandstone. Basalt breccia is also present at some localities. The youngest rocks are red aeolian sandstone of variable thickness, thought to represent a desert dune deposit. In the west of the basin the Permian strata rest on Carboniferous strata but in the east they are frequently in faulted or unconformable contact with the underlying Lower Palaeozoic rocks.

The Thornhill Basin is one of several Upper Palaeozoic basins in Southern Scotland which are thought to have developed following reactivation of Caledonoid structures. Several stress regimes have been proposed to account for the development of the Thornhill Basin (McMillan and Brand, 1995) but the most favoured envisages N-S and NNW-SSE tension related to dextral strike slip on major Caledonoid strike parallel faults, such as the Orlock Bridge fault. Minor Ba-U-V mineralisation is recorded at the Carboniferous/Silurian unconformity at the north end of Thornhill Basin at Dalveen [NS 875 075]. Drainage exploration carried out in this area is described by Leake and Cameron (1996).

Dumfries Basin

Permian rocks of the Dumfries Basin consist of breccias and debris flow deposits in the west and aeolian sandstone on east side (Brookfield, 1980). Streamflood channel deposits made of poorly sorted gravels are present near the edge of alluvial fan deposits on the western margin of the basin. Sheet flood and braided stream deposits also occur in the basin. In contrast to the Thornhill Basin to the north, there seem to be no volcanic rocks present in the basin. Extensive reddening of the greywackes between the present southern margin of the Thornhill Basin and the northern margin of the Dumfries Basin suggest that Permian rocks were once continuous between the two but have been removed by erosion. Limited rock and drainage sampling in the Clauchrie plantation in this area (Leake et al., 1996) showed no evidence of mineralisation in heavily oxidised greywackes with reduction spots.

Lochmaben Basin

The Permian rocks of the Lochmaben Basin comprise mostly aeolian sandstone with some breccia at the base derived from sources from the north (Brookfield, 1980). There is also a small amount of fluviatile sandstone at the western margin with ephemeral desert floor stream deposits and some temporary lake deposits. A small amount of basalt was discovered along the northern margin of the basin during recent BGS remapping of the area.

Moffat Basin

The Permian rocks of the Moffat Basin consist mostly of breccia derived from the east. Scree deposits on the eastern margin of the basin pass rapidly upwards into fine ephemeral stream deposits (Brookfield, 1980). The presence of palladian gold and gold with selenide inclusions in a tributary of the Smid Hope Burn to the north of the Moffat Basin (Leake et al., 1993) and at Glengap Burn, about 1 km to the east of the Moffat Basin (Leake et al., 1996), suggests that Permian rocks may have once covered more of the Southern Uplands and that interaction between oxidising fluids and the Lower Palaeozoic basement may have been extensive within some fault zones.

Other small areas of Permian rocks and Carboniferous red measures in Southern Scotland

Coastal exposures of Permian breccias and aeolian sandstone occur at Ballantrae Bay on the Clyde coast (Figure 1). The breccias are rich in locally-derived serpentinite debris. Small areas of reddened Carboniferous strata occur in the Dalmellington and Cumnock areas to the south and south-east of the Mauchline Basin respectively (Figure 1). The presence of alkali teschenite and essexite sheet intrusions in the same general areas suggest that Permian rocks, including basalts, were once present but have been removed by erosion. A Permian debris flow deposit derived from the ENE occurs as an outlier within the Southern Uplands terrane in the Snar Valley, to the north of Leadhills (Brookfield, 1980).

North-west England

Carlisle Basin

Triassic rocks are predominant at surface in the Carlisle Basin (Figure 1). On its northern margin there are outcrops of reddened rocks of probable Upper Coal Measures age around Canonbie but exposure is generally poor, except in the Liddle Water. Greenish patches are recorded in marls and seem to be associated with carbonaceous material. On the north-eastern and eastern margins of the basin there are outcrops of basal Permian conglomerate up to around 10 m in thickness. Red limestone fragments are common in the conglomerate but little or no red staining is seen in the Carboniferous sandstones and shale below. Overlying the conglomerate are the St Bees Shales, comprising red shales and mudstones with horizons of gypsum and nodules of red and green argillaceous limestone in the lower beds.

On the Solway coast, at Maryport, the Triassic Sherwood Sandstone Group is in faulted contact with Coal Measures. Reddened Coal Measures are present to the south of Maryport and in patches between Maryport and Whitehaven, especially in the region of old iron workings and small outcrops of Permian breccia to the east of Whitehaven. East of Maryport, the Lower and Middle Coal Measures have been oxidised and the St Bees Shales are exposed resting directly on reddened Carboniferous. Previous MRP drainage sampling between Maryport and Cockermouth (Cooper et al., 1991) found several copper anomalies, due to the presence of chalcopyrite, around Broughton Moor to the south of Maryport. Mercury anomalies, due to the presence of cinnabar, and isolated grains of gold were present in the same area. One gold grain polished and analysed by electron probe contained an inclusion of chalcopyrite and is compositionally completely different from the distinctive type of gold associated with the Permian rocks of southern Scotland or Devon. This suggests that the gold is derived from mineralisation in the Lake District or possibly the Southern Uplands, rather than the local red-bed environment, and that glacial transport was responsible for its presence in the area. Further work is required to prove this hypothesis and to eliminate entirely the possibility of local sources of the mineralisation, perhaps within Carboniferous rocks.

Along the south side of the Carlisle Basin, the Permian and Triassic succession rests unconformably on Carboniferous rocks of varying age and the thickness of Permian rocks increases south-eastwards towards the Vale of Eden. The lowest Permian rocks comprise the aeolian Penrith Sandstone and the overlying St Bees Shales or equivalent Eden Shales. Large areas of reddened rocks occur to the south of Carlisle, though much of this area has a thick covering of glacial drift; reddening extends for up to 6 km away from the outcrop of the Permian rocks and is well developed in the Coal Measures but less intense in the Dinantian limestone below (Trotter, 1939, 1953). Drainage sampling was carried out in the Chalk Beck which drains the Permian and Triassic and the underlying Carboniferous rocks on the northern edge of the Lake District and is described below (page 36).

Vale of Eden

Along most of the western margin of the Vale of Eden (Figure 1), the Triassic St Bees Sandstone is in faulted contact with Carboniferous and older rocks. More locally, especially around the Crowdundle Beck, the older Eden Shales and Penrith Sandstone are in contact with Carboniferous rocks and the Lower Palaeozoic rocks of the Cross Fell inlier. A band of hematite 0.4 m thick was recorded lying along bedding in the Melmerby Scar Limestone just below the sub-Permian unconformity in a tributary of Crowdundle Beck [6598 3043] (Arthurton and Wadge, 1981). Drainage sampling was carried out in the Crowdundle Beck and is described below (page 36).

In the southern part of the Vale of Eden, Namurian and Westphalian strata are largely absent and the Permian rests unconformably on Visean rocks as far down as the Great Scar Limestone. Limestones are dolomitised beneath the unconformity, and other rocks are reddened. All the Namurian and Westphalian strata of the Stainmore outlier are affected by reddening, though they are 2 km from the nearest outcrop of the Permian Penrith Sandstone. Some interleaving of red and grey measures is present in the Stainmore outlier and the presence of thin coals suggests potential for the precipitation of metals by reduction. Drainage sampling was carried in the Argill Beck which cuts through the partially reddened Westphalian strata of the Stainmore outlier and is described below (page 36). Drainage sampling was also carried out in Scandal Beck, at the southern margin of the Vale of Eden, at a site within the Permian Penrith Sandstone just downstream from its contact with Visean limestone.

Ingleton Coalfield

Permian breccia rests on reddened Westphalian rocks in the Ingleton outlier (Figure 2). The red strata are thought to be of Upper Coal Measures age. A panned concentrate sample was obtained from the Cant Beck draining the Ingleton outlier.

Clitheroe area

Three small outcrops of Permo-Triassic rocks occur to the west of Clitheroe, in Lancashire (Figure 2). They comprise red marl, red sandstone and red conglomeratic sandstone (Earp et al., 1961) and rest unconformably on Namurian and Dinatian rocks which are frequently reddened. Reddened Carboniferous rocks also occur in the area to the north-west of the Permian outcrops, suggesting that Permian rocks previously extended much further than their present extent. No sampling was carried out in this area.

East Lancashire

Permian and Triassic rocks rest unconformably on Westphalian and older Carboniferous rocks in the region to the west, south-west and south of Clitheroe. However, the thick glacial drift cover means that there are virtually no natural exposures and information about the rocks and their relationships with underlying strata comes mostly from boreholes. No sampling was carried out in this area.

North-east England

The Upper Permian rocks of north-east England comprise mostly dolomitic carbonate rocks and red mudstones and siltstones deposited in the tropical Zechstein Sea. At the base of the Upper Permian is a metal-rich, laminated, bituminous, argillaceous dolomite, the Marl Slate Formation, which is the lateral equivalent of the North-West European Kupferschiefer. Underlying these rocks are the Basal Permian (Yellow) Sands and Breccias, an aeolian desert sand deposit of varying thickness (Smith, 1989). The sub-Permian surface shows reddening but to a much lesser extent than in north-west England, typically between 6 and 12 m.

Tynemouth

Reddened Carboniferous strata are exposed beneath Permian rocks in the cliffs below Tynemouth Castle, around Cullercoats harbour, near Seaton Sluice and in a quarry at Clouysden Hill [284 701]. Disseminated pyrite is present in the Carboniferous rocks immediately beneath the unconformity and is thought to have originated from solutions percolating down from the sulphidic Marl Slate Formation which reduced the reddened Carboniferous rocks adjacent to the unconformity.

County Durham

Reddened Carboniferous rocks occur beneath the Permian in this area (Smith and Francis, 1967). In addition there are grey pyritic rocks up to 3 m thick immediately below the unconformity. Below the completely reddened zone, which reaches 20 m in thickness, there is locally a zone in which reddening is confined to sandstones. This reddening of the Carboniferous rocks is absent adjacent to coals seams, though some coals are totally oxidised. The Basal Permian (Yellow) Sands and Breccias are frequently pyritic below the surficial weathering zone, probably due to the deposition from solutions percolating down from the Marl Slate Formation. Small amounts of galena, chalcopyrite, pyrite, sphalerite and baryte are associated with the Marl Slate and adjacent rocks. Copper mineralisation, comprising mostly chalcopyrite and malachite, is present in brecciated dolomite in the abandoned railway cutting at Raisby [43502 53490] close to the east-west Butterknowle fault. No sampling was carried out in this area.

Richmond

Copper mineralisation occurs at several localities in the Richmond area, including Middleton Tyas, just west of the outcrop of Upper Permian rocks, where small tonnages of very rich ore were produced from veins and irregular bodies within the Upper Dinantian Underset Limestone and the top of the underlying sandstone. The mineralisation occurs as chalcopyrite, bornite and secondary copper sulphides. West of Middleton Tyas there are veins containing both copper and lead mineralisation which are linked to typical North Pennine lead veins, implying some kind of transition between lead and copper mineralisation in the area due to mixing of different mineralising fluids (Dunham and Wilson, 1985). Alternatively, the copper mineralisation may largely be of red bed / supergene type which originated from fluids circulating in the Permian and penetrating into the underlying rocks. Preferential deposition took place within chemically reactive horizons within the underlying Carboniferous sequence. Much of the area has a thick mantle of glacial drift which hampers exploration and conceals the relationship between the Permian sequence and the underlying Carboniferous rocks. Exploration carried out previously as part of the MRP involved extensive soil sampling, augmented locally by power augering to the bedrock/till interface and rotary percussion drilling into bedrock (Wadge et al., 1982). High values of Cu in soil are related to the presence of limestone in which copper is irregularly enriched and concentrated selectively in faults and joints. In addition, five cored holes were drilled, of which two went through the Permian into Carboniferous rocks beneath. No chemical analyses were obtained of material from these holes except for drill sludges over a 20 metre section of the Permian sequence, which did not show evidence for the presence of significant mineralisation. Oxidation was present in about 14 m of chert and cherty limestone below the unconformity in one of the holes but there was no visual evidence of any significant mineralisation. In the other hole which intersected the unconformity only 1.6 m of oxidised Namurian shale was recovered without obvious mineralisation. The metal rich Marl Slate Formation was not intersected in either of the holes.

Vale of York

South of Middleton Tyas for about 3 km the Brotherton Formation rests unconformably on Namurian strata and older Permian rocks are absent. South of this older Permian strata reappear and locally there is a breccia at the base of the Permian. Leaching and red staining of sandstone below the unconformity is local. Minor mineralisation of baryte, galena, fluorite and sphalerite is present in veins, breccias and vugs within the Permian limestone

In the Harrogate and Knaresborough area, Carboniferous sandstones below the Permian commonly show signs of leaching and red-brown and purple staining. Geologically the area is of interest because the Permian and Carboniferous sequences are displaced by a set of faults which are thought to be related to the continuation eastwards of the Craven faults. Furthermore, only in the Farnham area is the basal part of the Coal Measures present beneath the Permian; elsewhere the Carboniferous rocks are of Namurian age. Malachite, both as disseminations and as potato -sized masses, was worked in dolomitic limestone of the Cadeby Formation near Farnham, probably on Folly Hill [4349 4608]. Soils in this area contain up to 1600 ppm Cu (Cooper and Burgess, 1993). Copper mineralisation appears to be present within a substantial thickness of the Permian limestone and could have been derived from fluids associated with the overlying Triassic rocks, with fluid movement facilitated by the extensive faulting in the Farnham area. The area as a whole is mantled by drift and only the Permian limestone around Farnham projects above this.

Permian dolomitic limestone at Wormald Green [4300 4650] hosts mineralisation as calcitised displacive anhydrite nodules with sphalerite, marcasite, baryte and galena (Harwood and Smith, 1986). Further south there is also a report of malachite in thin veins within a large quarry of Permian limestone about 0.5 m south of Newton Kyme, near Tadcaster.

South Yorkshire and Nottinghamshire

From Leeds to the Nottingham area, Permian rocks unconformably overlie Westphalian rocks. The area is extensively mantled by drift deposits and most of the information about the Permian rocks and their relationships with underlying rocks is derived from boreholes. East of Wakefield, sandstones are partially reddened down to depths of at least 16 m. In the Goole and Doncaster areas some boreholes show that the reddened zone is missing in a zone about 1 m thick immediately below the Permian unconformity. Pyrite is also often present in the same reduced rocks, as in County Durham, probably reflecting downward percolation of reducing fluids after the late Permian marine transgression.

Retford-Gainsborough area

Staining of the Coal Measures is variably present in rocks at depths between 3 and 22 m below the unconformity. In addition, there are red-coloured rocks up to 125 m thick which constitute an original facies of the Upper Coal Measures. Lithologically these rocks are similar to typical Westphalian grey measures and contain some coals and seatearths. They are transitional between typical coal measures and the blocky red mudstones with thin sandstones but no coals, fossil bands or ironstones which make up the Etruria Marl facies. Sulphides occur in the Lower Marl member of the Don Group but they are less abundant than in the Marl Slate of Durham and include pyrite, sphalerite, galena and chalcopyrite. Zinc, Pb and Mo concentrations in this rock reach 1000 ppm, 1000 ppm and 100 ppm respectively.

Mansfield area

Veinlets and small patches of galena, baryte, pyrite and calcite are recorded in the dolomitic limestone of the Cadeby Formation at several localities in the Mansfield area while sphalerite is recorded from a dolomite bed within the Lower Marl Member of the Don Group (Smith et al., 1967). In the top 10 cm of the Cadeby Formation at Shirebrook, Mansfield and Kirkby-in-Ashfield minute amounts of galena, malachite, wulfenite, uraniferous asphaltite and baryte are found (Deans, 1961). Overlying argillaceous strata are thought to have acted as a cap rock to ascending solutions carrying Pb, Cu, Mo, U and Ba.

North and East Midlands

South Derbyshire

Permian strata thin rapidly westwards and southwards from Nottingham and are absent further south and west where Triassic rocks were deposited directly on a land surface with considerable relief. Baryte cement is present in the Sherwood Sandstone Group and in the overlying pebble beds at Stapleford and Dale Abbey, probably controlled by faulting.

Rivers depositing Triassic rocks in the Ashbourne area flowed from south to north across the area and the relief of the pre-Triassic topography was similar to that of the present day. Sherwood Sandstone Group pebbles suggest a provenance in the SW England to NW France region. Some of the rocks below the Triassic surface are not reddened while in other areas reddening is only to a shallow depth. However, some of the Carboniferous rocks well away from the present outcrop of the Triassic are reddened, reflecting a former more widespread Triassic rock cover. Neptunian dykes of red sediments are common in Visean limestones in the Caldon Low area [408 348] where they occupy fissures partly filled with spary calcite and hematite. The deepest fissure intersected in the Caldon Low borehole was at 292 m below surface and contained calcite replacing clastic grains. Dolomitisation of Dinantian limestones in the Ashbourne area reaches a maximum thickness of 30m and disappears with depth. Copper accompanies Pb and Zn in mineralisation in Dinantian rocks in the Weaver Hills (Chisholm et al., 1988). At Birchwood Park [415 341] a small inlier of Visean rocks within the Triassic outcrop is the location of Pb and Cu mineralisation that was formerly worked. The contact appears to be the main control of mineralisation. Calcareous sandstone is cemented by malachite, and malachite coats nodules of chalcopyrite, galena and cerrusite while there is also calcite, baryte and fluorite veining (Chisholm et al., 1988). Mineral exploration was carried out as part of the MRP along the concealed ridge of limestone beneath a thin cover of Triassic rocks, the Snelston ridge (Cornwell et al., 1995) to investigate the possibility of further mineralisation at the unconformity and particularly in the limestone beneath. Drilling intersected the unconformable contact but showed little evidence of mineralisation. Soil sampling over Limestone Hill, another small inlier further north, showed very high levels of Pb and Ba and lower amplitude Zn and Cu anomalies over the knoll reef limestone and Cu anomalies to the east and north of the limestone. Three holes were drilled in the area, two of which passed through the contact between Carboniferous and Triassic rocks. Replacement style Pb-Zn-Ba mineralisation was intersected in dolomitic limestone in the upper part of the knoll reef (10 m intersection). Malachite staining was present at the Triassic-Dinantian contact in one hole but no mineralisation was found in either the contact zone or the underlying Carboniferous rocks in the second hole.

Within the Triassic sequence in the area an E-W fault cutting Sherwood Sandstone Group near Wootton Lodge contains a vein with traces of galena and copper ores, and debris associated with the old workings at Wootton Grange Mine [40953 34355] contain baryte and galena. Baryte in veins and disseminations is recorded at several localities (Chisholm et al., 1988).

Charnwood Forest

The Mercia Mudstone Group overlaps the Sherwood Sandstone Group and oversteps onto the Precambrian rocks of Charnwood Forest. A marginal facies of coarse breccias and sandstones is developed around the Precambrian inliers, passing laterally within a few metres into normal Mercia Mudstone Group lithologies. Mineralisation is widely associated with these rocks (King, 1968). There are widespread indications of copper mineralisation associated with the unconformity at the base of the Triassic rocks, and occasional mineralisation within Triassic sandstones. Minerals typically present around the unconformity are cuprite, native copper, chalcocite and sometimes native silver. Traces of gold have been recorded in association with vein quartz, particularly in the Upper Siberia quarry at Bardon. As the gold is recorded as filigree in association with carbonate and hematite (King, 1968), similar in shape and association to that found at Hopes Nose in Devon, it can be concluded that it probably originated from oxidising solutions penetrating down into the Charnwood Forest massif from the Triassic red beds above.

Nuneaton

Cambrian rocks occur on the eastern flank of the Warwickshire coalfield where they are overlain by Namurian rocks to the west but faulted against Triassic rocks in the north and east. To the south-east, Triassic sandstone rests unconformably on Cambrian rocks. Baryte vein mineralisation with minor malachite, similar to material from Charnwood Forest, is associated with rocks immediately below the Triassic unconformity (King, 1968). No sampling was carried out in this area.

West Midlands

Cheshire Basin

This area and its surroundings were not investigated because of the attention the basin has received in a recent BGS multidisciplinary study (Plant et al., in preparation).

Staffordshire

Minor amounts of copper are recorded in the Triassic Sherwood Sandstone Group to the north of Cannock, as malachite cement and as malachite and a little cuprite together with galena in ferruginous and calcite-cemented gravel and sandstone (Molyneux, 1873). Similar copper mineralisation occurs in red-facies Keele Formation rocks of Westphalian D age to the south of Stoke on Trent but no details are known. No sampling was carried out in this area.

Bromsgrove-Redditch area

Rocks of Ordovician and Silurian age crop out in the Lickey Hills, to the south of Birmingham. In the same area there are outcrops of Clent Breccias, which are thought to be of Permian age, and locally derived conglomeratic rocks of Triassic age. In the Knowle borehole [1883 7777] green reduction spots are present in sandstone in the Mercia Mudstone Group. The cores of the spots are radioactive nodules up to 1 cm across and the reduced mudstone extends outwards in a halo 5 cm in diameter. Some nodules contain coffinite cores with outer margins of chalcopyrite and niccolite, while others are enriched in vanadium (Old et al., 1991). The Weatheroak Sandstone is a persistent horizon in the Mercia Mudstone Group which can be traced from Longbridge [02 76] to Redditch [07 66]. Copper mineralisation in the form of malachite is present in the basal few centimetres of the horizon at a number of localities. Heavily mineralised samples were obtained from road cuts near Moorfield farm [0639 7291] during the construction of the M42 motorway (K Ambrose, personal communication). The material consists of quartz cemented with copper minerals and dolomite. The copper minerals comprise cuprite, native copper, tenorite (CuO), chalcocite, covellite, malachite and probable chrysocolla, which is the most widespread. Minor amounts of Ba and As and traces of Zn and Ag accompany the copper. Copper mineralisation seems unusually common and rich in this area compared with the Triassic rocks as a whole. This could be related to the concealed extension into the area of the Lickey ridge of Lower Palaeozoic rocks.

Malvern Hills and Newent area

Rocks of the Mercia Mudstone Group are in faulted contact with the Lower Palaeozoic and Precambrian rocks of the Malverns along the eastern edge of the massif. There are also local pockets of rocks of the Sherwood Sandstone Group adjacent to the Malverns. At the southern boundary of the Malverns the Haffield Breccia, of probable early Permian age, rests unconformably on Silurian and Malvernian rocks. It comprises poorly sorted hematite-coated clasts of Malvernian rocks and Silurian sandstone in a matrix of purple to dark red-brown sandy siltstone and mudstone (Worssam et al., 1989). It is overlain unconformably by the Bridgnorth Sandstone, also probably of Permian age, which consists mostly of red-brown aeolian sandstone. This area is of interest because of the presence of Permian rocks resting unconformably on older rocks, an environment not common in the Midlands.

Further south, to the south of Newent, Bromsgrove Sandstone of the Sherwood Sandstone Group rests unconformably on Silurian rocks. A drainage sample was also taken from this environment.

Welsh Borders

In the Welsh Borders to the south and south-west of Shrewsbury, the Coed-yr-Allt Beds of Westphalian C age unconformably overlie Longmyndian, Cambrian and Ordovician strata over a wide area. These rocks are mostly greyish quartzose sandstones and shales with few, if any associated red horizons. The overlying Upper Carboniferous Keele Beds, which comprise purple and brown mudstones and mottled sandstones, and Permian breccia and sandstone, are only locally in faulted contact with the Precambrian and Lower Palaeozoic rocks. Galena is recorded in the Coed-yr-Allt Beds at Hanwood Colliery near Shrewsbury (Pocock et al., 1938). Copper occurs as chalcocite and malachite in or upon baryte veins or brecciated country rock in Longmyndian grits at Westcott, where it was mined, and at Cothercott Hill. It is suggested (Pocock et al., 1938) that the copper was formed subsequently to the baryte. This suggests that copper could be derived from red beds overlying the Longmyndian which have since been removed by erosion. No sampling was carried out in the area but some potential for red-bed copper and gold mineralisation is evident because of the frequent juxtaposition of red beds and older rocks across and within major fault zones.

North Wales

Oswestry

South of Oswestry, the Triassic Sherwood Sandstone Group oversteps the Westphalian to rest on Namurian and then Dinantian limestone and finally Caradocian shales. Red staining and traces of dolomitisation of limestone are present 5 km west of the present boundary of Triassic rocks and there is red and purple staining of Bala shales at three localities (Wedd et al., 1929). Copper is found in association with lead veins in this area but not to the same extent as further north. No sampling was carried out, but the area remains one of interest.

Vale of Clwyd and Great Orme

Westphalian rocks occur in the Vale of Clwyd but they are drift covered. Both and red grey measures are present and there is some interbanding of the two in boreholes. These are overlain by red sandstones of aeolian and fluvial origin of uncertain age which are most likely to be Upper Permian or Triassic. At the Little Orme, the Gloddaeth Purple Sandstone overlies Carboniferous Great Orme Limestone. It is of uncertain age but it could be unconformable on the underlying beds which would probably make it Permian or Triassic. Mines at Great Orme were worked from Bronze Age times for copper. A wide range of copper and other minerals have been reported from here including cuprite, malachite, native copper, and uraninite. Copper mineralisation occurs in Dinantian limestone close to the faulted margin of the red beds. In the Dyserth area, on the north-eastern edge of the Vale of Clwyd, brown iron ore containing lumps of green copper carbonate and copper oxide are present, and elsewhere there are pockets of iron ore along joints and faults in the limestone (Warren et al., 1984). No sampling was carried out in this area.

North Somerset and South Gloucester

The only Permian and Triassic rocks exposed in this area are the Triassic Mercia Mudstone Group. Apart from the typical mudstone facies there is a conglomeratic marginal facies which rests on Devonian and Lower Carboniferous rocks in the north, on Coal Measures rocks in the east and on Lower Carboniferous limestone in the south. Red-stained fissures in Carboniferous rocks are recorded up to 700 m below the base of the Triassic. Strata adjacent to the sub-Triassic unconformity commonly contain masses of coarsely crystalline calcite sometimes with specks of galena, sphalerite of copper secondary minerals (Green, 1992).

Radstock

In the area to the south of Radstock, basal dolomitic conglomerate rests on Pennant Series Upper Coal Measures rocks; the overlying mudstone of the Mercia Mudstone Group is overlapped by the Penarth Group and the Lias, representing deposits of the late Triassic transgression and subsequent marine environments. These marine rocks are significantly different in chemistry from the Triassic red beds. Accordingly they represent a potential precipitation barrier in the highest part of the Triassic sequence where material carried in oxidising solutions circulating within the red beds could be deposited as a result of reduction reactions. No systematic exploration of this level has been attempted in this study but a drainage sample taken from a site draining Mercia Mudstone Group rocks immediately below the contact with Penarth Group and Lias near Radstock contained gold (page 43).

Mendips

The thickness of Triassic rocks increases substantially from north of the Mendips towards the south, reaching over 450 m to the south of the Mendips. A basal dolomitic conglomerate overlies the Carboniferous limestone of the Mendips and passes laterally into red mudstones of the Mercia Mudstone Group. Hematite occurs in pipes and coating the sides of fissures in the Carboniferous limestone and Triassic dolomitic conglomerate or as patchy replacements of the latter. Also within the dolomitic conglomerate are pockets containing wad and rare secondary Pb and Cu minerals in vugs. A drainage sample was collected at a site draining the Mercia Mudstone Group and basal conglomerate resting on Carboniferous limestone near Wells.

West Somerset

Quantock Hills

The Devonian rocks of the Quantock Hills are unconformably overlain by Mercia Mudstone Group, mostly underlain by the Otter Sandstone Formation. The south-western boundary of the Quantocks is fault controlled, bringing mostly Mercia Mudstone against the Devonian rocks. North of the Quantocks there is a series of small elongate inliers of Devonian and Carboniferous rocks. Copper was worked in the eighteenth and early nineteenth century at Dodington on the north-east edge of the Quantocks, firstly as carbonate in the Otter Sandstone and then as sulphides as vein mineralisation in the Devonian rocks. Drainage samples were taken in this area and near Goathurst, towards the north-eastern margin of the Quantocks and the results are discussed below (page 43).

Brendon Hills

Between the Quantocks and Brendon Hills the Devonian rocks of Exmoor are unconformably overlain by Permian as well as Triassic rocks. The oldest rocks, the Wiveliscombe Sandstones, are generally thickly bedded, well graded and friable except where locally cemented by carbonate. Overlying these rocks are a succession of sedimentary breccias, mudstone, pebble beds and sandstones and finally the Mercia Mudstone Group. Drainage sampling was carried out at a site over the Budleigh Salterton Pebble Beds, of Lower Triassic age, and at two sites on the basal Permian Wiveliscombe Sandstones, one of which is downstream of its unconformable contact with Famennian Pilton Shales and is described below (page 43).

Tiverton Basin

The Tiverton Basin is parallel to the Crediton Trough and is similarly filled with Permian sedimentary breccia and sandstone with some interbedded basalt lavas. However, in contrast to the Crediton Trough, there has been no recent mapping of the area. Limited sampling in the area as part of previous MRP work (Cameron et al., 1994) suggested that gold was widespread in drainage sediment. Two further sites were sampled as part of this survey but there has been no attempt to carry out systematic exploration in the area.

South Wales

South Wales was an elevated area during the Permo-Triassic and only thin deposits of Triassic rocks are present. At Worms Head there is a small outcrop of Triassic conglomerate resting on Carboniferous limestone at Port Eynon while further east there are exposures of basal dolomitic conglomerate which pass laterally into siltstones and mudstones typical of the Mercia Mudstone Group. South of Llantrisant only the basal beds are present; these are much veined with calcite containing minor galena, together with pyrite and chalcopyrite in small discontinuous veins. Late in the Triassic a marine transgression lead to the deposition of the Penarth Group which oversteps the Mercia Mudstone Group and, as a marginal facies of sandstones and red mudstones, rests directly on Palaeozoic rocks (Wilson et al., 1990). Further inundation led to deposition of a marginal facies of the Lower Lias around the remaining upland areas.

In South Wales lead is the dominant mineralisation in the Dinantian limestones but it is also present in the Triassic and Jurassic marginal facies (Wilson et al., 1990). The mineralisation occurs mostly as calcite and baryte with disseminated galena. Minor chalcopyrite and sphalerite also occur in places associated with malachite, azurite and rosasite. In the marginal facies in a zone above the unconformity the mineralisation acts as cement to the conglomerates and breccias. There also appears to be exhalative mineralisation deposited on the Jurassic sea floor.

Hematite mineralisation was extensively worked in the area around Llanharry. It comprises colloidal and crystalline hematite, often altered to goethite, in association with quartz, calcite and dolomite and sometimes pyrolusite. The hematite ore occurs in fissures within the Dinantian limestone at their contact with Namurian mudstones, beneath the Triassic unconformity. Silver has been recorded in association with the hematite from Llanharry.

No sampling was carried out in South Wales though it is clear that the precious metal potential of the hematitic ores needs to be assessed. Similarly the interface between the red Triassic marginal facies and the underlying rocks should be investigated, especially as gold was detected in samples derived from an essentially similar environment in the Mendips.

DRAINAGE SAMPLING

Mauchline Basin

Drainage sampling in this area was undertaken in two stages. Initial sampling was carried out at closely spaced sites on the River Ayr east of Stair (121/2 and 123/4 on Figure 4), close to the boundary between the Permian alkali basalts and the underlying red Carboniferous strata (Figure 3). A total of 48 gold grains were obtained by panning from these sites. These grains were examined by the BGS gold characterisation method, details of which are given below. Because of the abundance of gold at this site and its chemical similarity with Devon gold, further more comprehensive drainage sampling of the area of the Permian rocks of the Mauchline Basin and parts of its surroundings was carried out. The locations of the sampling sites are shown in Figure 4. Samples were obtained by panning of drainage sediment beneath water level. In some cases samples were also taken from stream debris above the water line. Multiple pan-fulls of sediment were taken from the gold-bearing sites on the main rivers to obtain sufficient grains for gold characterisation studies. Generally single pans were taken from the small streams and tributaries.

Many of the panned concentrate samples were processed in the laboratory using a superpanner to extract gold grains. Comparison of number of grains observed in the field and number extracted in the laboratory show that there is good agreement for samples containing low numbers of grains (Table 1). In contrast, in the more anomalous samples the number of grains observed in the field was usually significantly less than those extracted from the same sample in the laboratory. Occasionally, grains may have been lost in the process of bagging the sample after panning. The difference between the number of grains analysed and the number of grains separated (Table 1) reflects loss of a few grains during polishing and the fact that a few grains were not uncovered during polishing.

Gold was also determined chemically in samples that had not been subjected to laboratory separation procedures and also in the residues of the samples from which grains had been extracted. The concentrates were ground in a P5 mixer mill and gold was determined after digestion in aqua regia and extraction into MIBK by graphite furnace Atomic Absorption Spectrometry at Acme Analytical Laboratories, Vancouver, Canada. Removal of gold grains from most samples prior to grinding lessened the problems associated with subsampling of samples containing discrete grains of metallic gold, material which is extremely difficult to comminute. There are a few samples from which gold has been extracted that reveal further gold by analysis (Table 1). This could reflect grains overlooked after the gravity concentration procedure, perhaps because of oxide coatings, or composite grains which are less obvious visually and lower in density.

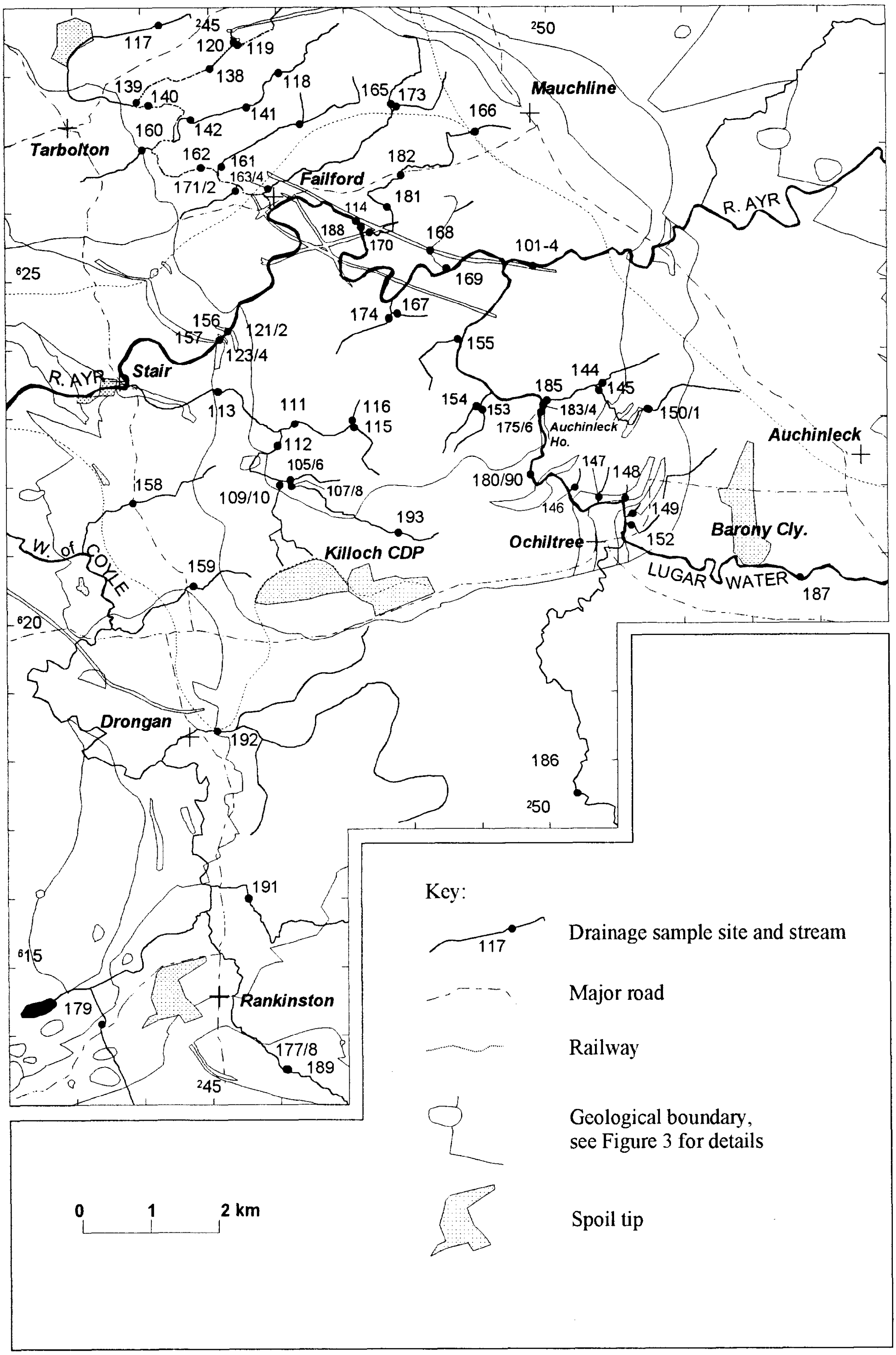

Figure 4 Drainage sample site locations, Mauchline Basin

Table 1 Gold content of panned concentrate samples, Mauchline Basin

	Au grains in field	Au grains lab	Au grains analysed	Au grains mapped	Au by analysis ppb
PTP 101	3	2	2		nd
PTP 102	2	3	2		nd
PTP 103	2	4	2		nd
PTP 104	2	9	8	3	257
PTP 105	0	nd	0		8
PTP 106	0	nd	0		1
PTP 107	1	0	0		nd
PTP 108	0	1	1		1
PTP 109	0	nd	0		nd
PTP 110	1	1	1		21
PTP 111	0	1	1		2
PTP 112	0	nd	0		1
PTP 113	0	1	1		1
PTP 114	3	8	6		421
PTP 115	1	3	2		3
PTP 116	1	1	0		23
PTP 117	0	nd	0		1
PTP 118	1	0	0		10
PTP 119	0	nd	0		1
PTP 120	0	nd	0		1
PTP 138	2	2	2		1
PTP 139	0	nd	0		1
PTP 140	0	1	0		2
PTP 141	0	1	1		2
PTP 142	2	2	2		1
PTP 143	0	nd	0		1
PTP 144	1	1	1		1
PTP 145	1	1	1		1
PTP 146	2	4	2		193
PTP 147	2	6	5	2	1
PTP 148	0	1	1		1
PTP 149	2	3	3		1
PTP 150	0	nd	0		19
PTP 151	0	nd	0		1
PTP 152	4	4	1		2
PTP 153	1	nd	0		2380
PTP 154	0	nd	0		8
PTP 155	0	nd	0		305
PTP 156	10	nd	0		750
PTP 157	20	nd	0		2680
PTP 158	1	nd	0		5
PTP 159	0	nd	0		1
PTP 160	0	nd	0		1
PTP 161	2	5	3		5
PTP 162	0	nd	0		1

Table 1 Gold content of panned concentrate samples, Mauchline Basin (continued)

	Au grains in field	Au grains lab	Au grains analysed	Au grains mapped	Au by analysis ppb
PTP 163	0	nd	0		2
PTP 164	6	0	0		10
PTP 165	0	nd	0		15
PTP 166	1	0	0		<1
PTP 167	3	4	1		3
PTP 168	0	nd	0		135
PTP 169	1	0	0		1
PTP 170	0	nd	0		5
PTP 171	3	2	2		26
PTP 172	1	0	0		262
PTP 173	0	nd	0		356
PTP 174	0	nd	0		4
PTP 175	6	6	6	1	187
PTP 176	24	51	43	2	81
PTP 177	0	nd	0		10
PTP 178	0	nd	0		nd
PTP 179	1	3	3		3
PTP 180	0	nd	0		nd
PTP 181	0	nd	0		6
PTP 182	0	nd	0		342
PTP 183	1	nd	0		13
PTP 184	0	nd	0		14
PTP 185	0	nd	0		3
PTP 186	1	2	1		2
PTP 187	1	1	1		2
PTP 188	2	nd	0		6
PTP 189	0	nd	0		4
PTP 190	10	15	14		3
PTP 191	0	nd	0		1
PTP 192	0	nd	0		1
PTP 193	1	nd	0		2

nd not determined

It is possible to calculate the concentration of gold in a sample by weighing the gold grains and comparing it with the weight of the sample. This is difficult if the grains are small and has not been carried out as part of this work. The class intervals on the gold distribution map (Figure 5) are therefore set at a combination of numbers of grains and analytical levels.

In addition most of the samples were analysed for Ti, V, Mn, Fe, Ni, Cu, Zn, As, Se, Y, Zr, Sn, Ba, Ce, Pb and Bi by XRF and for Hg by cold vapour atomic absorption spectrometry after oxidising acid attack at the BGS Analytical Laboratories in Keyworth. The results of these analyses are given in Table 2.

Table 2 Chemical composition of Mauchline panned concentrate samples (XRF)

	TiO_2	V	MnO	Fe_2O_3t	Ni	Cu	Zn	As	Se	Y	Zr	Sn	Ba	Ce	Pb	Bi	Hg
	%	ppm	%	%	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
PTP 104	9.976	1138	0.246	42.11	102	124	394	12	3	76	>1%	114	1.77%	172	352	19	8.8
PTP 105	5.159	298	0.134	11.44	45	30	143	<5	1	59	8444	14	-	141	36	10	0.73
PTP 106	1.483	97	0.05	4.06	15	6	49	<5	<1	14	1746	<5	83	40	7	<3	
PTP 108	6.334	674	0.181	22.19	75	42	239	5	<1	29	2416	30	2031	48	137	<3	0.06
PTP 110	4.345	430	0.139	13.93	98	23	165	<5	<1	27	2163	34	-	45	56	4	0.04
PTP 111	3.44	254	0.097	9.64	31	15	93	<5	<1	36	4229	10	1935	84	27	5	0.31
PTP 112	13.777	1747	0.272	34.89	125	24	425	<5	<1	16	879	20	-	21	24	7	0.09
PTP 113	6.205	686	0.165	18.98	66	25	235	<5	2	21	1119	22	1161	23	36	6	0.11
PTP 114	2.689	244	0.078	11.86	28	27	91	7	<1	75	>1%	25	4663	258	47	45	
PTP 115	3.655	292	0.096	11.99	30	12	88	<5	<1	35	4590	9	2822	93	25	4	1.7
PTP 116	2.827	172	0.072	7.06	19	11	65	<5	<1	64	7764	<5	945	202	20	4	0.24
PTP 117	3.232	255	0.126	11.73	21	24	100	<5	<1	35	3591	8	1072	42	42	3	0.1
PTP 118	6.613	683	0.214	21.56	43	16	218	6	<1	58	7110	10	1778	62	88	3	0.87
PTP 119	5.106	575	0.165	15.57	29	54	198	<5	<1	20	1431	157	-	17	196	<3	0.09
PTP 120	7.468	875	0.221	20.76	37	25	257	<5	<1	22	2410	43	-	14	66	<3	1.8
PTP 138	7.022	805	0.213	23.29	37	27	236	<5	<1	30	2438	45	668	24	73	6	26
PTP 139	7.556	746	0.222	22.61	32	30	247	<5	<1	57	8985	24	1506	72	57	7	5
PTP 140	2.381	265	0.166	12.11	30	19	138	<5	<1	41	926	23	1542	17	50	<3	8.1
PTP 141	4.182	340	0.155	15.08	31	9	130	6	2	72	9478	36	458	97	47	8	10.2
PTP 142	3.276	342	0.133	16.17	31	16	123	8	<1	31	3030	18	4134	39	62	6	6
PTP 143	0.714	34	0.02	1.6	3	5	20	<5	<1	19	2792	8	213	40	11	<3	0.07
PTP 144	6.509	691	0.173	21.77	55	20	196	<5	<1	29	4052	<5	992	50	123	3	0.05
PTP 145	18.798	2466	0.377	44.44	116	50	693	<5	1	8	640	20	-	5	66	6	0.05
PTP 146	7.442	803	0.191	26.5	73	42	266	6	<1	35	3115	18	2.25%	73	107	6	22
PTP 147	9.119	1069	0.255	36.63	96	41	373	9	2	43	3450	42	8800	79	568	4	0.95
PTP 148	4.964	470	0.142	19.67	49	21	161	6	<1	37	3169	11	95	74	71	4	0.1
PTP 149	5.659	598	0.159	24.6	70	22	228	<5	<1	28	2408	28	-	55	117	3	1.1
PTP 150	8.852	1033	0.212	23.56	53	37	331	<5	2	31	2389	54	2633	59	112	3	0.27
PTP 151	15.586	2024	0.355	36.54	109	73	473	<5	<1	23	251	13	-	15	39	<3	0.06
PTP 152	3.781	331	0.114	13.08	51	151	161	<5	<1	27	2174	143	1201	54	838	<3	0.18
PTP 153	5.897	544	0.154	17.15	48	33	203	<5	4	39	3765	18	3906	79	55	<3	5.3
PTP 154	4.717	457	0.149	18.11	49	20	162	7	<1	35	3031	7	93	76	50	3	0.21
PTP 156	12.547	1314	0.249	45.75	141	134	469	10	<1	185	>1%	142	2.09%	501	289	118	19
PTP 157	12.696	1510	0.238	57.18	140	145	424	23	2	94	>1%	187	1.53%	292	348	147	22
PTP 158	3.782	379	0.192	23.67	407	1226	843	-	<1	42	1625	754	648	64	>1%		1.8
PTP 159	6.398	736	0.22	23.9	72	85	339	14	1	27	1445	47	4849	48	300	<3	0.1
PTP 160	1.258	119	0.107	7.43	39	15	72	<5	<1	23	2186	23	216	27	44	<3	0.36
PTP 161	3.846	250	0.122	13.6	25	33	122	<5	3	123	>1%	13	240	168	94	24	3
PTP 162	1.946	226	0.185	14.33	34	34	91	<5	<1	44	1962	97	438	25	830	<3	1.6
PTP 165	4.361	453	0.172	19.95	39	14	174	6	<1	46	4820	37	1439	54	72	<3	3.4
PTP 166	8.108	963	0.231	26.86	62	31	361	<5	<1	21	2090	141	97	30	280	<3	1.7
PTP 167	4.622	335	0.129	15.14	34	62	504	6	<1	84	>1%	65	4219	152	879	11	0.97
PTP 168	5.947	545	0.147	23.85	62	41	251	<5	<1	81	>1%	36	2924	151	591	7	1.2

Table 2 Chemical composition of Mauchline panned concentrate samples (XRF) (continued)

	TiO_2	V	MnO	Fe_2O_3t	Ni	Cu	Zn	As	Se	Y	Zr	Sn	Ba	Ce	Pb	Bi	Hg
	%	ppm	%	%	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
PTP 169	1.906	234	0.075	11.23	30	24	167	<5	<1	14	1331	53	1815	24	247	4	0.34
PTP 170	4.392	518	0.184	20.63	40	260	187	<5	<1	39	2314	138	2642	30	1512	<3	3.1
PTP 171	4.05	437	0.168	22.33	42	35	163	7	<1	49	6531	22	357	60	109	<3	0.57
PTP 173	2.039	167	0.157	9.68	17	12	68	<5	<1	55	4929	9	149	51	17	4	0.25
PTP 175	2.854	347	0.116	13.89	45	18	107	<5	<1	21	1813	16	2203	56	38	<3	
PTP 176	9.819	1070	0.204	41.72	115	54	314	6	2	87	>1%	31	1.08%	302	135	11	5.6
PTP 181	4.297	482	0.183	18.49	45	21	182	6	<1	45	3096	30	3454	37	132	<3	0.41
PTP 182	8.573	1001	0.244	30.51	76	47	389	<5	<1	34	2964	83	2659	37	262	4	1.8
PTP 185	8.677	1049	0.287	36.32	100	65	457	16	<1	36	1845	356	8400	54	318	<3	0.28
PTP 187	12.676	1622	0.291	51.44	134	117	595	23	2	40	4407	103	3.01%	89	369	11	1.8
PTP 190	16.219	1525	0.298	48.31	135	34	412	6	<1	96	>1%	14	-	229	129	11	1.6
PTP 191	9.825	986	0.269	25.55	212	37	439	<5	<1	32	2170	11	-	82	51	<3	0.62

Distribution of gold in panned concentrate samples

The incidence of gold in the panned concentrate samples in the Mauchline area is shown in Figure 5. Gold was present in 38 of the 76 panned concentrate samples collected. Though most of the drainage samples were collected over the area underlain by Permian rocks, the samples collected outside the basin in the south-west of the area indicate that the source of gold is probably mostly within the outcrop of Permian rocks and immediately adjacent rocks, especially since the gold-rich sample from the extreme south-west of the area is probably derived from volcanic necks of similar age to the lavas of the Mauchline Basin. The presence of gold in samples from the south-east of the area (Figure 5) shows that there are also sources outside the outcrop of the Mauchline Basin. Not all samples derived from within the outcrop of Permian rocks are gold bearing; rather, there are distinct centres of gold enrichment within the basin (Figure 5). It is probable that gold is more concentrated in the large rivers (River Ayr and Lugar Water), which are steeply incised as they flow through the basin, than in the small rivers and tributaries.

Discrete areas showing the greatest enrichment in gold in drainage can be recognised and can be roughly contoured to give a tentative indication of the trend of anomalous zones (Figure 6). There is no evidence that gold is generally associated with the volcanic rocks rather than the overlying sandstones. The largest area is in the south-east of the basin to the north of Ochiltree and appears to trend north-west. The second area may, at least in part, be its continuation to the north-west but may also have a north-east trending component and link up with the isolated anomaly in the River Ayr to the east of its confluence with the Lugar Water (samples 101-4). The original anomalous site in the river Ayr to the east of Stair could link up to the north-east with the other anomalous site on the river Ayr near Burnfoot Bridge (sample 114) and anomalies further to the north-east, though this is speculative. Further more isolated anomalies are present to the north-west of Failford (sample 161) and near Knockshinnoch in the extreme south-west of the area. Further more detailed drainage sampling would be required to define the extent of these drainage anomalies more effectively. However, there seems to be some evidence that a major control in the incidence of gold is a north-west trending zone about 8 km long cutting through the middle of the basin. There are also suggestions that north-east trending zones cutting the basin may also control the incidence of gold. Further work, including overburden sampling, is needed to confirm these deductions.

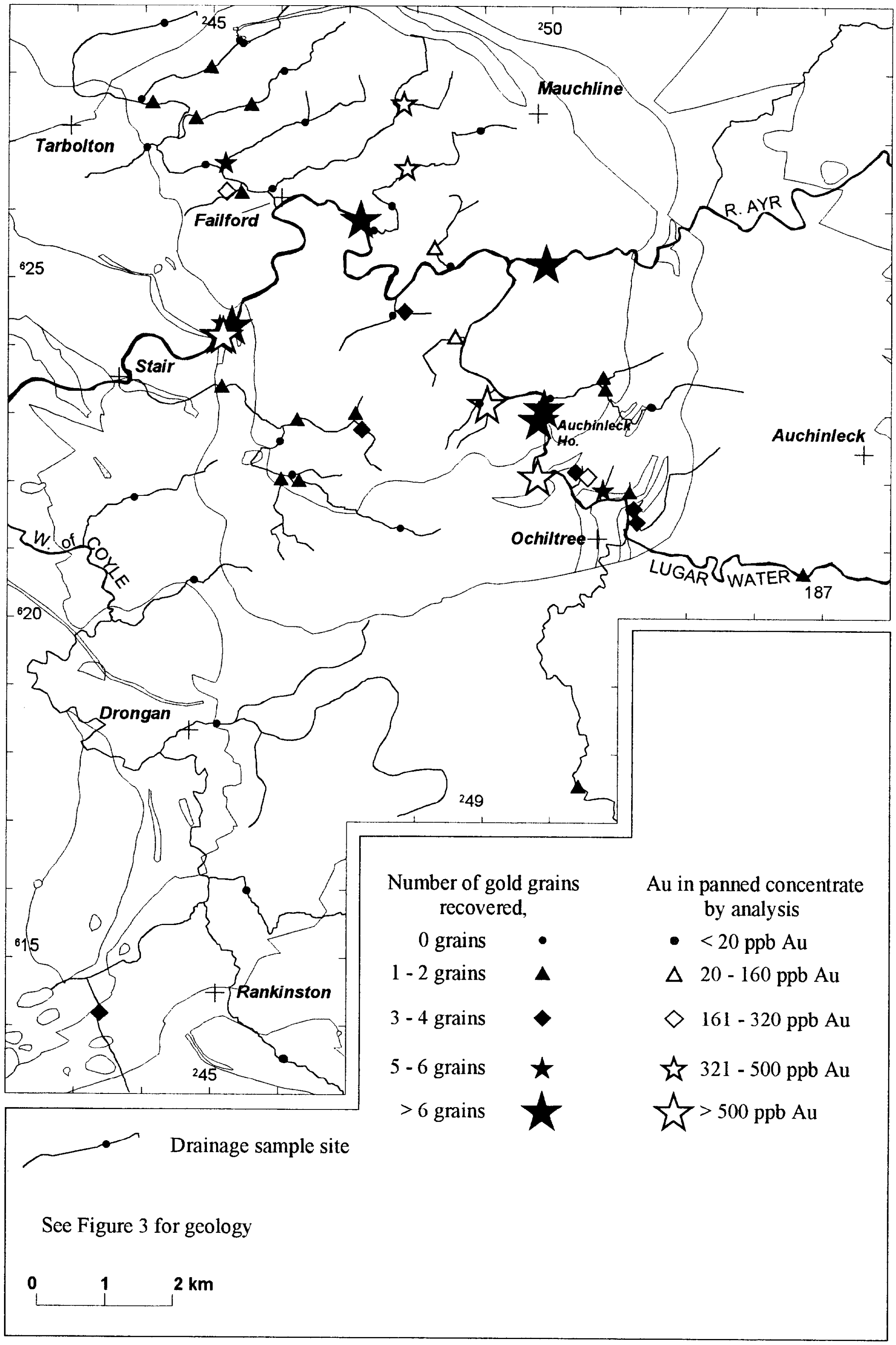

Figure 5 Incidence of gold in drainage panned concentrates in the Mauchline Basin. Number of gold grains extracted at each site or, where physical extraction not carried out, concentration of gold found by chemical analysis.

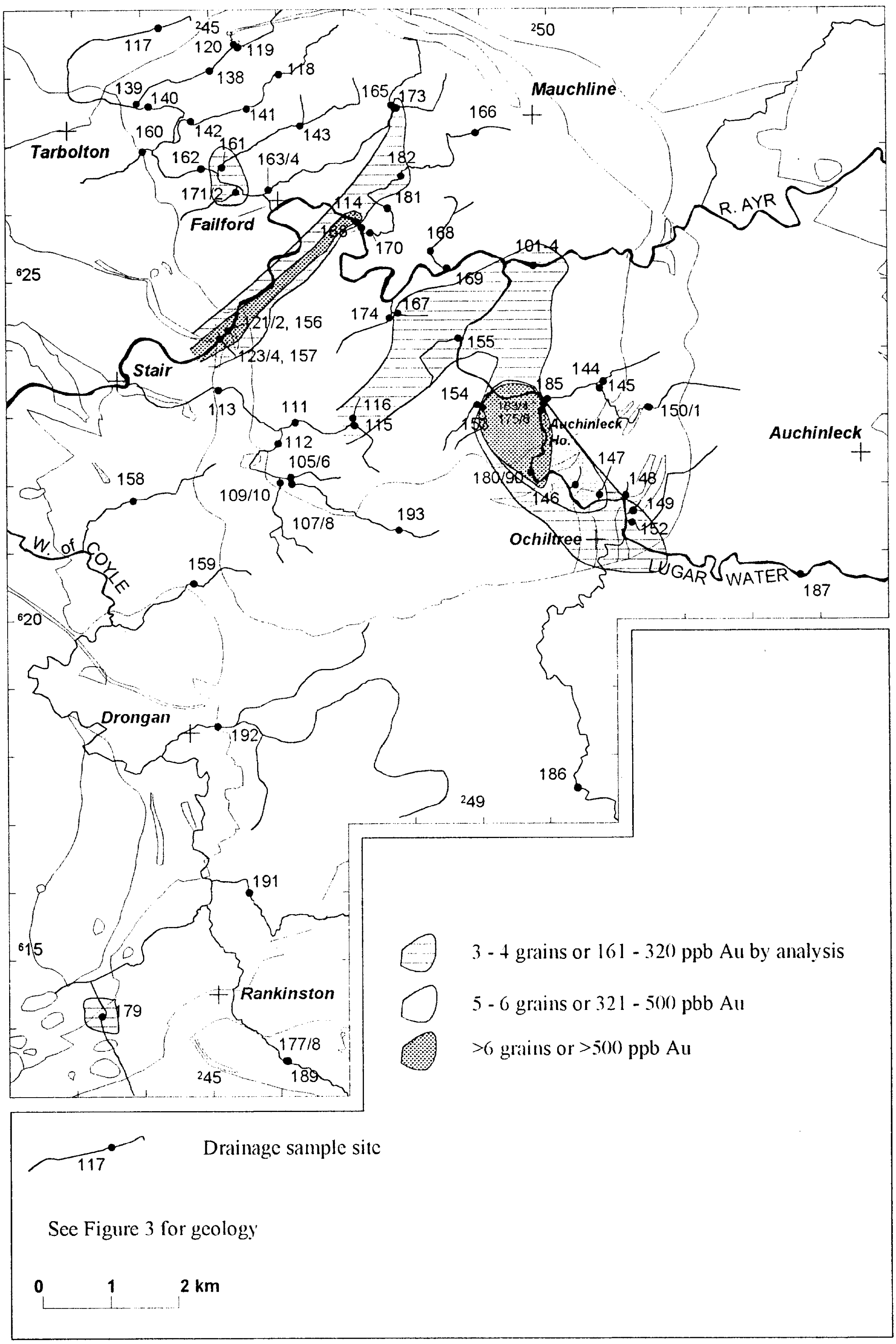

Figure 6 Interpreted contoured distribution of gold in drainage panned concentrates in the Mauchline Basin. Contours based on number of grains in sample or Au determined by chemical analysis.

Distribution of Ti, V and Mn in panned concentrate samples

These elements show a strong positive correlation with each other (Table 2), which is illustrated by the Ti distribution (Figure 7). High levels of titanium reflect chiefly the presence of ilmenite which is derived mostly from the outcrop of the volcanic rocks (Figure 3). The correlation between Mn and Ti is less strong than that between Ti and V but there is no indication of a significant source of Mn other than ilmenite in the samples as a whole.

Distribution of Fe in panned concentrate samples

Iron shows a strong positive correlation with Ti at lower levels but less so at higher levels. Samples which show a combination of high Fe and relatively high Fe/Ti ratio, a combination most likely to reflect the presence of hematite or iron-rich carbonate of hydrothermal origin with which gold may be associated, are shown in Figure 8. Although gold enrichment is associated with both high and low Fe concentrations, for the higher Fe samples, gold is associated more with samples with a high Fe/Ti ratio than with others. This association suggests that gold may have some correlation with an iron-rich mineral additional to the background Fe+Ti oxides associated with the volcanic rocks.

Distribution of Ni in panned concentrates

Nickel shows a very strong positive correlation with iron and reflects background concentrations which vary with the chemistry of the source rocks. Three samples are enriched above these background concentrations, where high Ni is accompanied by a relatively high Ni/Fe ratio (Figure 9). The sample (PTP 158) with the highest Ni level (407 ppm) is heavily contaminated with a number of metallic elements. The source of the nickel in the other two samples is unclear.

Distribution of Cu in panned concentrates

Copper, like Ni, shows a general positive correlation with Fe, reflecting presumably a small but significant copper content of the background magnetite and ilmenite derived particularly from the igneous rocks of the area. There are three samples containing copper in excess of the background (>150 ppm). One of the these anomalies (1226 ppm) is associated with the highly contaminated sample enriched in a range of metals. The other two anomalous samples (Figure 9) also probably reflect contamination, in view of their high lead contents (838 ppm and 1512 ppm Pb respectively).

Distribution of Zn in panned concentrates

At low levels (<300 ppm) Zn shows a strong positive correlation with Fe. Above this level there is much greater scatter, with several samples showing relatively high Zn/Fe ratios. The highest amplitude anomaly is associated with the highly contaminated sample (PTP 158). Other samples showing lower amplitude Zn enrichment are scattered throughout the area (Figure 9) but they are generally not associated with the most Au-rich samples. The zinc-rich spinel gahnite has been identified in one concentrate and may account for much of the Zn in these samples.

Distribution of As and Se in panned concentrates

Concentrations of As are relatively low in the samples from the Mauchline area, reaching a maximum of 23 ppm. There is some positive correlation of As with Ba but no correlation with abundance of Au. Selenium levels reach a maximum of 4 ppm. No correlation between the higher concentrations and Au anomalies is evident.

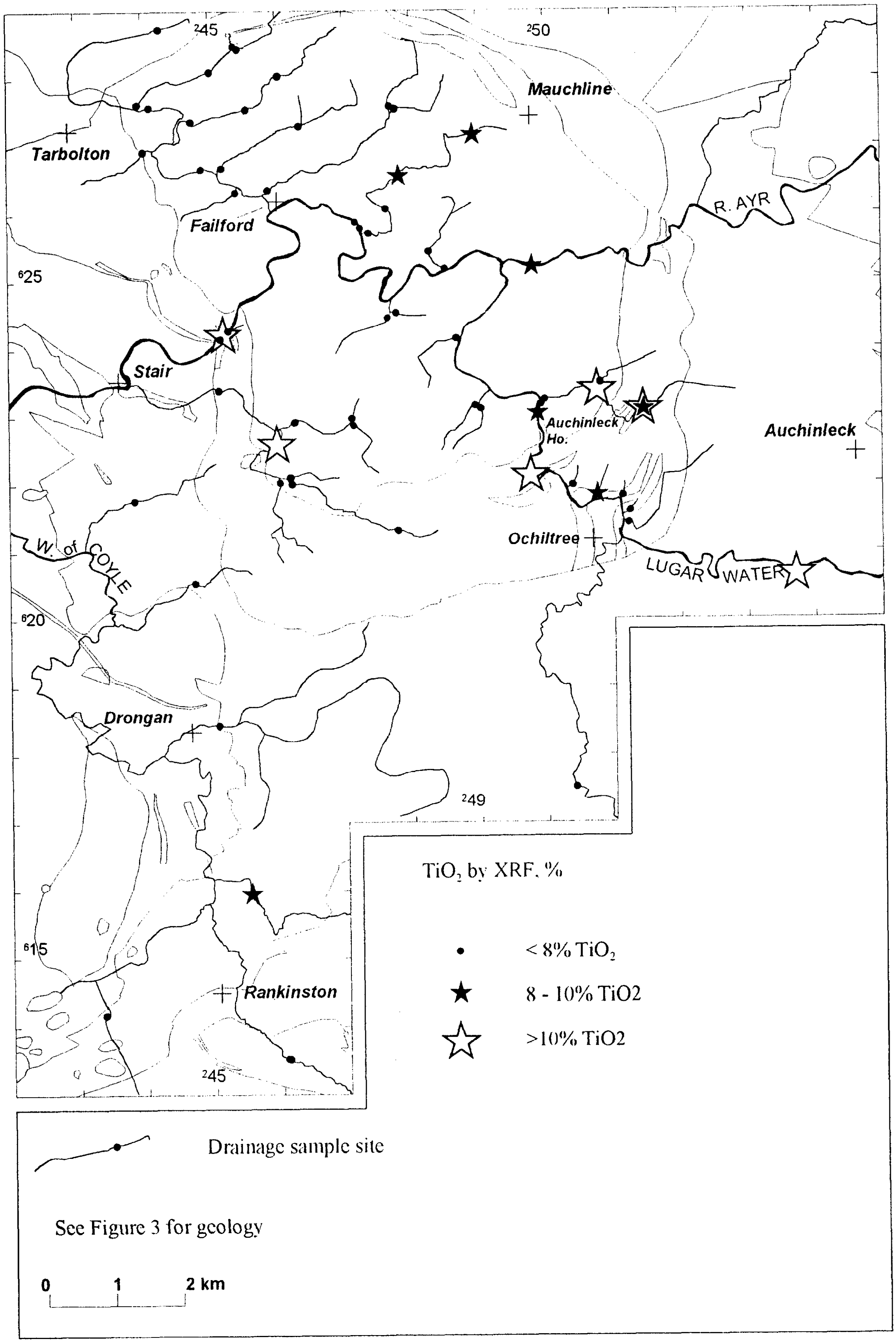

Figure 7 Distribution of Ti in drainage panned concentrates in the Mauchline Basin

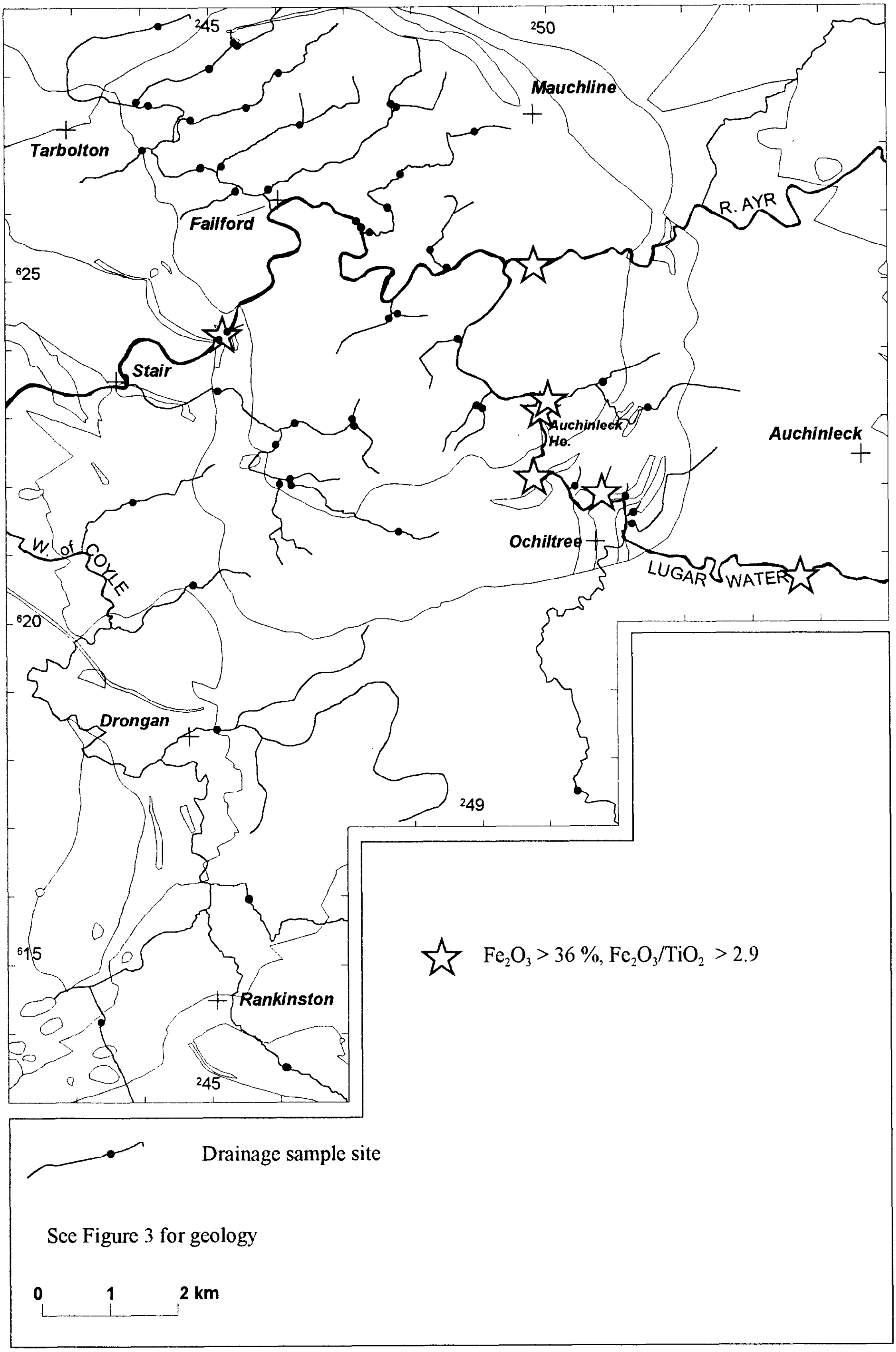

Figure 8 Distribution of Fe-rich drainage panned concentrates in the Mauchline Basin with Fe_2O_3-TiO_2 ratio > 2.9.

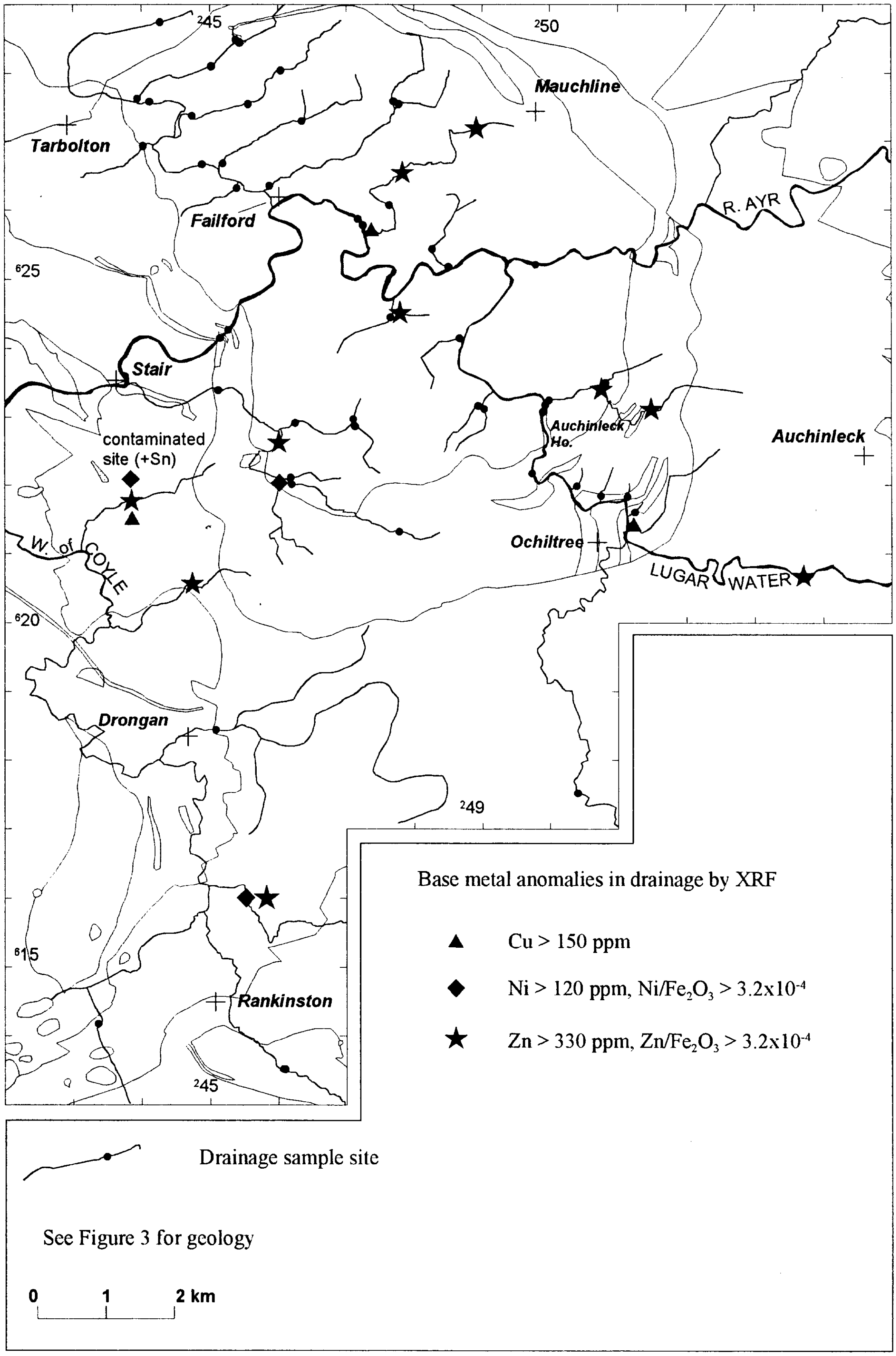

Figure 9 Distribution of Cu, Ni and Zn anomalies in panned concentrate samples from the Mauchline Basin. Ni anomalies are those with Ni> 120 ppm and Ni-Fe_2O_3 ratio > $3.2x10^{-4}$. Zn anomalies are those with Zn > 330 ppm and Zn-Fe_2O_3 ratio > $3.2x10^{-4}$

Distribution of Y, Zr and Ce in panned concentrates

There are strong positive correlations between Y, Zr and Ce. Enrichment in Zr is associated chiefly with samples derived from the Permian red sandstones in the core of the Mauchline Basin (Figure 10). Zirconium is also enriched at some of the most Au-rich sites, indicating a general upgrading of heavy minerals. Monazite has been identified in two samples and probably represents the major host of the rare earth elements in the Mauchline concentrate samples.

Distribution of Sn in panned concentrates

Tin is present above the 50 ppm level in about a quarter of the samples (Figure 11), to a maximum of 754 ppm in the heavily contaminated sample (PTP 158). It is probable that most of the Sn present in samples from the Mauchline Basin is derived from metallic contamination as at every site anomalous Sn is accompanied by elevated Pb content. Several tin-bearing grains have been extracted from four samples, three of which are also rich in Au. The grains comprise tin alloyed with, in turn, Cu, Bi, Hg and Pb, together with essentially pure tin. It is probable that the tin-mercury grains are natural in origin as similar grains have been found in Devon and in the Thornhill Basin (Leake and Cameron, 1996) in association with gold with a red-bed signature. Furthermore the association of Sn with Au in the source mineralisation is indicated by the presence of a rim of a tin-gold alloy to one of the gold grains that has been mapped using the automated electron microprobe, as described below. However, it is most likely that Sn of natural origin is much subordinate to Sn derived from human activity. Widespread experience from drainage surveys throughout the country indicates that in rural agricultural areas tin mostly derived from solder is a very common contaminant of drainage sediment.

Distribution of Ba in panned concentrates

Barium is enriched in several samples (maximum 3.01%) due to the presence of baryte. The distribution of the most Ba-rich samples (Figure 12) shows most to lie within a zone trending north-west through the centre of the basin. Some degree of positive correlation between Ba and Fe, Cu, Hg and, to a lesser extent, Au is evident from the chemical analyses of the concentrate samples. This is an important clue to the nature of the source of at least some of the alluvial gold as it indicates that structurally controlled mineralisation intersects the basin and is likely to carry gold. Thus the alluvial gold is not likely to be derived mostly from placer horizons within the Permian sandstones or from a weak dissemination within the alkali basalts. On the contrary, it indicates that gold was highly mobile within the fluids circulating through the basin.

Distribution of Pb in panned concentrates

Lead is enriched in many of the samples, to a maximum of more than 1% in the highly contaminated sample (PTP 158). It is probable that the main Pb-bearing phases present are metallic contaminants like lead shot and lead glass which are very widespread in agricultural areas. No positive correlation between Pb and Au is evident from the chemical data.

Distribution of Bi in panned concentrates

The concentration of Bi is highly variable, reaching a maximum of 147 ppm. A slight positive correlation between Bi and Fe is evident within the background population, with concentrations up to 11 ppm. The distribution of anomalies, shown in Figure 13, shows that high concentrations are scattered, but concentrated in the north of the area. The greatest Bi concentrations are associated with Au-rich samples from the river Ayr in the west of the area but there is no general correlation between the two elements and the form of the Bi is not known.

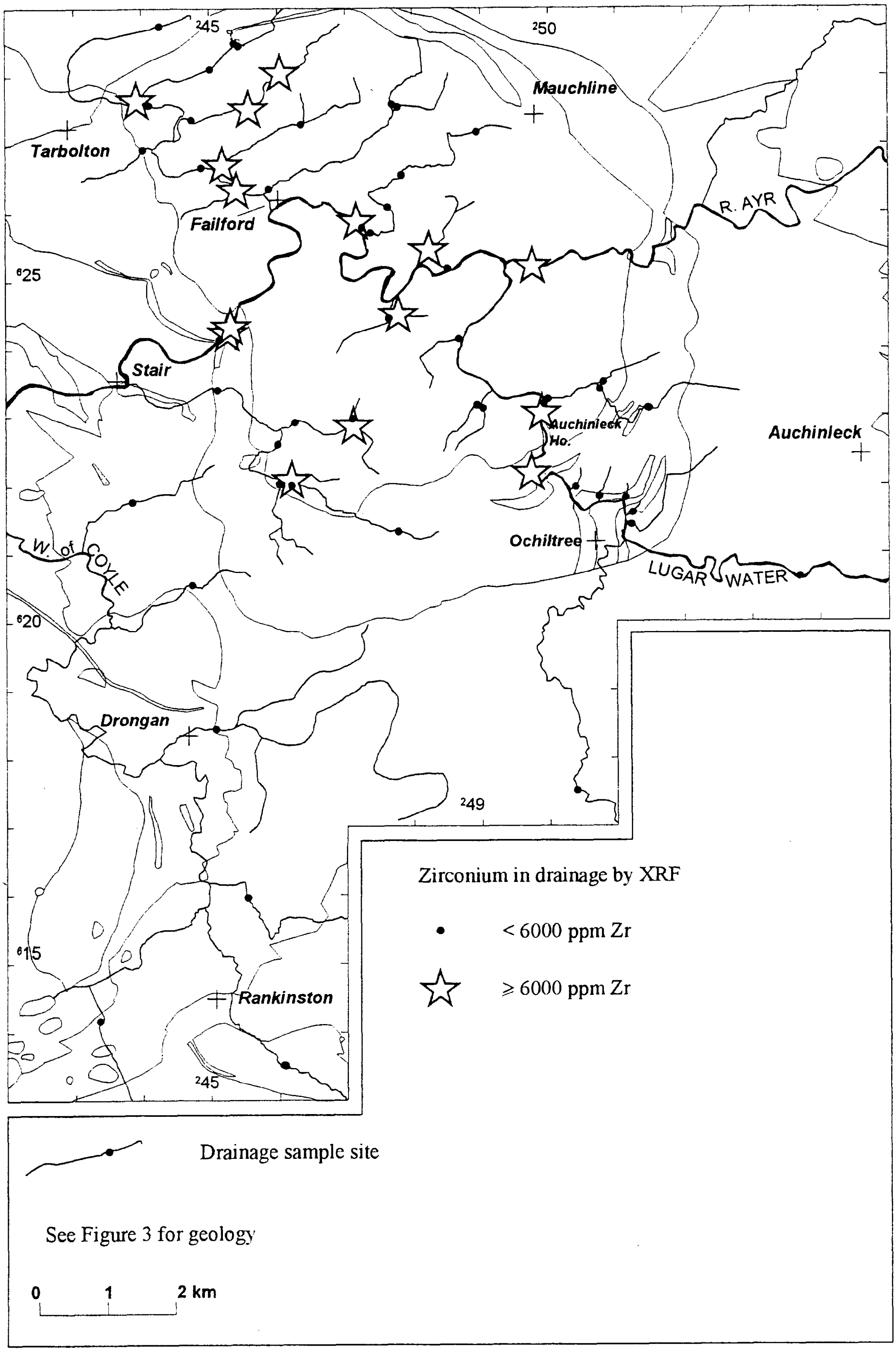

Figure 10 Distribution of Zr-rich drainage panned concentrates in the Mauchline Basin

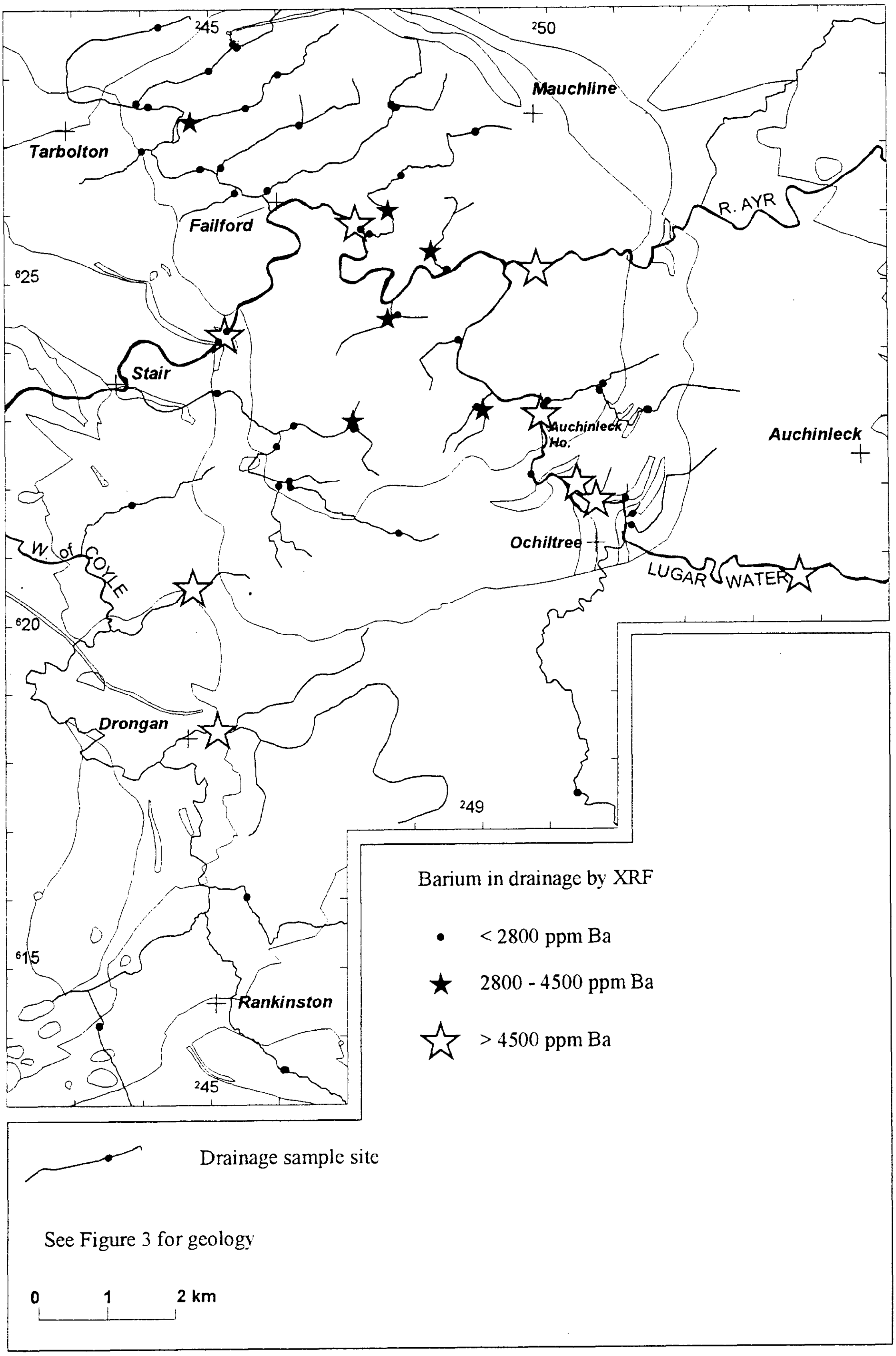

Figure 11 Distribution of Sn-rich drainage panned concentrates in the Mauchline Basin

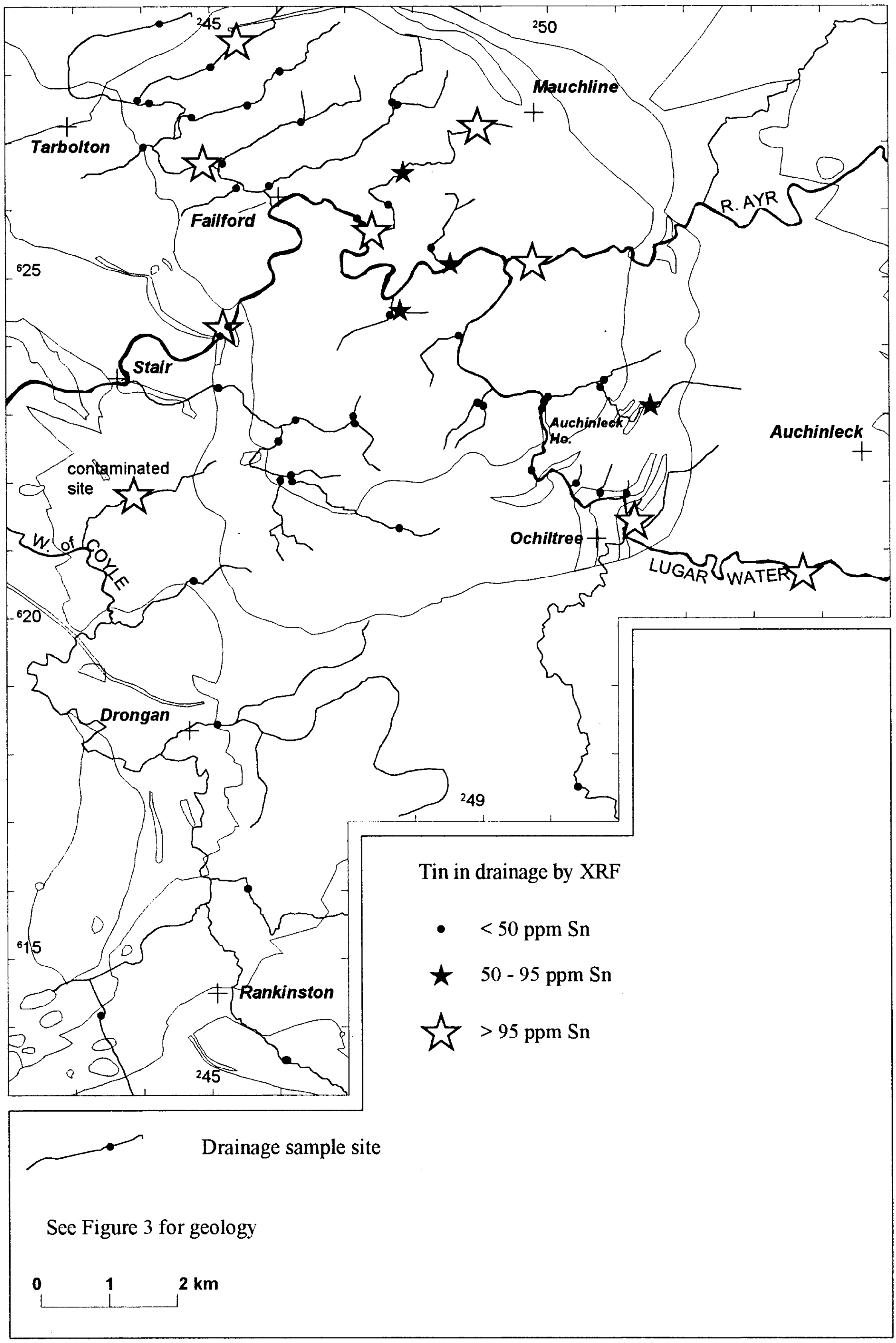

Figure 12 Distribution of Ba-rich drainage panned concentrates in the Mauchline Basin

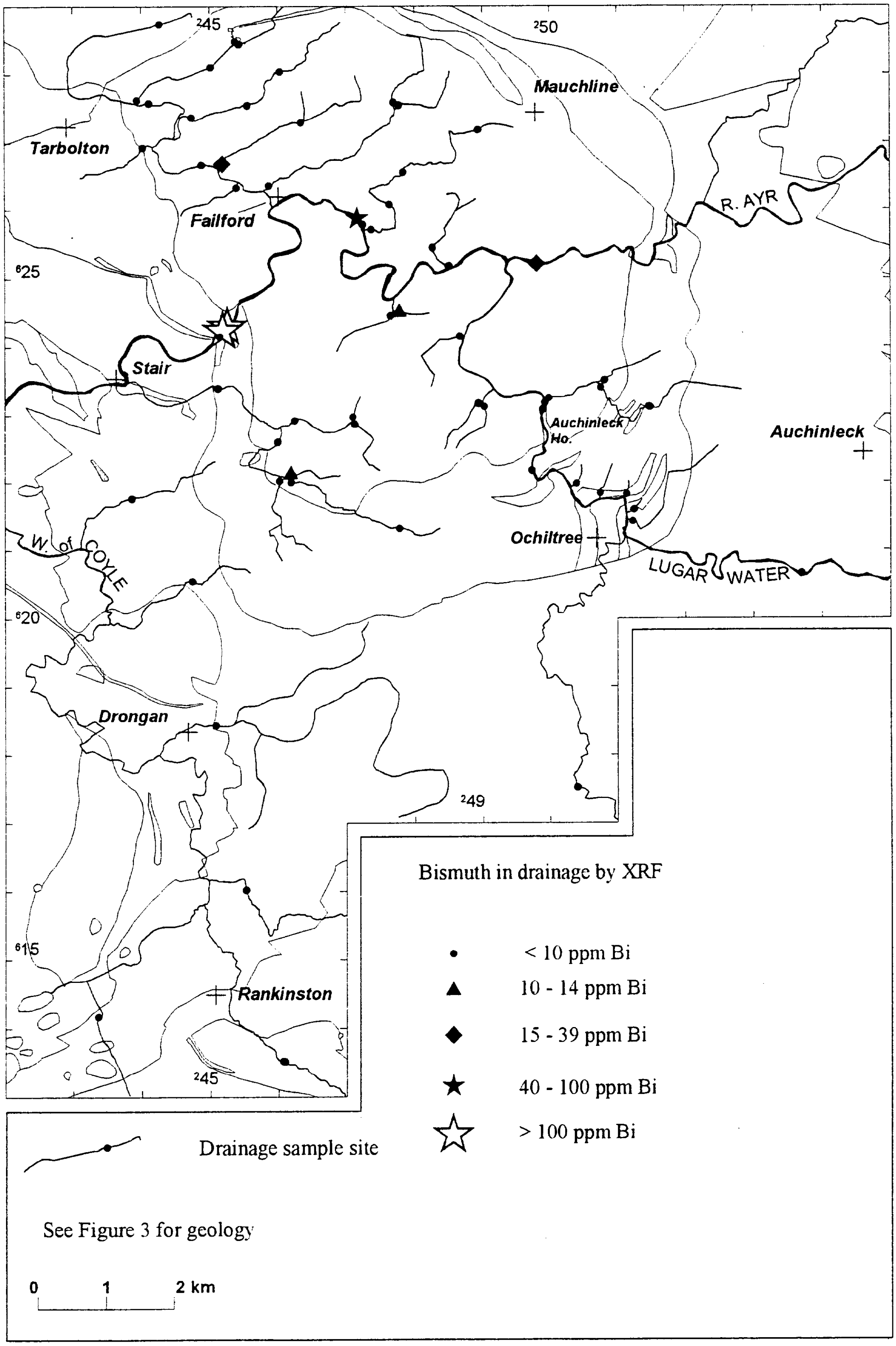

Figure 13 Distribution of Bi in drainage panned concentrates in the Mauchline Basin

Distribution of Hg in panned concentrates

Mercury contents of the concentrates vary by the same order of magnitude as gold contents, with a range from 0.04 to 26 ppm. Samples with the highest contents of Hg by analysis and cinnabar by observation (Figures 14 and 15) are associated particularly with the south-east and north-west parts of the area. In the south-east, Hg and Ba enrichments are closely associated but in the north-west this is much less evident and some Hg-rich samples contain only background levels of Ba. Cinnabar has been observed in many of the samples and it is particularly coarse-grained and conspicuous in sample PTP 146. In view of the ease with which cinnabar is broken in smaller fragments, the existence of relatively coarse pieces of the mineral at this site indicates close proximity to a bed-rock source.

Snar Valley

Alluvial gold is known to be abundant in the Snar Water to the south of the outcrop of Permian rocks on the basis of the detailed survey of alluvial gold in the Leadhills area carried out in association with Leeds University Department of Adult Continuing Education. The nature of this gold suggests that most of it does not originate from fluids associated with the Permian rocks (BGS unpublished data).

Thornhill Basin

Details of the location of alluvial gold finds in the Thornhill area and the chemistry of drainage samples are given in Leake and Cameron (1996). The gold occurs mostly in streams on the eastern side of the basin where Permian rocks, including alkali basalt, are in contact with Lower Palaeozoic rocks.

Carlisle Basin

A panned drainage concentrate was taken from Chalk Beck [333900 547800] downstream of the contact between the St Bees Shales of late Permian age and a narrow fault-bounded sliver of Visean shales and limestone. Further upstream the St Bees Sandstone and St Bees Shales are repeated and unconformably overlie reddened Westphalian and Namurian strata. No gold was observed during panning but 47 ppb Au was found as a result of subsequent analysis of the sample. This level of gold is lower than that typically associated with samples from the Mauchline and Thornhill Basins. However, further sampling to collect gold grains and to establish whether they are likely to be derived from the red-bed environment or from another type of source is recommended.

Vale of Eden

A panned concentrate sample (sample 133, Figure 16) was taken from Crowdundle Beck on the eastern margin of the Vale of Eden at [364580 530600] close to the boundary fault between the Triassic St Bees Sandstone and the underlying Permian Eden Shales. No grains of gold were recovered from the sample and analysis showed only a background concentration (2 ppb Au). However, the sample was extremely rich in baryte (estimate 44% Ba) and also showed enrichment in silver (40 ppm) and, to a lesser extent, lead (165 ppm).

Alluvium and bank panned concentrate samples (samples 134, 135, Figure 16) were obtained from the Argill Beck at [382901 513181], close to the contact between the Visean and Namurian strata with the Westphalian strata of the Stainmore outlier further upstream. No gold was recovered physically from the samples and analysis showed background concentrations. The alluvial sample showed enrichment in Cu (411 ppm), Zn (637 ppm), As (52 ppm), Ba (2.77%) and Pb (400 ppm).

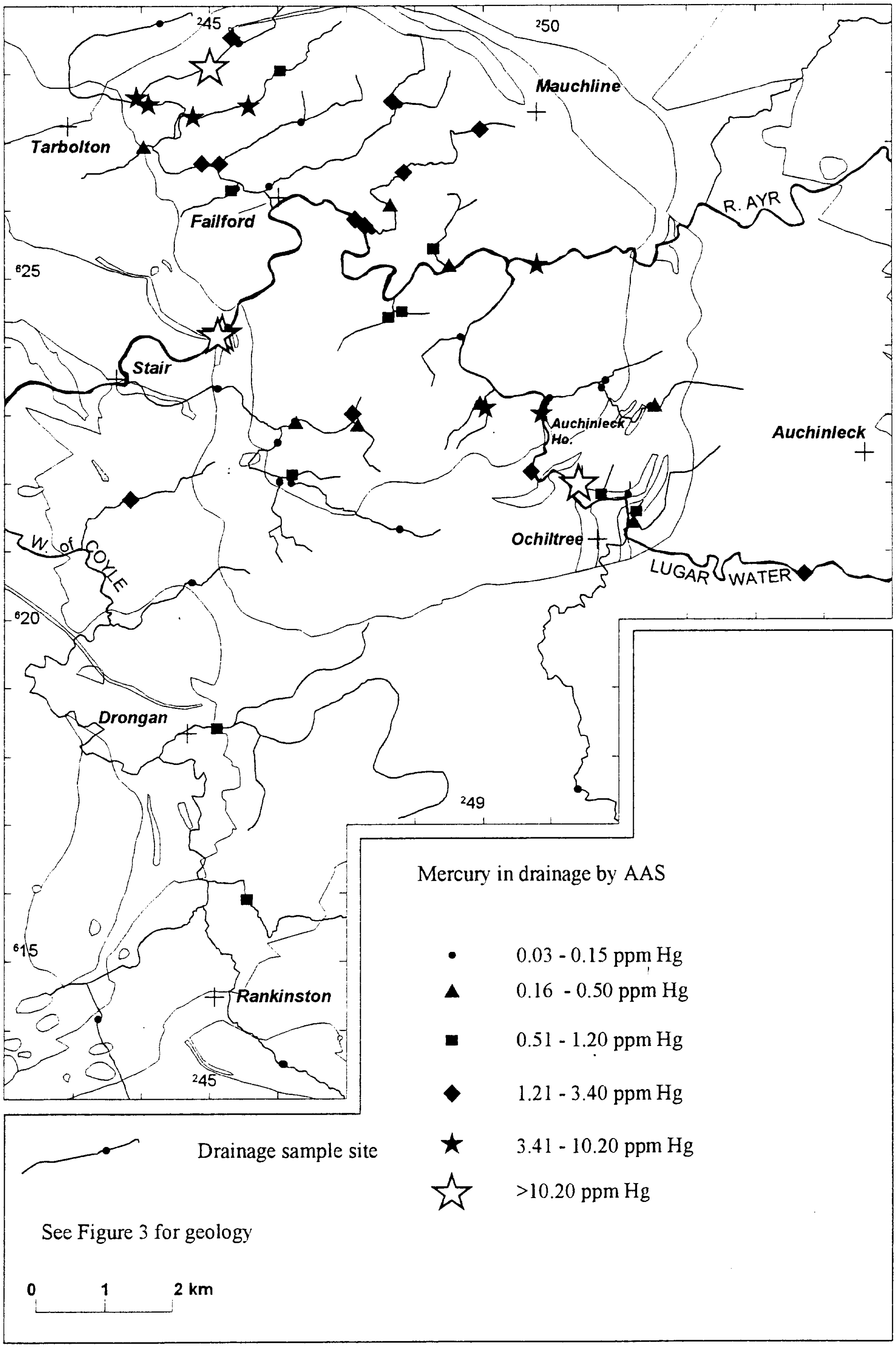

Figure 14 Distribution of Hg in drainage panned concentrates in the Mauchline Basin

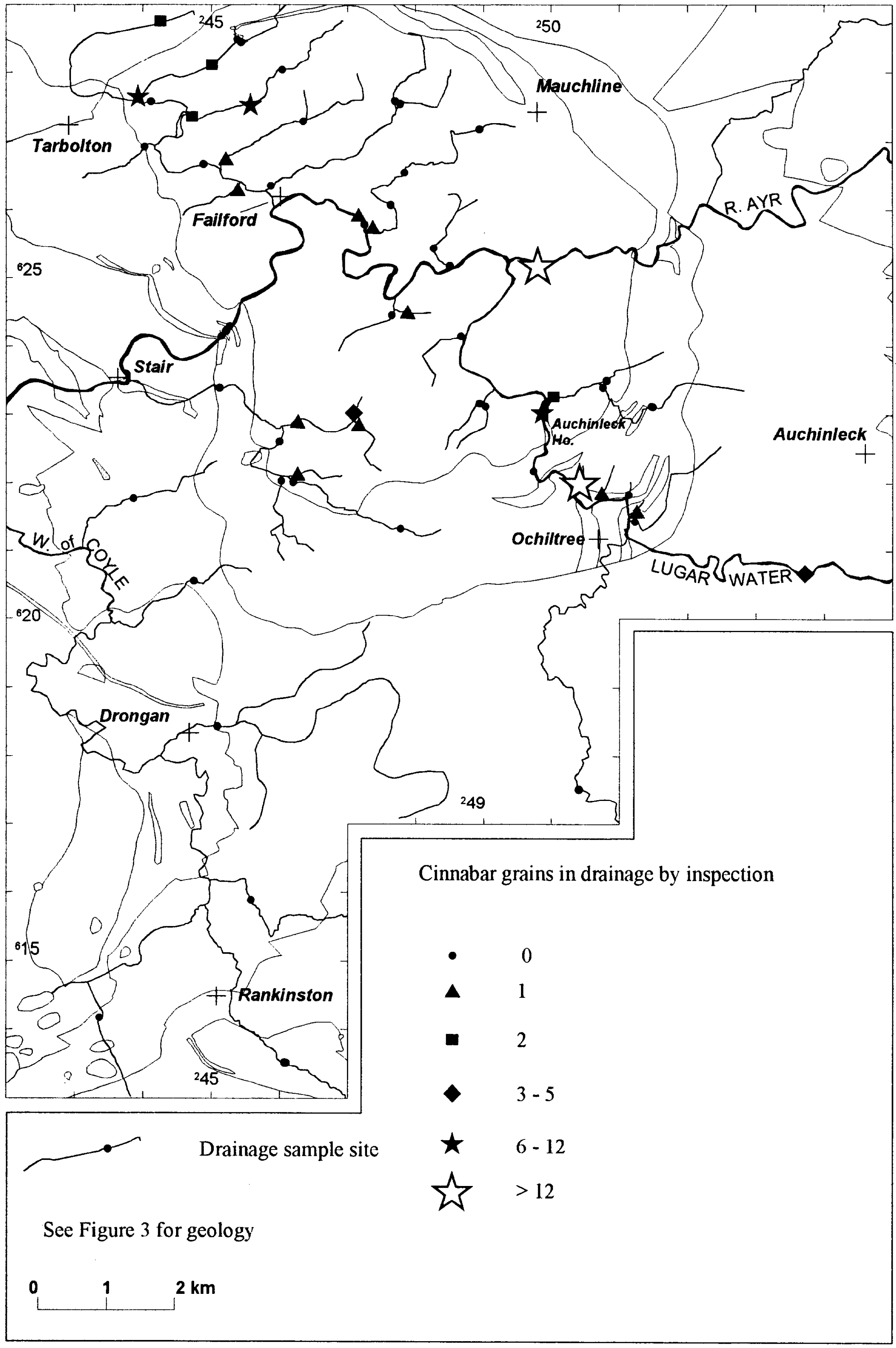

Figure 15 Distribution of cinnabar grains in drainage panned concentrates in the Mauchline Basin

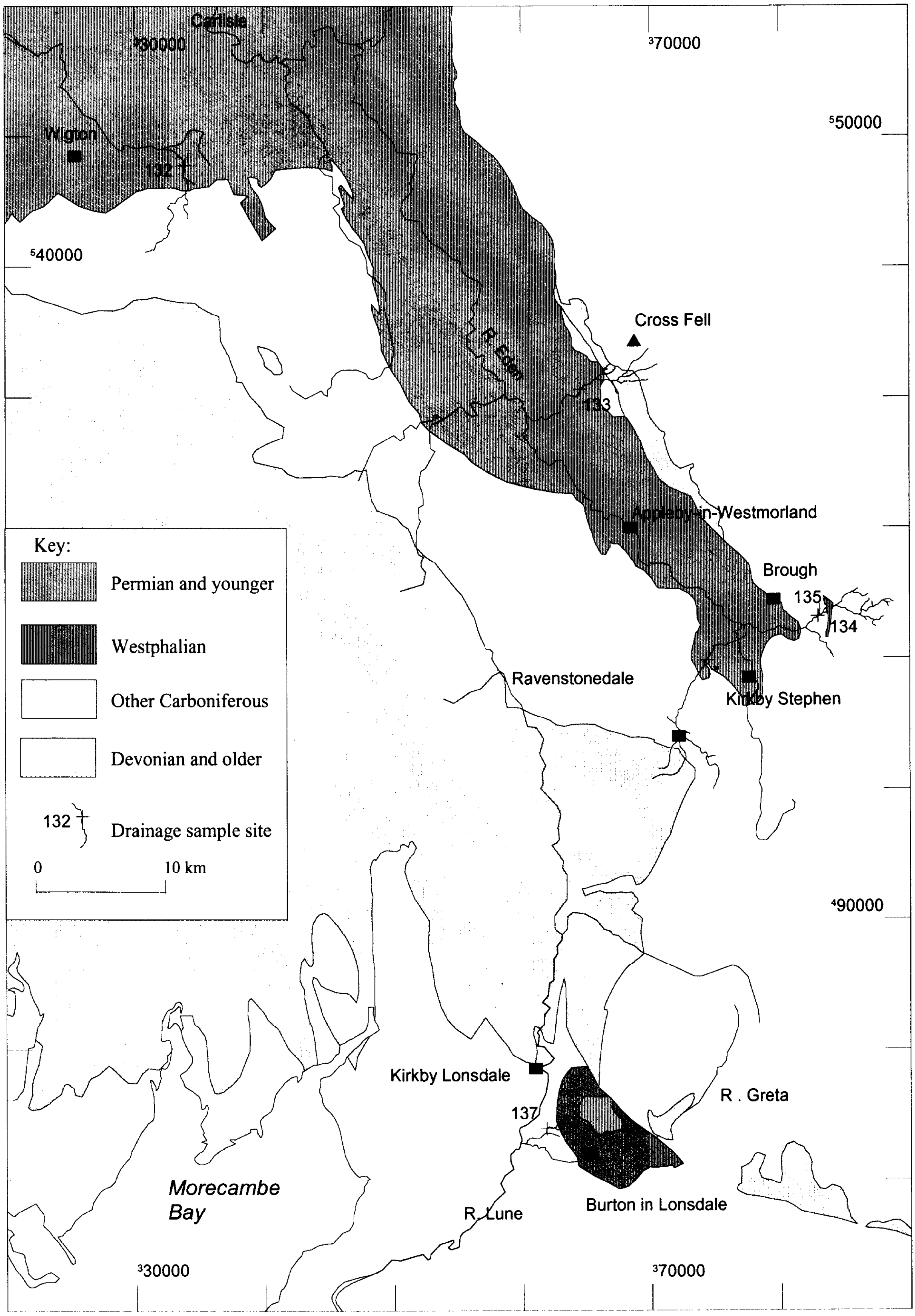

Figure 16 Simplified geology and drainage sampling sites in north-west England

The panned concentrate from the Sandal Beck at [374330 509850] just downstream of the contact between Permian Penrith Sandstone at the southern margin of the Vale of Eden and the Visean Great Scar limestone (sample 136, Figure 16) did not contain any visible gold.

Ingleton Coalfield

A panned concentrate sample obtained from a site in the Cant Beck at [361850 473890], draining the Ingleton outlier of reddened Westphalian and Permian rocks (sample 137, Figure 16), yielded no gold by physical extraction.

Charnwood Forest

Panned concentrate samples were obtained from three sites in the Charnwood area (Figure 17). One sample was obtained well within the Charnwood Forest massif from Dry Brook [44573 31689], close to the contact between Charnian rocks and the Triassic Sherwood Sandstone Group. This sample was heavily contaminated with metallic and other waste but contained no gold that was physically extractable or detectable by analysis. In contrast, three grains of gold were extracted from a sample (197) taken from further downstream in the Black Brook [4458 31873] over alluvium and Sherwood Sandstone Group rocks, just north of the northern margin of the outcrop of the Charnian. Subsequent sampling at a nearby site in the same stream (sample 347) failed to locate any further visible gold. Gold was found by analysis (390 ppb) in a panned concentrate sample (sample 199) from the Grace Dieu Brook at Thringstone [44327 31775] and subsequently one gold grain was extracted from a further sample from the same site (sample 348). Microchemical mapping of two of the Dry Brook grains is described below. Though the Thringstone site was heavily contaminated with metallic grains, the native copper present was of a form which could be natural in origin. In addition, grains of cinnabar, baryte and galena were identified in the sample. The site is situated very close to the faulted contact between Charnian rocks and Triassic Sherwood Sandstone Group at the north-west margin of the Charnian outcrop. Previous records of gold at outcrop and the results of this drainage sampling suggest that several gold-bearing structures are present in the area and that further work would be justified to test the extent, size and grade of such mineralisation.

Weatheroak area near Redditch

Three drainage samples were collected in the area around the locality of rich copper mineralisation near Moorfield Farm to the east of Redditch (Figure 18). This area is well within the outcrop of Triassic rocks and away from contacts with older rocks. One sample (194), from a site possibly draining the mineralised sandstone exposed in the road cut at [40574 27228], yielded one gold grain and several grains of cassiterite. A sample (195) draining another outcrop of mineralised Weatheroak Sandstone near Weatheroak Hall also contained one very small gold grain but the adjacent sample (196), draining from the north at [40573 27444], showed 2.0 ppm Au by analysis and a further gold grain extracted physically. This area merits further sampling to establish if this quantity of gold persists upstream of the most anomalous site and whether gold is present in other nearby streams.

South Malverns and Newent

A drainage sample (346) was taken from a site at the south end of Malverns (Figure 18), approximately at the contact between the Haffield Breccia of Permian age and the Silurian Wenlock Limestone at [37323 23476]. The stream drains mostly from the Wenlock Shale. One small grain of gold was extracted from the sample. A further sample (344) was taken from a stream draining the Triassic Bromsgrove Sandstone Formation, resting unconformably on Ludlovian shale to the south of

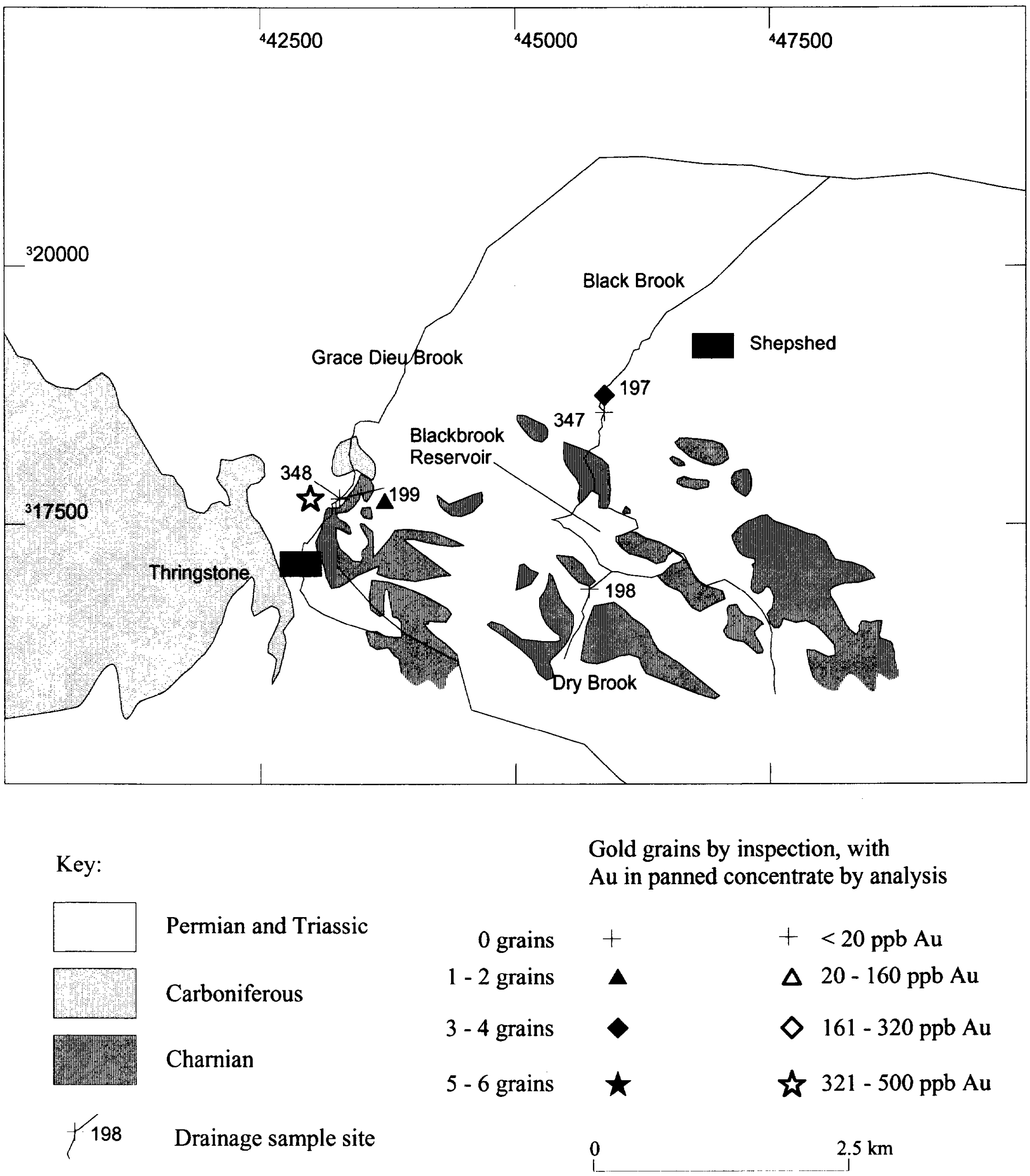

Figure 17 Simplified geology, drainage sampling sites and incidence of gold in Charnwood

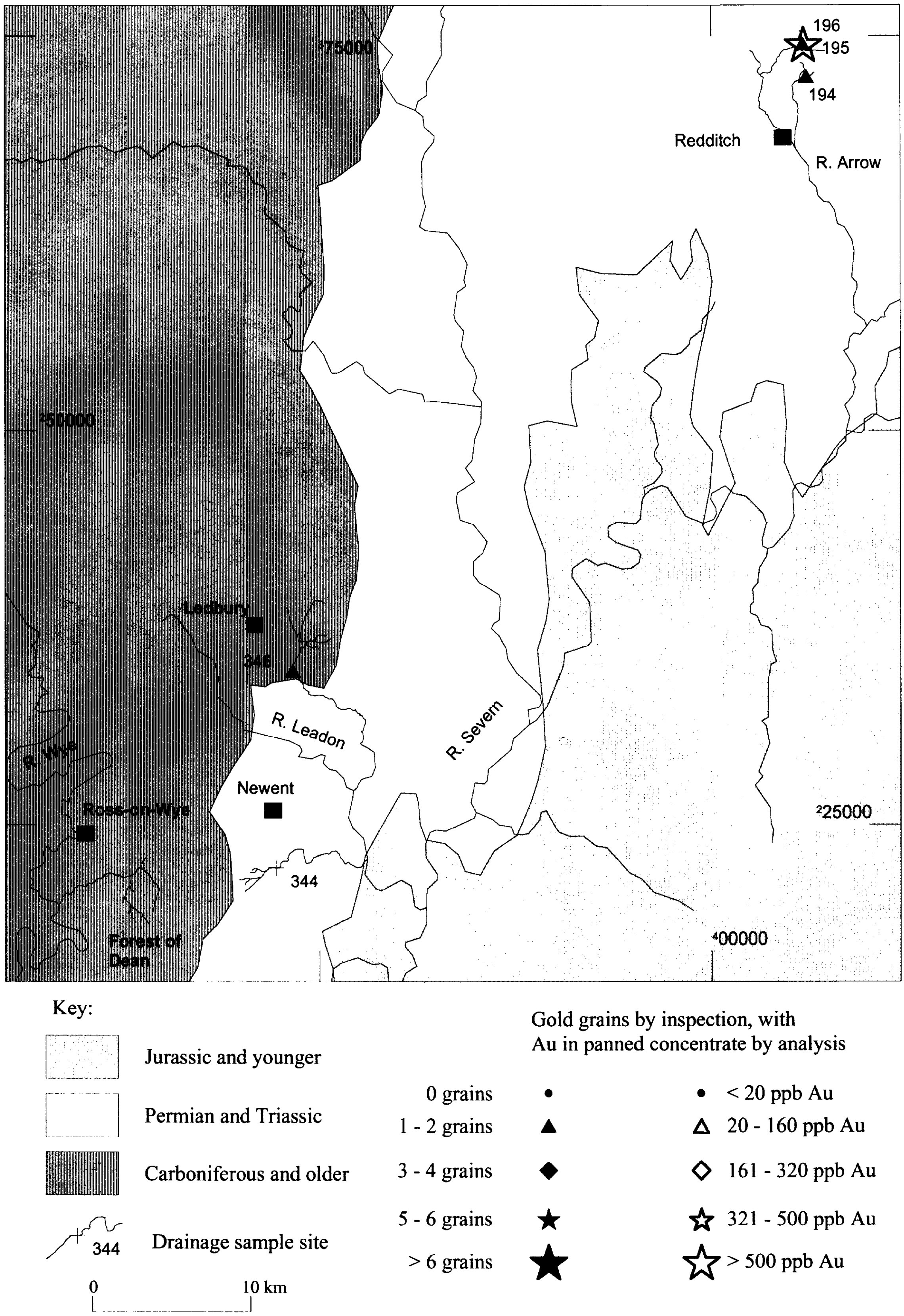

Figure 18 Simplified geology, drainage sample sites and incidence of gold in the south-west Midlands of England

Newent at [37220 22228]. No gold was recovered from this sample and chemical analysis showed only a background level (10 ppb).

Radstock and Mendips

A panned concentrate sample (343) was taken from Snail's Bottom to the south of Radstock (Figure 19) at [368050 152229]. The site drained a landslipped mass of typical mudstone from the Mercia Mudstone Group overlain by Penarth Group and Lower Lias rocks, upstream of which is Triassic dolomitic conglomerate resting on Pennant Series of Westphalian age. One grain of gold was observed during panning, and subsequent analysis of the sample gave 892 ppb Au. The sample was contaminated with copper metal but contained fibrous goethite which may reflect mineralisation.

A panned concentrate sample (342) was taken at [357820 142537], from a stream to the north-east of North Wootton near Wells (Figure 19). The sampling site is situated on the Mercia Mudstone Group with dolomitic conglomerate overlying Carboniferous Blackrock Limestone on the higher ground in the catchment area. There are also exposures of Penarth Group and Lower Lias in the area. No gold was observed during panning of a carbonate-rich sample containing pyrite and hematite, but the result of chemical analysis showed 1.76 ppm Au.

Quantock Hills

A panned drainage sample (340) was taken at [324920 134340], from a small stream at Andersfield Farm near Goathurst (Figure 19). The site is on the Mercia Mudstone Group with the Otter Sandstone Formation a few metres further upstream and Devonian Morte Slates beyond that. The sample contains minor baryte but no gold was observed. However, chemical analysis gave a value of 147 ppb Au. A further drainage sample (339) was taken from downstream of the old mining activity at Dodington on the northern edge of the Quantocks (Figure 19), at [317947 140830]. The sampling site was over the Mercia Mudstone Group outcrop downstream from the extreme northern end of the outcrop of Devonian rocks. No gold was observed but a few grains of a green mineral, possible a copper secondary mineral, were present together with a minor amount of pyrite. No chemical analysis was carried out on this sample.

East of the Brendon Hills

A panned drainage sample (338) was taken at [314320 129762], from a small stream at Denbury Farm near Ash Priors (Figure 19) The site drained an area of Budleigh Salterton Pebble Beds (Lower Triassic). One grain of gold was observed during panning and subsequent analysis gave a value of 1.14 ppm Au.

Two panned drainage samples were taken from Frys Farm to the south-east of Wiveliscombe (Figure 19). One site (336) comprised a very small stream draining the Wiveliscombe Sandstone and overlying Permian strata at [309878 126420]. No gold was observed in this sample and subsequent chemical analysis gave only 17 ppb Au. The other site (337) comprised a larger stream draining the Wiveliscombe Sandstone and its unconformable contact with Devonian shales at [30962 121651] and gravels overlying these rocks. Ten gold grains were observed in a concentrate derived from 4 pans of sediment. Subsequent chemical analysis of this concentrate gave 14.32 ppm Au. This sample was also analysed for a wide range of elements by ICP-ES and showed enrichment in La and P which also characterises samples derived from Permian rocks of the Crediton Trough (Cameron et al., 1994). Other elements present in anomalous quantities in this sample are As (152 ppm), Mo (14.1 ppm) and

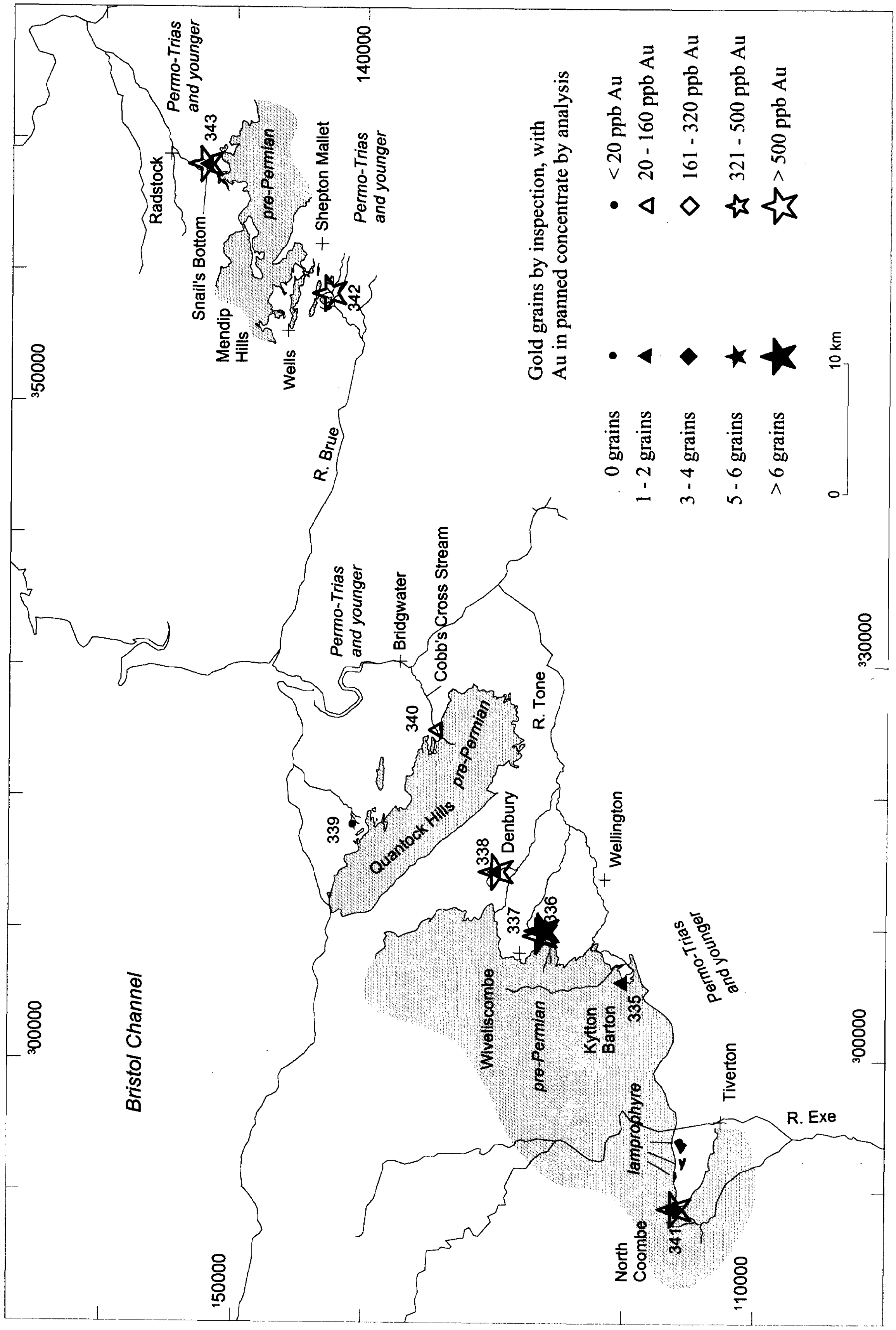

Figure 19 Simplified geology, location of drainage sample sites and incidence of gold in south-west England.

Pb (174 ppm). The relative abundance of gold in this sample compared with the adjacent sample suggests that the unconformity between the Permian and Devonian rocks is a more likely source of the gold than the Wiveliscombe Sandstone itself.

Tiverton Basin

A panned concentrate of drainage sediment (sample 335) was taken at Kytton Barton (Figure 19) at [305850 120290], upstream from the site previously sampled near Holcombe Rogus (Cameron et al., 1994). The stream drains the Dinantian Doddiscombe Beds, comprising black laminated shales, from which overlying Permian red sandstones have been removed by erosion. The site was chosen because black shales of this type may be expected to react readily with oxidising solutions circulating in the Permian red-bed sequence. Two gold grains were observed in the sample, suggesting that gold may be widespread in the area and that more detailed exploration is justified.

A concentrate sample (341) was also obtained at the extreme western end of the Tiverton Basin (Figure 19) from a tributary of the river Exe at [28856 11569], close to the unusual potassic ultramafic pipe intrusion named after the nearby Holmead farm. The site is some 30 m vertically below the projected base of the unconformable Permian. Three gold grains were observed during panning and subsequent analysis gave 1.82 ppm Au.

GOLD GRAIN CHARACTERISATION

Physical separation of gold grains from drainage samples allows the gold grain characterisation procedures developed at BGS to be carried out. The extracted gold grains, together with a small number of silvery-coloured grains, were mounted in resin, ground and polished to reveal a section through each grain. These grains were examined in detail microscopically to locate visible inclusions. Subsequently the composition of the grains and associated inclusions was determined using a Cambridge Instruments Microscan 5 electron microprobe fitted with a LINK systems energy dispersive analyser.

Mauchline Basin

All gold grains from the Mauchline Basin exposed by polishing were analysed quantitatively by electron microprobe and the results are given in Appendices 1 and 2. Where differences in colour were evident from microscopic examination of grains, multiple points were analysed to cover the range in composition present. Heterogeneities visible optically comprise films of Ag-enriched gold penetrating through the body of the gold grain, rims, and more irregular intergrowths of gold with different colours. In addition, microchemical mapping of segments of 8 grains was carried out using the Cameca SX 50 automated electron microprobe as described in Leake et al. (1991). Mapping was carried out to show the extent of internal chemical variation within the gold grains and to assist in the identification of microscopic inclusions.

Gold grain composition
For the graphical comparison of compositions of grains from different sites only one analysis per grain was utilised. For heterogeneous grains the composition of the earliest segment of the grain or grain core was taken. Individual grain compositions, 169 in total, were plotted on a cumulative percentage plot for all the grains from the Mauchline Basin and its surroundings in Figure 20. On this plot a considerable range in the silver content of the gold grains is apparent. About 28% of the grains contain less than the detection limit of the probe analysis system used (0.3% Ag). Breaks in slope on the silver plot at around 4.6% Ag and 7.3% Ag may indicate separate compositional populations.

About 26% of the grains contain copper above the 0.6% level and there is a sharp break in slope at about the 3.5% Cu level (Figure 21) which may reflect a maximum level of copper solution in gold under the temperature conditions of the primary mineralisation. In three grains gold is intergrown with the gold-copper intermetallic compound Au_3Cu (ideal composition 9.7% Cu) and the higher levels of copper found by analysis represent the composition of this compound or a mixture of this and adjacent gold. Only about 8% of the grains contain detectable palladium, in the range 1.2 to 6.1%.

Cumulative frequency plots of silver contents of gold from the four sites with most grains (124, 104, 176 and 190) are shown in Figure 22. The range in silver content and the shapes of the curves are essentially similar, except perhaps in the case of sample 104. Though this is the smallest sample, the lower range in silver content and somewhat different shape is probably significant. Differences between the other sites are minor, suggesting that the gold from these sites is derived from essentially the same type of source.

There are significant differences between the compositions of gold grains from the Mauchline Basin and South Devon and the Crediton Trough (Leake et al, 1991; Cameron et al, 1994). There are proportionally smaller numbers of Pd-bearing grains in the Mauchline Basin than in Devon, whereas the proportion of Cu-rich gold grains is much higher in the Mauchline Basin gold. The intermetallic compound Au_3Cu is present as concentric zones or large sectors in some Mauchline Basin grains while in Devon grains it is present as scattered relatively small patches, sometimes associated with the other copper-gold intermetallic compound auricupride (AuCu). The silver content of the Mauchline Basin grains is generally much higher than in the Devon grains. The reason for these differences is not yet clear but must reflect differences in the mineralising solutions which were responsible for gold transport in the red-bed environment.

Inclusions within gold grains

The commonest inclusion in the gold grains is tiemannite (HgSe). Other inclusions comprise copper selenides, selenides of Bi, Pb, Ag and Cd, and palladium telluride. This inclusion assemblage is very similar to that found in gold from the Crediton Trough in Devon. In addition, there are individual grains with cobaltite and chalcopyrite inclusions respectively, which may be derived from sources more typically associated with the Lower Palaeozoic rocks of the Southern Uplands.

Gold grain mapping

The limited amount of gold grain mapping carried out using the Cameca SX50 automated electron microprobe showed that some of the grains were internally compositonally complex. The degree of complexity is more than can be observed microscopically and the composition of many of the features was not determined by spot analyses. The features of each of the mapped grains are described below. Several of the grains were mapped more to help with the identification of inclusions than to investigate particular types of compositional heterogeneity.

Grain 104/1 shows variable Pd enrichment with diffuse boundaries. In addition there is an incomplete marginal zone of Ag enrichment and a few patches of similar composition near to the grain margin.

Grain 104/2 consists of four compositional types. Two compositional classes of penetrating Ag-enriched films are present cutting in a complex manner through the grain matrix which shows less enrichment in Ag. Compositional boundaries tend to be sharp. In addition there is a partial overgrowth of pure gold.

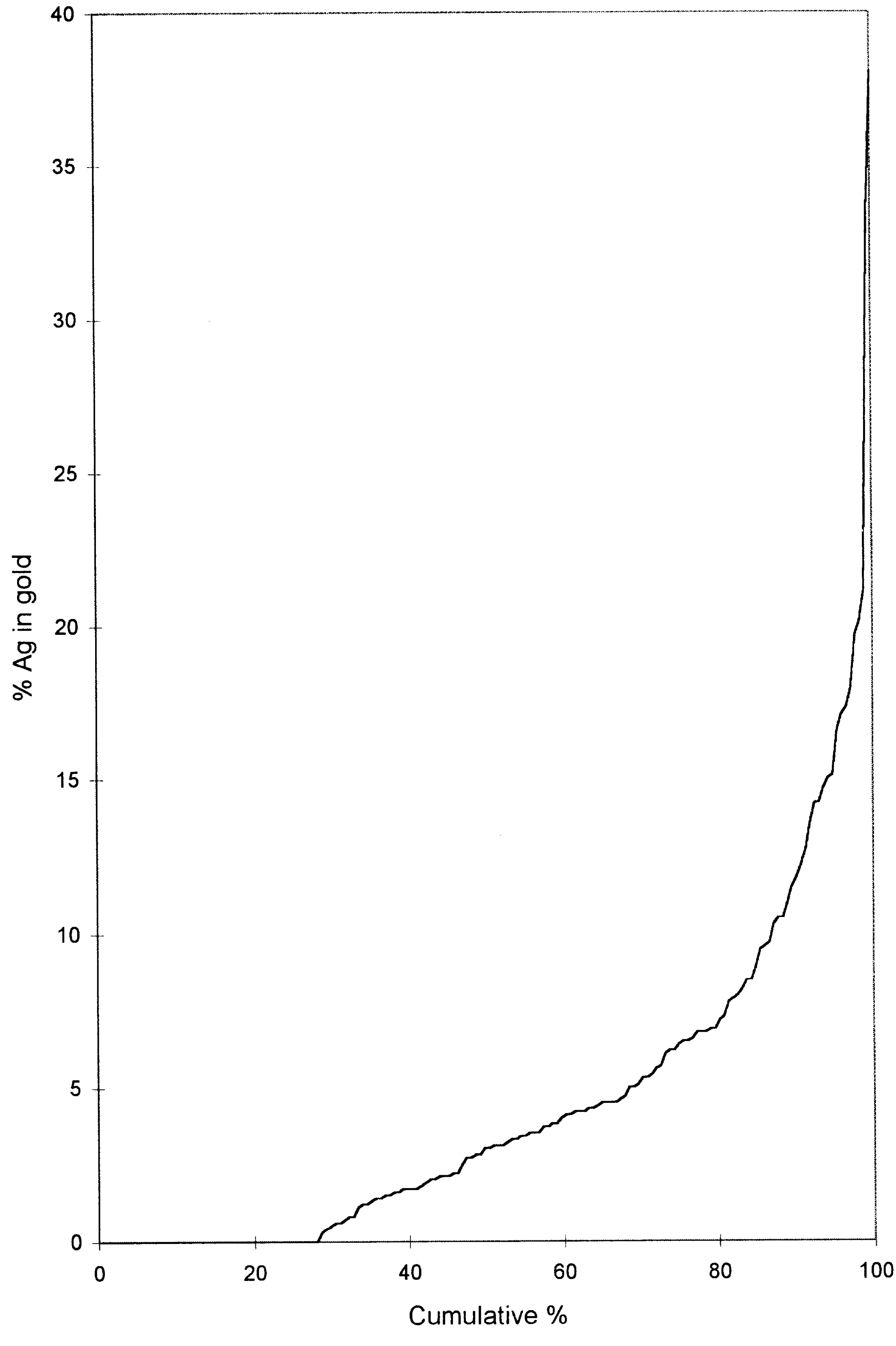

Figure 20 Silver content of all gold grains from the Mauchline Basin

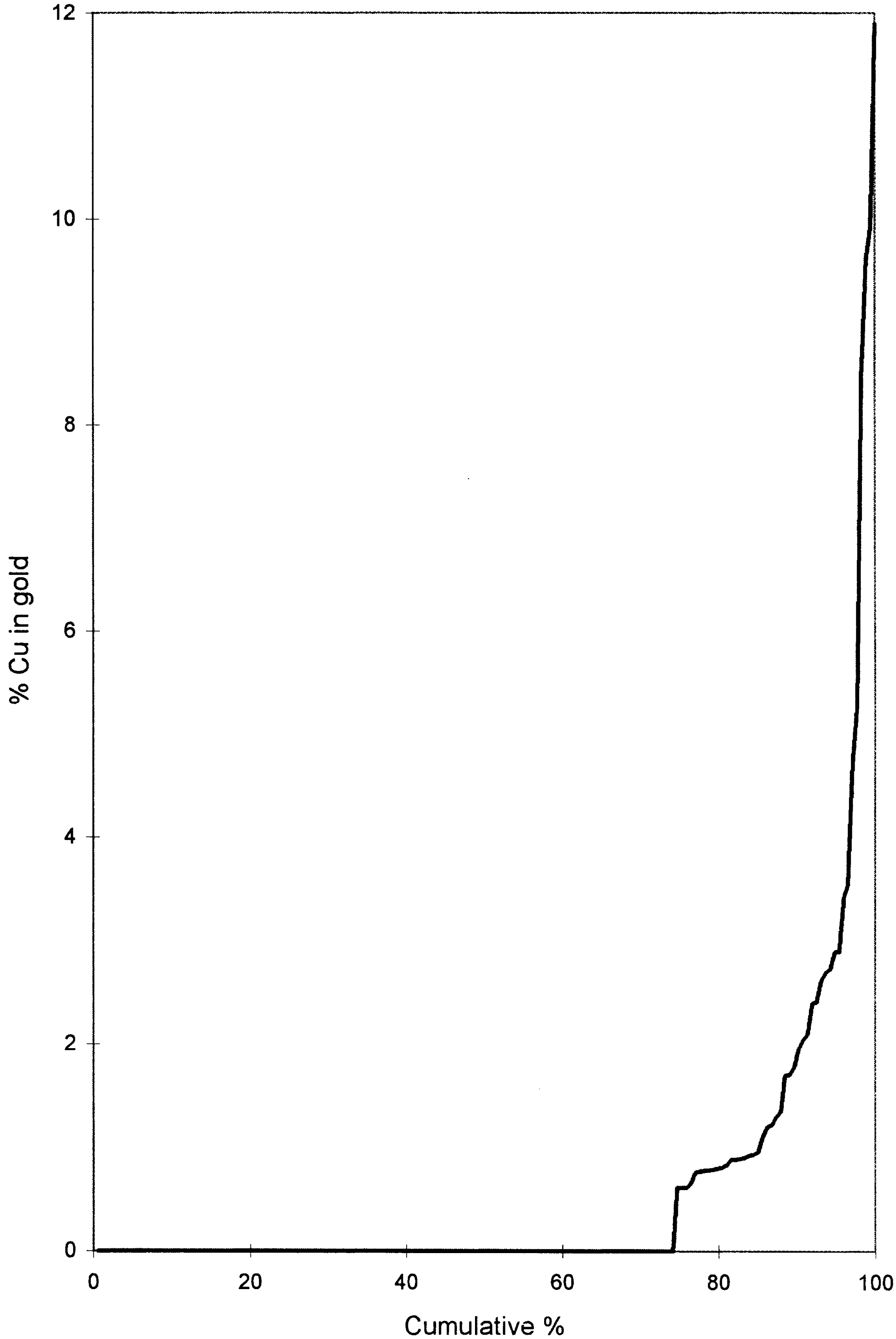

Figure 21 Copper content of all gold grains from the Mauchline Basin

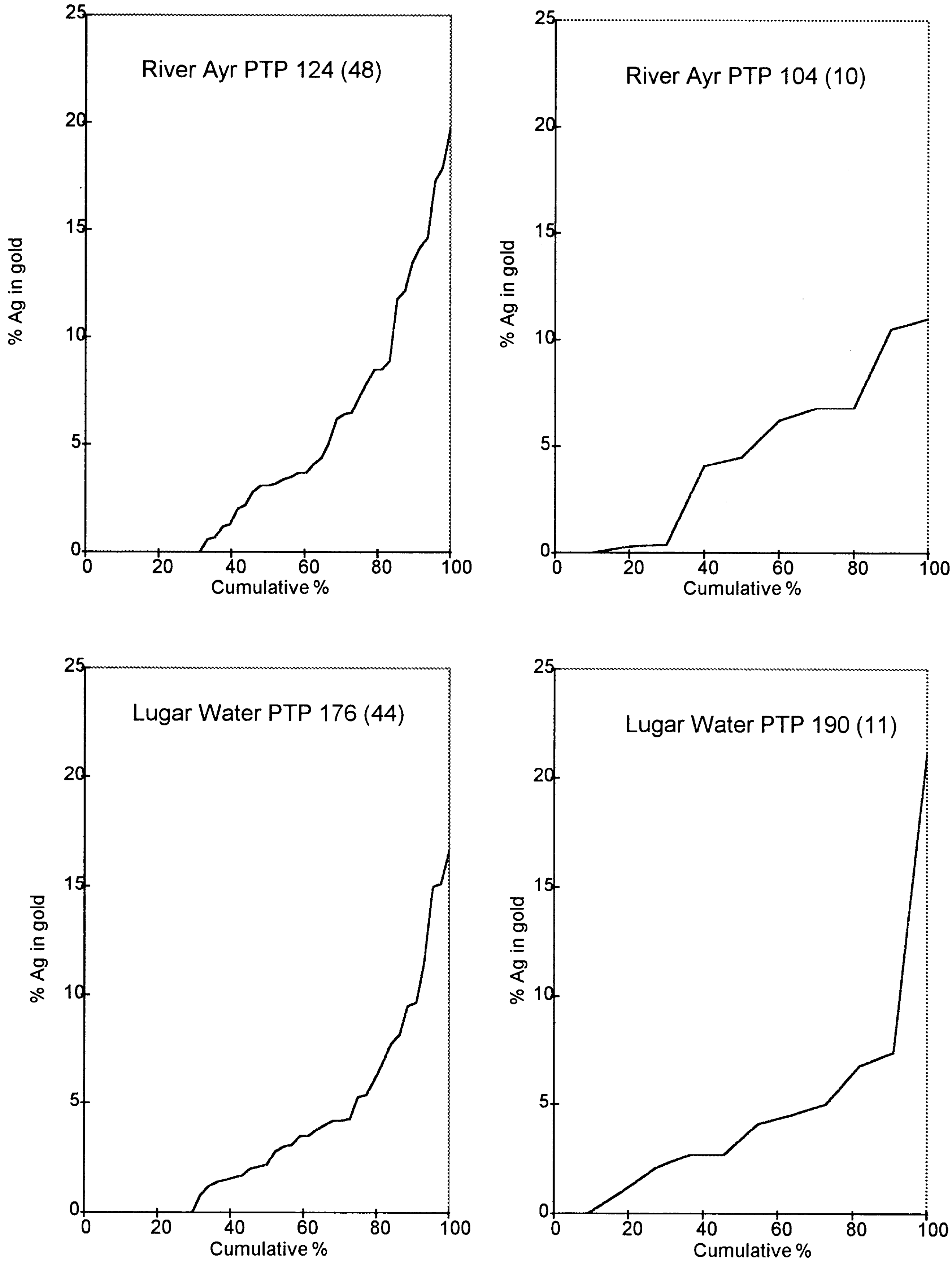

Figure 22 Silver content of gold grains from four sites in the Mauchline Basin. Numbers of grains in each sample in brackets.

Grain 104/6 shows roughly concentric growth zonation with at least seven different compositions apparent. The core of the grain shows slight enrichment in Cu and outside this are two other more Cu-rich zones, one of which consists of the intermetallic compound Au_3Cu and correlates with a pink-coloured zone visible in reflected light. Outside this is a thin irregular zone showing marked enrichment in Ag and a wider zone with only slight enrichment in Ag. This is followed by porous material showing slight enrichment in Cu but no Ag and finally a partial rim of nearly pure gold. Compositional boundaries trend to be relatively sharp.

Grain 147/1 shows discontinuous films and patches showing enrichment in Ag. Boundaries are relatively diffuse.

Grain 147/3 consists of an irregular network intergrowth of pure gold and Ag-enriched gold. Boundaries between the compositional types are diffuse.

Grain 175/6 consists of Pd-rich gold showing diffuse compositional zoning and a few small patches enriched in Cu (probably of Au_3Cu). In addition, there is a partial rim and crack filling of pure gold.

Grain 176/4 consists of pure gold penetrated by a network of Ag-enriched films, probably two generations with differing Ag contents. Compositional boundaries are relatively sharp.

Grain 176/14 is a very complex grain showing several stages of growth. The core of the grain consists of pure gold intergrown with a network of films and patches of Ag-enriched gold. Outside this is an almost complete rim of variable thickness and an irregular penetrating zone which is enriched in Hg. Outside this is a thin discontinuous zone enriched in Ag and to a lesser extent also in Hg. On one edge of the grain is a zone about 10 μm wide of a gold-tin alloy with a composition close to AuSn. The interrelationships of the compositional types in this grain suggest that this rim is of natural origin.

Interpretation of Mauchline Basin data

The grain mapping indicates that the history of grain growth in the Mauchline area is relatively complex. Grains either show concentric or asymmetrical growth zonation or a network intergrowth of different compositions with the penetrating gold replacing the original core growth. Similar textures have been observed in Devon gold and presumably reflect a changing mineralising fluid chemistry with time and multiple phases of mineralising activity. Several of the grains show diffuse compositional boundaries. This suggests that the grains originated at relatively high temperature or were subjected to relatively high temperature during a phase of growth. This may indicate that the alkali basalt lavas and their feeders were important in providing energy and perhaps elements to the mineralising fluids.

In addition, native copper mineralisation was located in situ in sandstone rafts within the sequence of volcanic rocks. This is significant because, in this environment, gold would be precipitated in a similar way to native copper.

Comparison between the abundance of alluvial gold in the Mauchline area compared with other areas underlain by Permian and Triassic rocks in Britain that have been investigated as part of the project suggest that this area may have the greatest potential for gold mineralisation of the red bed type outside Devon. The north-west-trending zone of mineralisation indicated from the drainage exploration coincides exactly with a major lineament in the aeromagnetic data which could indicate a deep-seated fault along which basic igneous rocks were intruded, including at a later date Tertiary dykes. Several grains of cinnabar (HgS), a mineral frequently associated with some types of gold mineralisation, were also observed in the samples and the numbers counted are shown in Figure 15. Cinnabar seems to be most concentrated at the north and south ends of the presumed gold-bearing structure.

The fact that the presumed north-west-trending mineralised zone (Figure 6) is cut several times by the major river valleys is fortunate, as it may be possible to trace it in exposures which occur in the side and bottom of these deeply-incised valleys. Thus the next stage of exploration which is required in the Mauchline Basin is to carry out systematic rock sampling in such areas, with a view to locating gold enrichment in bedrock. Between the main rivers it will be necessary to carry out deep overburden sampling because of the blanket of glacial drift. The distribution of alluvial gold indicates that other sources of gold are likely in the area but as yet these cannot be defined to the same extent. On the basis of the drainage survey, together with the results of gold-grain mapping carried out so far, there may be at least three types of gold present in the area. Silver-rich gold seems to be confined to the presumed north-west-trending mineralised zone while copper-bearing gold is more widespread and possibly more closely associated with the outcrop of the Permian volcanic rocks. The gold in the sample from the south-west part of the area could be associated with the volcanic vents which are concentrated in the area or derived from an important zone of NE-trending faulting which cuts through the area.

Thornhill

Chemical analyses of sixteen gold grains from the area and microchemical maps of five grains are given in Leake and Cameron (1996). The grains are similar in composition to grains from Mauchline and like them contain inclusions of selenide minerals and, in one grain, a partial rim of stibiopalladinite. These compositional characteristics are consistent with sources associated with the Permian red beds and their contacts with more reduced rocks.

Charnwood Forest

Microchemical mapping of two of the Charnwood gold grains was carried out, together with quantitative point analyses (shown in Table 3).

Table 3 Quantitative point analyses of Charnwood gold grains

grain	Locality	Au%	Ag%	Cu%	Sum
PTP 197/2	Black Brook	98.0	<0.5	1.36	99.4
PTP 197/2	Black Brook	96.7	<0.5	1.39	98.1
PTP 197/2	Black Brook	100.6	<0.5	0.94	101.5
PTP 197/3	Black Brook	69.9	26.3	6.9	103.1
PTP 197/3	Black Brook	68.8	25.8	6.45	101.0
PTP 348/1	Grace Dieu	60.2	23.1	19	102.3

One of the grains (PTP 197/2) contains a large number of inclusions showing enrichment in copper at two concentrations. The point analyses in Table 3 probably reflect larger areas showing lower level copper enrichment and represent Cu alloyed within gold. Smaller spots showing higher Cu enrichment are probably of a gold-copper intermetallic compound, probably Au_3Cu, since no other element seems to be associated with Cu. There are also a small number of spots showing Ag enrichment in the centre of the grain. They correspond with areas of low Cu on the copper map and have the appearance of Ag-rich mineral inclusions. However, no other element seems to be associated with the silver. Unless silver is associated with an element not examined, which would be very unusual, then these areas must represent areas of silver-rich gold or even native silver intergrown intimately with Cu-rich gold and Au_3Cu in the centre of the grain.

The combination of high levels of Ag and Cu (Table 3) in the other two grains is unusual. The phase diagram of the Cu-Au system indicates that copper would only go into solution within gold to a large extent at high temperature. Within the typical hydrothermal range (<350°C) the solubility of copper in gold is limited by the stability of the gold-copper intermetallic compounds. Thus the compositions of both grains indicate that they are either of high temperature origin or represent a mixture or intergrowth of intermetallic compounds Au_3Cu, or AuCu and native silver.

The composition of grain PTP 197/2 is entirely consistent with derivation from oxidising red-bed type mineralisation. The other two grains are more problematic but completely unlike gold grains derived from mesothermal shear zone type mineralisation that might occur within the Charnian rocks or gold which could have had a primary association with the Charnian volcanic rocks.

ROCK SAMPLING

Mauchline Basin

Some rock samples were obtained as part of the reconnaissance survey but no systematic sampling was carried out as part of the follow-up of the alluvial gold. Details of the rock samples are given in Appendix 3

Several samples were taken to establish whether carbonate, thought to originate from oxidation of coal due to the influence of oxidising solutions penetrating beneath the Permian unconformity (Mykura, 1960), was potentially enriched in gold. In addition, samples of sandstone and alkali basalt, the main components of the Permian sequence, were collected, together with samples of sills, both within the Permian sequence and in the underlying rocks, which are thought to be coeval or later than the exposed Permian volcanic rocks. Chemical analyses of these rocks are shown in Table 4. The elements Mg, K, Ca, Ti, Mn, Fe, Co, Ni, Zn, As, Se, Zr, Ba and Pb were determined by XRF at the BGS Analytical laboratories. Au was determined in the same way as for concentrate samples and Ag and Bi were determined by ICP-ES after aqua regia digestion at Acme Analytical Laboratories Ltd of Vancouver, Canada.

Samples of four of the softer rocks were panned in the field and the resulting concentrates were analysed for Au and other elements by ICP-ES. The results of these analyses, for potentially the most informative elements, are shown in Table 5 below. In addition, two grains of gold were extracted from the concentrate obtained by panning sample PTR 218.

No Au in significant amounts was found by analysis of any of the rock samples, but two grains of gold were recovered from soft altered basalt (PTR 218) by panning. As the exposure was adjacent to the Lugar Water, it is possible that these gold grains were alluvial in origin which had become trapped in the bedrock. Previous experience has shown that gold grains are readily trapped within cracks in bedrock in the bed of a stream or in exposures adjacent to the stream. However, the altered basalt that was sampled was soft and without any cracks within which gold could be lodged, which suggests that the gold grains are more likely to be derived from the rock. The chemical analysis of the panned sample from the rock and, to a lesser extent, the analysis of the rock, indicate that it has been affected by hydrothermal alteration or mineralisation. The high concentration Fe in the panned concentrate from PTR 218 compared with those from the dolerites (PTR 201, 220), in spite of similar contrents in the rock samples (Table 4), suggests that hydrothermal alteration may have oxidised the iron and increased its solubility in aqua regia compared with fresh basalt. Similarly, the higher concentrations of As, Ag, Mo, Ba, Hg and Pb in the panned concentrate from PTR 218 suggest hydrothermal introduction of metallic elements with which the gold is possibly associated.

Table 4 Chemical analyses of rocks from Mauchline Basin and surrounding area

	MgO	K_2O	CaO	TiO_2	MnO	Fe_2O_3	Co	Ni	Cu	Zn	As	Se	Zr	Ba	Pb	Ag	Au	Bi
PTR1	3.5	0.14	7.04	0.284	0.124	7.74	48	49	184	15	19	<1	400	64	19	0.5	2	5
PTR2	1.6	0.61	5.15	0.5	0.599	47.17	<1	36	101	20	<5	2	70	231	4	0.5	2	17
PTR3	0.3	1.86	0.14	1.239	0.018	3.53	44	53	142	14	27	1	241	326	25	1.6	1	2
PTR4	5.2	1.26	15.65	0.436	0.168	9.46	24	27	9	40	<5	<1	179	247	10	0.4	<1	4
PTR5	5.7	1.33	15.18	0.478	0.121	6.7	14	19	9	35	5	<1	230	160	6	<0.3	1	3
PTR6	1.2	1.56	0.54	0.665	0.469	25.13	26	42	6	24	<5	<1	189	248	6	<0.3	1	11
PTR7	0.4	2.07	0.11	0.869	0.005	0.86	3	8	47	7	<5	<1	263	283	3	<0.3	4	<2
PTR8	2.9	1.35	0.29	0.215	0.036	1.25	12	28	3643	36	<5	<1	201	372	5	1.3	2	<2
PTR9	9	0.88	8.25	1.669	0.143	11.81	50	267	38	110	<5	1	105	300	20	<0.3	1	4
PTR10	5	1.66	0.65	0.399	0.053	2.16	18	53	3323	59	<5	<1	209	331	12	1.2	1	3
PTR11	3.2	0.85	8.06	0.819	0.157	6.46	7	17	13	96	7	1	1195	745	7	0.4	2	4
PTR12	2.9	0.76	7.72	1.227	0.136	5.51	8	16	32	386	<5	<1	1542	241	24	0.3	2	3
PTR201	8.3		4.86	2.287	0.101	12.58		65	104	45	<5		163	89	5		5	
PTR202	1.6		0.36	0.188	0.018	2.51		10	22	10	<5		182	53	<3		<2	
PTR203	1.5		0.57	0.182	0.012	1.45		8	3	4	<5		153	91	4		5	
PTR204	9		5.18	2.457	0.124	14.18		40	68	45	<5		160	124	3		<2	
PTR205	7.9		7.64	2.258	0.089	12.07		44	92	26	<5		173	62	<3		<2	
PTR206	0.1		<0.05	0.038	0.007	0.56		6	5	5	<5		40	275	5		<2	
PTR207	0.3		<0.05	0.059	0.01	0.79		7	4	3	<5		49	327	8		<2	
PTR208	0.3		<0.05	0.055	0.007	0.71		7	3	5	<5		48	328	7		2	
PTR209	0.2		<0.05	0.136	0.038	1.22		6	10	11	<5		142	340	4		<2	
PTR210	14.3		7.36	1.776	0.121	10.18		270	47	74	<5		128	426	<3		<2	
PTR211	18.9		4.45	1.77	0.136	10.02		207	49	68	<5		111	356	<3		<2	
PTR212	13.8		8.31	1.563	0.132	10.07		304	35	77	<5		115	357	<3		<2	
PTR213	18.2		5.13	1.743	0.129	10.66		279	29	72	<5		118	406	3		<2	
PTR214	0.5		0.21	0.11	0.032	1		10	6	7	<5		115	120	<3		<2	
PTR215	15.5		7.06	1.586	0.132	10.41		359	38	84	<5		115	422	<3		<2	
PTR216	6.4		8.51	2.099	0.177	12.12		60	106	82	<5		153	<5	<3		<2	
PTR217	11.2		8.37	1.666	0.136	10.22		317	24	79	<5		124	392	<3		<2	
PTR218	19		1.71	2.12	0.13	11.54		220	28	80	<5		130	516	14		<2	
PTR219	2.9		9.8	0.014	0.149	9.1		502	33	28	<5		<1	57	<3		<2	
PTR220	16.1		4.8	0.981	0.147	13.81		355	49	95	<5		56	175	17		<2	
PTR221	12.4		6.18	1	0.138	12.63		307	54	83	<5		66	182	6		<2	
PTR222	2.8		0.08	0.192	0.011	0.82		23	213	33	<5		148	317	5		<2	

MgO, K_2O, CaO, TiO_2, MnO and total Fe as Fe_2O_3 in %, Au in ppb, other elements in ppm

Table 5 Chemical analyses of panned rock samples (ICP-ES, after aqua regia attack)

	V	Cr	Mn	Fe	Cu	Zn	As	Te	Ag	Mo	Ba	Au	Hg	Pb	Bi
PTR201	74	38	188	2.35	27.5	14.3	<0.5	0.1	<30	0.3	104	1	6	2.4	<0.1
PTR202	10	10	50	0.55	7.5	4.2	<0.5	0.1	<30	0.2	15	<1	6	0.8	<0.1
PTR218	878	578	1715	24.96	37.8	277.1	6.6	0.5	48	2.1	1519	2	563	132.6	2.0
PTR220	464	227	1114	7.48	24.3	211.4	<0.5	0.2	<30	0.5	44	<1	330	2.6	<0.1

Fe in %, Ag, Au and Hg in ppb, other elements in ppm

Two samples of sandstone raft within the Permian alkali basalt are highly enriched in Cu, though not in Au, Ag or other metallic elements. This rock consists of detrital grains of quartz and feldspar with thin early diagenetic hematite coatings. In addition, there are subparallel zones of bleaching 2-4 mm wide in which a chemical reaction has caused reduction and removal of the hematite coatings. These are centred on hairline fracture veinlets of native copper. There are also vein-like "blooms" of interconnected grain boundary films of native copper. The native copper is partially altered to cuprite. Clear calcite post-dates the native copper and occurs in the fractures with malachite.

Copper is also enriched to a lesser extent in the sample of sandstone containing reduction spots (PTR 222, Table 4). XRF scanning of a reduction spot taken from this sample showed enrichment in Cu accompanied by lower amplitude enrichment in Ag and Se and possibly Ge.

The samples of Middle Coal Measures pyritic seatearth and dark shale (PTR 1, 3) are enriched in Cu and, to a lesser extent, As, but there is no indication of Au enrichment. No metals are enriched in the samples of carbonate rock which are considered to be derived from the oxidation of coal but the sample of seatearth with carbonised plant remains (PTR 12) shows some enrichment in Zn (Table 4).

Chemical differences are evident between the different types of basic rock present in the area. The teschenitic dolerite intrusions within and above the alkali basalts are richer in Ti and much poorer in Ni than the alkali basalts (Table 4). The teschenite intrusions from below the Permian sequence are similar to the alkali basalts in Ni content but lower in Ti. The Cu content of the samples of alkali basalt (24-49 ppm Cu) is relatively low compared with basalts in general and in comparison with the teschenitic intrusions from within and above the unit (68-106 ppm Cu). This may indicate that there has been considerable leaching of metals, including precious metals, from the alkali basalt shortly after deposition. Such metal-enriched fluid could be the precursor of mineralising solutions which were responsible for the mineralisation source of the alluvial gold.

Snar Valley

Two samples of the Permian sedimentary breccia from the Snar Valley inlier were analysed for gold by ICP-ES and by XRF for a range of elements. The results are shown below in Table 6. In addition, a panned concentrate was obtained from the same material as PTR 223 and analysed for Au and a range of elements by ICP-ES (Table 7).

Table 6 Chemical analyses (XRF) of samples of Permian breccia from Snar inlier

	MgO	CaO	TiO_2	MnO	Fe_2O_3	Ni	Cu	Zn	As	Zr	Ba	Pb	Au
PTR223	3.2	0.48	0.971	0.069	6.87	40	15	65	<5	250	414	<3	<2
PTR224	3.6	0.53	1.037	0.073	7.11	44	13	67	<5	325	406	8	<2

MgO, CaO, TiO_2, MnO and total Fe as Fe_2O_3 in %, Au in ppb, other elements in ppm

Table 7 Chemical analysis of panned concentrate from breccia from Snar Inlier (ICP-ES, after aqua regia attack)

	V	Cr	Mn	Fe	Cu	Zn	As	Te	Ag	Ba	Au	Hg	Pb	Bi
PTR223	61	62	455	3.87	18.7	55	5	0.1	40	513	46	63	169.2	0.1

Fe in %, Au and Hg in ppb, other elements in ppm.

The panned sample is similar chemically to the ordinary rock sample except that Au and Pb are enriched. These differences probably reflect the difficulties of providing an adequate sample of such a coarse-grained rock as the Snar sedimentary breccia. The presence of a low amplitude anomalous level of gold suggests that further investigation of the Permian rocks of the Snar Valley inlier would be merited.

Tynemouth

One sample each of basal Permian red breccia and of reddened mudstone of Westphalian age containing darker bands with coarse mica from below the unconformity exposed in the northern cliffs below Tynemouth castle were analysed for Au, Pd and Pt by ICP-ES and graphite furnace AAS after fire assay fusion, and for a range of elements by XRF. No concentrations of precious metals above background levels were detected and there was no evidence of enrichment in other metallic elements.

Ashbourne

Rock sampling was carried out around Nibs End farm near Thorswood House, some 6 km to the west of Ashbourne, where Triassic Sherwood Sandstone is in contact with Carboniferous Widmerpool Formation rocks. At the contact is a breccia with limestone fragments set in a red matrix, but there is little evidence of significant interaction between the solutions circulating within the Sherwood Sandstone and the underlying rocks. Some debris from an old adit comprises very reddened limestone, but no copper secondary minerals were seen. Maximum levels of Cu and Au found in three samples of reddened limestone were 33 ppm and 5 ppb respectively.

Weatheroak area near Redditch

Two samples of bleached Weatheroak Sandstone containing malachite and possible Cu silicate from a stream section near Weatheroak Hall [40607 27444] showed enrichment in copper (1185 ppm Cu) but no enrichment in other elements, including gold. The material is similar to that from the M42 road cut but because of surficial leaching has lost much of its copper content.

CONCLUSIONS

The sampling undertaken as part of this work has demonstrated that alluvial gold is widely distributed in areas underlain by red-bed sediments of Permian and Triassic age. In addition, the nature of this gold is recognisably different in its chemistry and inclusion assemblage from mesothermal and other types of gold found in other parts of the country (Leake and Chapman, 1996). These findings support the mineralisation model developed from MRP work in Devon (Leake et al., 1991) which proposes that the oxidising solutions which typically circulate within red-bed basins are capable of transporting significant amounts of gold and that deposition of this gold would be favoured where the solution is reduced either by reaction with unoxidised rocks or with fluids generated within a more reducing environment.

Drainage sampling, usually on a very limited scale, was carried out in 23 areas underlain by red beds of Permian and Triassic age, with attention paid especially to streams draining contacts between the red beds and underlying rocks. In 15 out of the 23 areas sampled, gold was found either physically or by chemical analysis. Gold was found where Permian red sandstones are in contact with Lower Palaeozoic rocks (greywackes and shales) at Thornhill and at the south end of the Malverns. Where Permian red beds rest on red Carboniferous shales and sandstones, gold was abundant in the Mauchline and Somerset area, but absent or insignificant in the Vale of Eden, Stainmore and Ingleton areas. Similarly, gold was not found where Permian red sandstones are in contact with Carboniferous limestone in the Vale of Eden. Gold occurs in areas where Triassic conglomerate, sandstone and mudstone rest unconformably on Precambrian slates and volcanic rocks and Carboniferous limestone in Charnwood Forest and the Mendip-Radstock areas respectively. In contrast, little or no gold was found where Triassic sandstone is in contact with Silurian shales west of Gloucester or Devonian rocks in the Quantock Hills. Gold is also present well within the region of outcropping Permian and Triassic rocks, in the Weatheroak area near Redditch, and also to the east of the Brendon Hills.

The most widespread and abundant gold seems to associated with areas where alkali basalt is present within the Permian sequence, as in the Mauchline and Thornhill areas and also in Devon. Palladium is absent within the gold from the Charnwood area but is widespread in the material from the Mauchline and Thornhill areas, as well as Devon. This suggests that the alkali basalt in the Permian sequence in these areas may act as a crucial low-grade source of precious metals which, on oxidation, releases gold and other metals into solution within fluids circulating within the basin. However, gold also appears to be present in solutions circulating in red beds without volcanic rocks in the sequence. In southwest England gold is associated with areas like the Crediton Trough and the Tiverton Basin, where volcanic rocks are present, but it also occurs further north in Somerset where the volcanic rocks appear to be absent.

RECOMMENDATIONS

Detailed rock sampling, augmented by deep overburden sampling and drilling where necessary, is recommended in the Mauchline Basin, particularly to the north-west of Ochiltree, to locate in bedrock the source of the alluvial gold. This will allow an assessment of the likelihood of concentrations of gold of economic interest within bedrock. Particular attention has to be given to the third dimension since the richest mineralisation may be associated with the interface between Permian and older rocks where oxidation-reduction reactions are likely to have been most intense. Further drainage sampling should be carried out in all those other areas where alluvial gold has been found in the course of this survey. Sampling should be extended to investigate the variation in gold abundance within the streams of interest and also in adjacent streams. On this basis it should be possible to establish whether any target of potential interest is likely to exist within bedrock in each area. Reconnaissance work should be extended to cover potential areas of interest in South Wales and to favourable parts of the Welsh Borders not investigated.

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APPENDIX 1 Quantitative electron microprobe analyses (in wt %) of gold grains from orientation site (River Ayr, E of Stair) in Mauchline Basin

sample	grain	part	Au	Ag	Cu	Pd	Hg	Sn	Sum
PTP122	1		96.1	3.1	0	0	0	0	99.2
PTP122	2		96.4	0	0	2.3			98.7
PTP122	3		63.1	13.5	0	0	18.7		95.3
PTP123	1		94.8	3.7	0	0			98.5
PTP124	1		89	7.1	0	3			99.1
PTP124	1	dark	91.4	1.3	0	5.3			98
PTP124	2		99.6	0	0	0			99.6
PTP124	3		90.8	8.4	0	0			99.2
PTP124	4		82.7	17.3	0	0			100
PTP124	4	film	57	38.3	0	0	2.4		97.7
PTP124	5		94.7	3.1	0	0			97.8
PTP124	6		83.2	14.3	0	0			97.5
PTP124	7		95.1	3.1	0	0			98.2
PTP124	8		80.4	17.5	0	0			97.9
PTP124	9		98.8	0	0	0			98.8
PTP124	9	film	79.2	18.1	0	0			97.3
PTP124	18		92.8	4.3	0	0			97.1
PTP124	19		98	0	0	1.2			99.2
PTP124	19	rim	96.4	0	0	2.9			99.3
PTP124	20		97.2	4.2	0	0			101.4
PTP124	21		98.6	0	0	0			98.6
PTP124	23		98.2	0	1.2	0			99.4
PTP124	24		97.8	1.2	0	0			99
PTP124	25		90.7	6	0	0			96.7
PTP124	26		91.5	8.5	0	0			100
PTP124	31		89.3	6.3	1.1	0			96.7
PTP124	32		98.4	0	0	0			98.4
PTP124	33		94.5	0.7	5.3	0			100.5
PTP124	34		91.8	7.9	0	0			99.7
PTP124	35		101	0	0	0			101
PTP124	36		98.1	0	1.3	0			99.4
PTP124	37		94.4	3.6	0	0			98
PTP124	38		98.5	0	0	0			98.5
PTP124	40		96.6	3.5	0	0			100.1
PTP124	41	centre	97.9	0	0	2.1			100
PTP124	41	centre	93.2	0	0	3.1			96.3
PTP124	41	edge	91.4	0	0.8	0			92.2
PTP124	42		79.3	19.5	0	0			98.8
PTP124	43		99.6	0	0	0			99.6
PTP124	44		87.3	12.1	0	0			99.4
PTP124	45		93.8	5	0	0			98.8
PTP124	46		96	0	2.4	0			98.4
PTP124	47		96.3	2.2	2.1	0			100.6
PTP124	49		97.1	2.8	0	0			99.9

APPENDIX 1 Quantitative electron microprobe analyses (in wt %) of gold grains from orientation site (River Ayr, E of Stair) in Mauchline Basin (continued)

sample	grain	part	Au	Ag	Cu	Pd	Hg	Sn	Sum
PTP124	50		85.5	13.3	0	0			98.8
PTP124	51		89.7	8.8	0	0			98.5
PTP124	52		94.4	0	0	4.3			98.7
PTP124	53		97.4	2	0	0			99.4
PTP124	54		99.2	0	0	0			99.2
PTP124	55		87.2	11.7	0	0			98.9
PTP124	56		92.5	6.3	0	0			98.8
PTP124	57		93.2	0.6	2.9	0		1.8	96.7
PTP124	58		90.7	7	0	0			97.7
PTP124	59		94.8	3.3	0	0			98.1

APPENDIX 2 Quantitative electron microprobe analyses (in wt %) of gold and other grains from Mauchline Basin

sample	grain	part	Au	Ag	Cu	Pd	Hg	Sn	Sum
101	1		104	0	0.77	0			104.8
101	2		96	4.11	0	0			100.1
102	1		97.9	1.39	2.73	0			102
102	2		100	0	0.81	0			101.1
102	2	other colour	96.8	0	0	2.53			99.29
102	2	edge	98.1	0	0.89	2.31			101.3
103	1		97.6	4.94	0	0			103
103	1		95.3	4.45	0	0			99.78
103	2		95.1	5.15	0	0			100
103	2		95.5	0.35	0	5.17			101
104	**1**		**95.1**	**0.25**	**0**	**6.06**			**101.4**
104	**2**		**88.8**	**11**	**0**	**0**			**99.82**
104	3		94.2	6.89	0	0			101.1
104	4		95	6.94	0	0			102
104	5		91.5	10.8	0	0			102.3
104	**6**	**core**	**99.7**	**0**	**0.78**	**0**			**100.5**
104	**6**	**band**	**92.2**	**1.09**	**9.91**	**0**			**103.2**
104	**6**	**outside band**	**99.9**	**0**	**0.76**	**0**			**100.6**
104	**6**	**porous**	**97**	**0**	**1.22**	**0**			**98.22**
104	7		94.6	6.3	0.96	0			101.9
104	9		84.3	17.3	0	0			101.7
108	1		87.1	10.5	0	0			97.51
110	1		102	0.56	0	0			102.7
111	1		101	0	0.79	0			101.5
113	1		99.2	1.1	1.71	0			102
114	1		100	0.51	0	0	1.43		102
114	2		95.3	4.54	0	0	1.53		101
114	2		93.6	7.27	0	0			100.9
114	3		94.3	5.65	0	0			100
114	5		98.2	3.4	2.7	0			104
114	6		92.5	7.36	0.93	0			100.8
114	6		100	0	0	0			100.4
114	6	film ?	87.3	13.3	0	0			100.6
114	7		103	0	0	0			103
115	1		102	0	0	0			102
115	2		102	0	0	0			102
138	1		83.6	16.7	0	0			100.4
138	1		84.7	14	0	0			98.65
138	2	yellow	97.5	4.33	0	0			101.8
138	2	paler	83.1	18.3	0	0			101.5
141	1		91.6	10.6	0.61	0			103
141	1		90.9	10	0	0			100.9
142	1		90.7	9.81	0	0			100.5
142	2		58.3	38.3	0	0	4.24		101

APPENDIX 2 Quantitative electron microprobe analyses (in wt %) of gold and other grains from Mauchline Basin (continued)

sample	grain	part	Au	Ag	Cu	Pd	Hg	Sn	Sum
144	1		103	0.82	0	0			104.2
145	1		100	0	2.41	0			103
146	3	pink Au3Cu	92.5	0	11.9	0			104.4
146	3	au	98.3	0	4.71	0			103
146	4		94.5	0	8.46	0			103
147	**1**		**95.4**	**4.3**	**0**	**0**	**1.95**		**102**
147	**1**		**101**	**0**	**0**	**0**			**100.9**
147	**1**		**97.6**	**3.9**	**0**	**0**			**101.5**
147	**1**		**98.9**	**4.12**	**0**	**0**			**103**
147	**1**		**97.8**	**4.69**	**0**	**0**			**102.5**
147	2		100.9	0	0	0			100.9
147	**3**		**96.4**	**3.4**	**0**	**0**			**99.8**
147	**3**		**95.6**	**4.74**	**0**	**0**			**100.3**
147	4		100	3.37	0	0			103.4
147	5		96.6	8.69	0	0			103.3
148	1		99.8	1.76	0	0			101.6
149	1	pale	55.3	41.3	0	0	4.95		101.6
149	1	yellow	97.5	4.55	0	0			102.1
149	2		102	1.98	0	0			104.3
149	3		96.5	5.35	0	0			102
152	1	grey		1	75.31			yes	
152	1	darker grey			68.12		12.5		
152	4	yellow	95.7	4.73	0	0			100.4
152	4	paler	85.7	14.4	0	0			100.1
161	1		96.4	3.64	1.79	0			102
161	2		95.3	6.68	0	0			102
161	5		97.8	2.1	0	0			99.9
161	5		99	1.48	0.88	0			101.4
161	5		99	1.7	0	0			100.7
167	4		97.3	5.75	0	0			103
171	1		80.5	20.3	0	0			101
171	2		85.1	16.1	0	0			101.2
171	2	darker	102	1.75	0	0			103.9
175	1		100	1.88	0	0			102
175	1	?film	92	8.96	0	0			101
175	1		98.4	3.38	0	0			101.8
175	1		102	0	0	0			102.4
175	2		94	8.26	0.78	0			103
175	3		101	0	0	0			100.9
175	4		99.8	0	0	0			99.82
175	5		100	0	0	0			100.3
175	**6**		**97.9**	**2.46**	**0**	**0**			**100.4**
176	2		95.4	4	0	0			99.38
176	3		89.2	9.42	0.9	0			99.49

APPENDIX 2 Quantitative electron microprobe analyses (in wt %) of gold and other grains from Mauchline Basin (continued)

sample	grain	part	Au	Ag	Cu	Pd	Hg	Sn	Sum
176	**4**		**91.8**	**9.8**	**0**	**0**			**101.6**
176	5		91.4	8.13	0	0			99.57
176	6		99.9	1.61	0	0			101.5
176	7		98.7		0	0			98.67
176	8		95.7	4.18	0	0			99.9
176	8		88.4	9.82	0	0			98.19
176	9		96.9	0.8	2.9	0			100.6
176	10		95.1	3.57	3.42	0			102.1
176	11		101		0	0			100.9
176	12		84.4	15	0	0			99.42
176	13		84.3	14.9	0	0			99.2
176	**14**	**centre**	**99.6**	**1.55**	**0**	**0**			**101.1**
176	**14**		**85**	**14.9**	**0**	**0**			**99.8**
176	15		98	2.09	2.62	0			103
176	16		101		0	0			101
176	19		98.9		1.7	0			101
176	20		96.5	4.31	0	0			101
176	20		94	5.7	0	0			99.66
176	21		100	1.75	0	0			102
176	21		99.4	1.63	0	0			101
176	22		101		0	0			101
176	24		102		0	0			102
174	24		103		0	0			103.2
174	24		101		0	0			100.8
176	24	rim	62.6		0	0		36.8	99.34
176	24	rim	61.8	6.23	0	0	9.02	21.9	98.95
176	24	margin grain	46		0	0		54.7	100.7
176	26	upper	97.4	4.31	0	0			101.7
176	26	lower	98	4.96	0	0			103
176	28		84.5	16.8	0	0			101.4
176	29		96.1	6.25	0	0			102.3
176	30	right	98.2	2.28	2.05	0			102.6
176	31	marginal	93.1		9.61	2.02			104.8
176	31	another margin	91.4		9.62	3.94			104.9
176	31	centre	103		0	0			103.4
176	32		102	1.28	0	0			103
176	33		103		0	0			102.5
176	34		96.7	5.38	0	0			102.1
176	35		98.7	1.46	3.55	0			103.8
176	36		98.4	3.92	1.96	0			104.3
176	37		101	2.11	0	0			103.1
176	38		95.4	5.48	0	0			100.9
176	39		103		0	0			102.6
176	40		96.7	7.13	0	0			103.8

APPENDIX 2 Quantitative electron microprobe analyses (in wt %) of gold and other grains from Mauchline Basin (continued)

sample	grain	part	Au	Ag	Cu	Pd	Hg	Sn	Sum
176	41		104		0	0			103.8
176	42		98.2	3.12	0	0			101.4
176	43		98.7		0.92	0			99.59
176	44		95	3.51	0	0			98.5
176	45		101		0.88	0			101.8
176	46		98.2	3.03	0	0			101.3
176	47		89.8	11.7	0	0			101.5
176	49		97.8	2.88	0.65	0			101
176	50		92.5	7.94	0	0	1.68		102
179	1		91.7	9.7	0	0			101
179	1		90.2	9.57	0	0			99.76
179	2		88.8	13.1	0.61	0			102
179	3		95.7	5.04	0	0			100.8
186	1		99		1.35	0			100
187	1		96	4.23	0.83	0			101
187	1		101		0	0			100.5
187	1		100		0	0			100.2
190	1		79.8	21.4	0	0			101
190	2		92.7	7.42	0	0			100
190	2		93.4	6.88	0	0			100.3
190	3		98.5	2.76	0	0			101
190	3		97.7	2.7	0	0			100.4
190	5		96.2	4.51	0.61	0			101
190	5		95.5	4.05	0	0			99.51
190	6		96.1	4.58	0	0			101
190	6		96.1	4.49	0	0			100.6
190	7		101		0	0			101
190	7		98.5	1.56	0	0			100.1
190	7		96.3	4.59	0	0			100.9
190	8		94.1	6.86	0	0			101
190	9		95	5.04	0	0			100
190	10		100	2.19	0	0			102
190	11		99.9	0.96	0	0			101
190	11		99.7	1.75	0	0			101.4
190	11		99.1	2.3	0	0			101.4
190	12		103		0	0			103.3
190	13		101	3.13	0	0			103.8
190	14		102		0	0			102
190	16		96.1	2.68	0	0			98.8
194	1		102		0	0			101.7

Mapped grains shown in bold

APPENDIX 3 Rock samples from Mauchline Basin and surroundings

	Location	Age	Description
PTR1	241820 623280	Middle Coal Measures	seatearth + pyrite
PTR2	241820 623280	Middle Coal Measures	siderite nodule + coal
PTR3	241820 623280	Middle Coal Measures	dark shale/?coal mush
PTR4	241785 623200	Middle Coal Measures	carbonate ? derived from oxidation of coal
PTR5	241785 623200	Middle Coal Measures	carbonate ? derived from oxidation of coal
PTR6	241782 623198	Middle Coal Measures	sandstone + hard pan
PTR7	241782 623198	Middle Coal Measures	shale above carbonate
PTR8	245200 624273	Permian	sandstone raft in basalt
PTR9	245201 624273	Permian	basalt
PTR10	245202 624273	Permian	sandstone raft in basalt
PTR11	253805 628102	Middle Coal Measures	carbonate above seatearth
PTR12	253805 628102	Middle Coal Measures	seatearth+carbonised plants
PTR201	**245360 628501**	**Permian**	**teschenitic dolerite in contact with sandstone**
PTR202	**245360 628500**	**Permian**	**bleached sandstone**
PTR203	245340 628662	Permian	baked sandstone
PTR204	245341 628662	Permian	teschenitic dolerite
PTR205	245342 628640	Permian	teschenitic dolerite
PTR206	245845 626304	Permian	sandstone,silicified?
PTR207	245845 626304	Permian	soft orange sandstone
PTR208	245848 626303	Permian	soft red sandstone+ discordant vein
PTR209	247440 622680	Permian	sandstone +discordant ?silicified vein
PTR210	249900 623010	Permian	basalt+calcite? veinlets
PTR211	249900 622950	Permian	altered basalt
PTR212	249898 622982	Permian	basalt
PTR213	249899 623010	Permian	basalt
PTR214	249970 622722	Permian	white sandstone
PTR215	249897 623040	Permian	hard basalt
PTR216	249899 623040	Permian	dyke of dolerite
PTR217	249900 623080	Permian	basalt
PTR218	**249900 623060**	**Permian**	**soft altered basalt**
PTR219	247225 625080	Permian ?	loose block vein in basalt?
PTR220	**246060 613490**	**Permian ?**	**altered teschenite sill in Lower Coal Measures**
PTR221	246200 613450	Permian ?	teschenite
PTR222	249790 622110	Upper Coal Measures?	loose block sandstone with reduction spots

Panned concentrate from rock also analysed for samples in bold type