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EXPLORATION FOR GOLD IN THE THORNHILL BASIN, SOUTHERN SCOTLAND.

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This data package relates to work carried out by the British Geological Survey on behalf of the Department of Trade and Industry

SUMMARY

Alluvial gold has been discovered in association with Permian red beds of the Thornhill basin some 20 km north of Dumfries in southern Scotland. The gold occurs mostly in streams on the eastern side of the Thornhill basin where the Permian rocks are in faulted contact with the Lower Palaeozoic rocks. The higher values of gold are situated on the outcrop of the Permian red sandstones, usually with the outcrop of the Permian alkali basalts just upstream or, in one case, on the Lower Palaeozoic rocks just east of their contact with the Permian volcanics. Automated electron microprobe grain characterisation shows the gold to be similar to that from the Crediton Trough and the South Hams areas of Devon with some Pd-rich compositions and inclusions of several selenide minerals.

The discovery strongly supports the model developed for the controls of gold transport and deposition within the red bed environment. This model envisages the leaching of gold from a dispersed large volume source such as alkali basalt, 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. Such a solution is likely to precipitate all, or most, of the gold if it meets a more reduced environment so that the contact zones between red beds and more reduced underlying rocks, whether unconformable or faulted, comprise the most favourable environment for gold precipitation. There is sufficient evidence from the distribution of gold in drainage samples around Thornhill to suggest that mineralised structures carrying gold occur at contacts between the Permian strata and the underlying Lower Palaeozoic rocks and, possibly, also in structures cutting the Permian rocks.

Follow-up exploration is recommended to locate and assess the economic potential of the mineralisation. Most of the anomalies occur in streams which cut the boundary faults at high angles. Because of the limited dispersion of coarser particles of gold in streams traversing bedrock in this area, detailed drainage sampling for gold may serve to locate cut-offs. In addition, overburden sampling by pitting could be used to establish if gold is concentrated in boundary structures. Drill holes through the contact zones will be the only means of establishing the grade and the extent of gold mineralisation arising from the interaction between mineralising fluids circulating in the Permian red bed sequence and the underlying greywacke–shale sequence.

INTRODUCTION

The work forms part of an investigation of the potential for gold mineralisation associated with Permian and/or Triassic red beds in Britain. This work 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, 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 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. Such a solution is likely to precipitate all, or most, of the gold if it meets a more reduced environment. Thus the contact zones between red beds and more reduced underlying rocks, whether unconformable or faulted, comprise 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. In Devon the Permian sequence includes alkali basalts and unusual alkali lamprophyric lavas and these may represent the primary source of much of the gold and, more particularly, palladium and platinum.

The nature of the gold associated with the oxidising environment of gold transport and deposition is distinctive. This conclusion arises from BGS gold characterisation data which comprise electron microprobe determinations of the internal chemistry of sectioned alluvial gold grains. BGS has investigated thousands of gold grains from many sites and environments of mineralisation in Britain and overseas. Palladium, a platinum group element, is frequently alloyed with the red bed type of gold, in amounts up to about 6% Pd, because under these conditions this element behaves in a similar way to gold. Copper may also be present within the gold or associated with the gold as the intermetallic compounds Au_3Cu and AuCu (auricupride). In some cases platinum may also be present within the gold. A silver-rich gold is often intergrown with the silver-poor palladium-bearing gold. Microscopic inclusions of sulphide and other minerals can also be found in most alluvial gold, generally in between 10 and 20% of grain sections. A very distinctive feature of the red bed type gold is the absence of sulphide inclusions and the presence of selenide minerals and sometimes tellurides. This characteristic arises because selenides and tellurides are stable under more oxidising conditions than corresponding sulphide minerals.

The Thornhill basin is one of several areas of Permian and Triassic rocks in which reconnaissance drainage sampling has been carried out. It was chosen for particular attention because it contains alkali basalt of Permian age which provides a close parallel with the Crediton Trough and other parts of the Permian sequence in Devon. On the basis of the model developed in Devon, a prediction was made that gold of the distinctive red bed type should be associated with the Thornhill red bed sequence, particularly in contact zones with underlying more reduced rocks, in this case Lower Palaeozoic greywackes and shales. The drainage sampling described in this report was carried out to test this model and to locate any anomalies that could merit further follow-up by the private sector. Follow-up work has not been carried out as part of this project because of the termination of the existing Minerals Reconnaissance Programme.

The Thornhill basin lies in Dumfries and Galloway, some 20 km north of Dumfries, in southern Scotland (Figure 1). It is primarily an area of agricultural grassland surrounded, particularly in the north and east, by moorland on the higher ground. Much of the land belongs to a single landowner (Buccleuch Estates), and there are no nationally designated planning constraints. A number of small

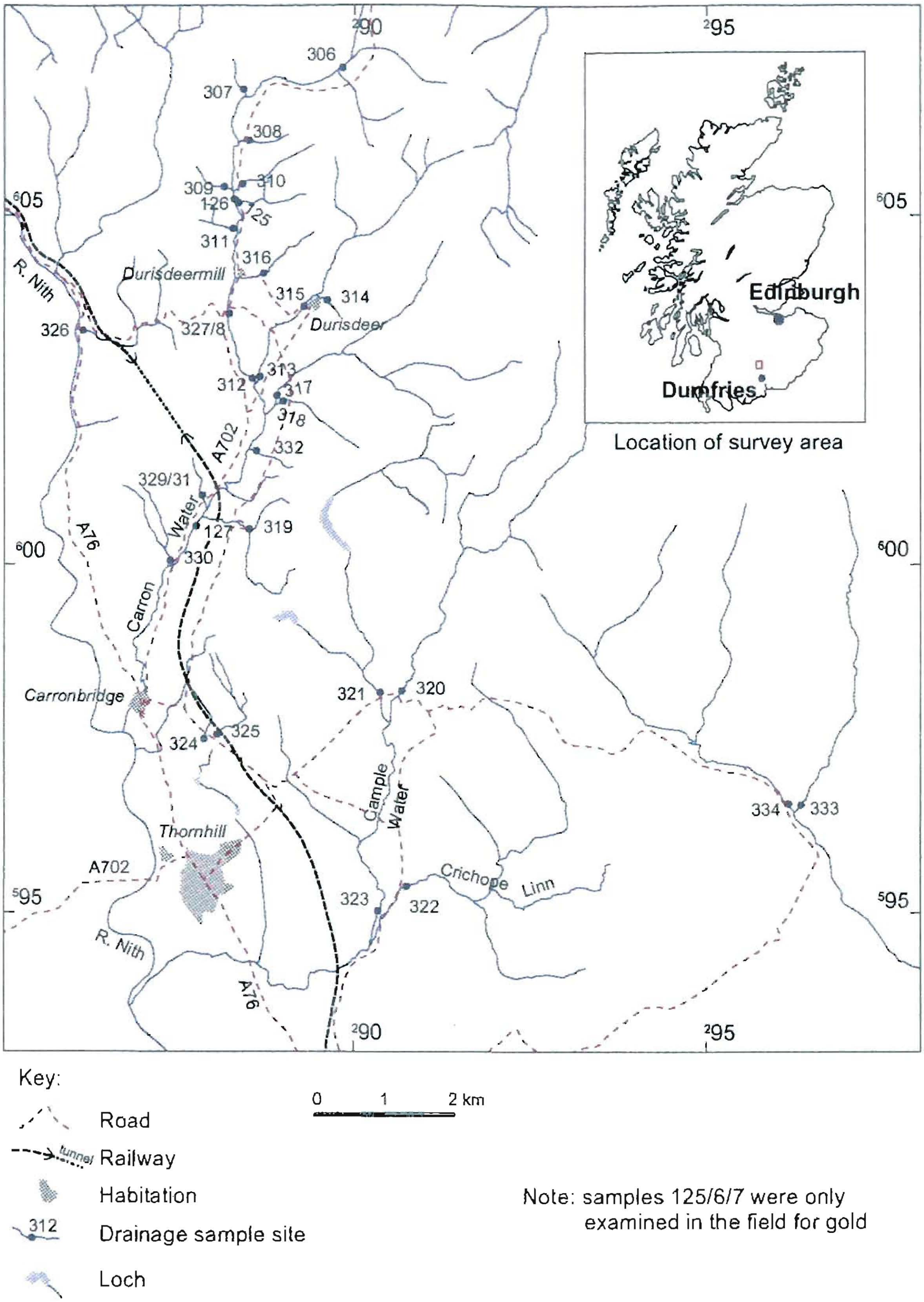


Figure 1 Simplified location map of the Thornhill survey area.

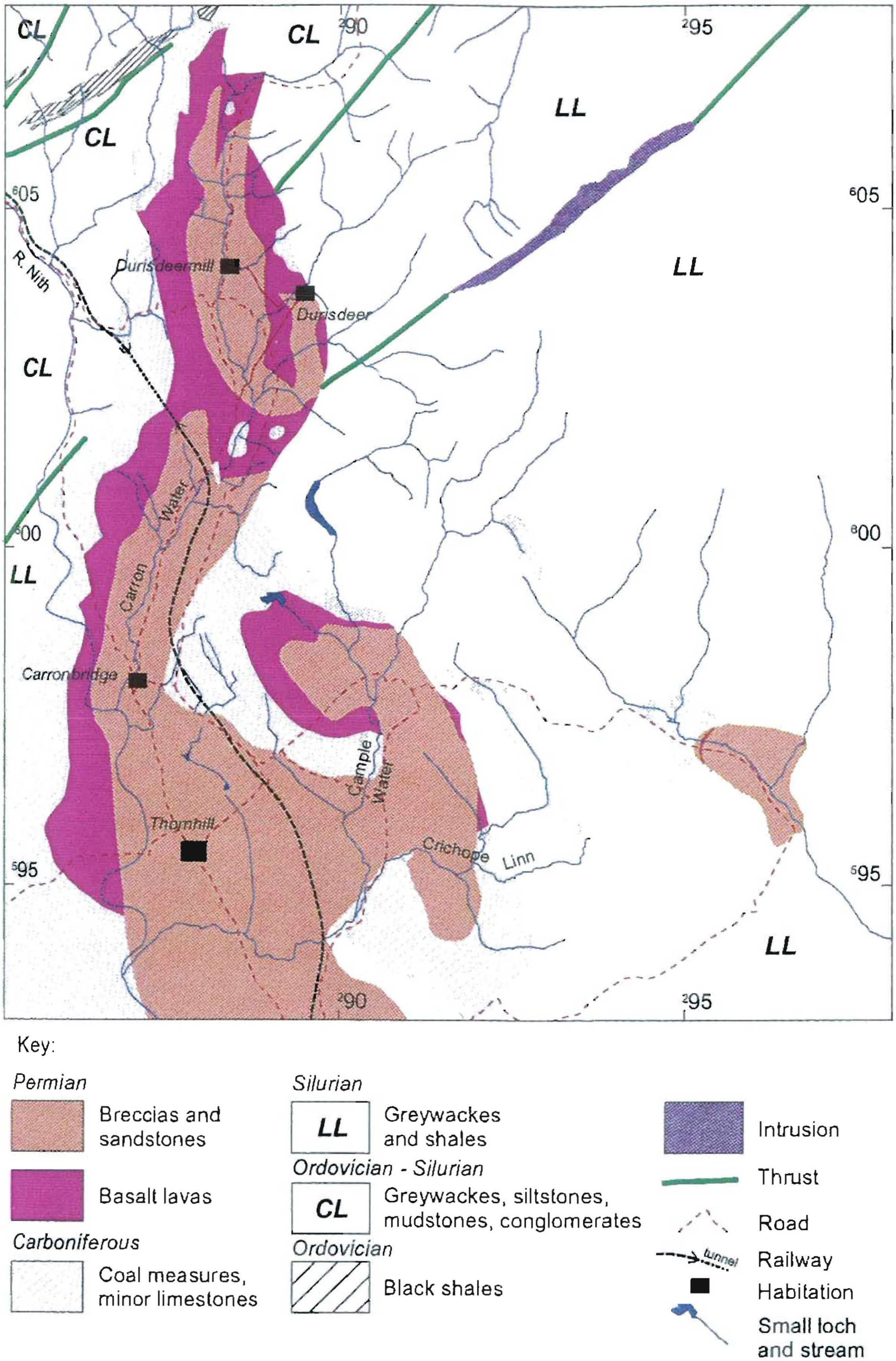


Figure 2 Simplified geological map of Thornhill area. After Macmillan and Brand, 1995 and BGS Geological map sheets 9E and 15E (Scotland).

villages and isolated farms are scattered over the area with the small town of Thornhill lying in the south of the area. The basin is crossed by the River Nith which is joined by the Carron Water north of Thornhill. Both river valleys allow good access, main roads link Thornhill to Dumfries, Kilmarnock, Glasgow and Edinburgh, and Nithsdale also carries the main Dumfries to Glasgow railway line (Figure 1).

GEOLOGY

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, locally overlying older Carboniferous rocks including limestone, and, in turn, overlain by Permian basalt, red breccias and sandstones. The Westphalian strata, divided into Lower, Middle and Upper Coal Measures, comprise fine to medium grain sandstones, siltstones, mudstones and seatearths. No coal seams have been observed at surface or in boreholes though they occur in strata of similar age in the nearby Sanquhar coalfield. 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 interlayered with alkali olivine basalt of Permian age. The basalt is much decomposed and up to 45 m thick (Simpson and Richey, 1936), separated into at least three flows with sandstone partings or surfaces with fissures filled with sandstone. Basalt breccia is also present at some localities. The youngest rocks are red aeolian sandstones 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 within Southern Scotland which are thought to have been controlled by the 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.

SAMPLING AND ANALYSIS

Panned concentrate samples were taken from 30 drainage sites to the north and east of Thornhill, as shown in Figure 1. Drainage varies from small discontinuous streams extensively modified by man on the flat drift covered ground to streams within gorges cut through the Permian and Carboniferous rocks to upland streams running off the higher ground around the basin. Samples from gorge sections, such as in the Carron Water, were taken from sediment resting directly on bedrock, but access to some of the deeper gorges proved too difficult.

Two of the samples were taken from catchments of Lower Palaeozoic rocks and two from the small outlier of Permian rocks at Locherben to the east of Thornhill, while the remainder were largely, if not entirely, derived from the Permian and Carboniferous rocks of the Thornhill basin. The drainage sediment was obtained by digging into stream gravel. Panning provided a sample typically between 15 and 40 g in dry weight, to facilitate the physical extraction of gold grains from the samples in the field and laboratory.

In the laboratory, after sieving to produce a < 0.5 mm fraction, gold grains were extracted by hand picking from superpanner heavy concentrates of 7 of the samples. Subsequently, the < 0.5 mm fraction samples were recombined and then ground in a Tema mill with a Cr-steel pot. Subsamples were taken to provide material for XRF determination of Mg, Ti, Fe, Ni, Cu, Zn, As, Zr, Sn and Ba at the BGS chemical laboratories in Keyworth and for the determination of gold and other elements at Acme Analytical Laboratories of Vancouver, Canada. In the smaller samples (ca. 10 g), gold was determined after digestion in aqua regia and extraction into MIBK by graphite furnace Atomic Absorption. In 14 larger samples (> 15 g) gold determination was accompanied by ICP-ES analysis for 33 elements and determination of Hg by cold vapour atomic absorption. The chemical analyses of the panned concentrate samples are given in Tables 1 and 2.

Table 1 Chemical composition of Thornhill panned concentrate samples (XRF analyses) and number of extracted gold grains

Sample PTP	grains	Au* ppb	MgO %	TiO_2 %	Fe_2O_3*%	Ni ppm	Cu ppm	Zn ppm	As ppm	Zr ppm	Sn ppm	Ba ppm
127	5	-	-	-	-	-	-	-	-	-	-	-
306		6	4.1	0.957	7.85	74	45	90	17	417	14	829
307		3	3.1	2.079	21.26	84	92	115	107	826	254	419
308		3	1.1	0.977	13.79	33	63	69	8	2130	12	382
309		25	2.1	1.287	24.57	24	17	88	10	2386	11	218
310		145	1	2.163	31.96	68	71	109	13	2922	13	1145
311		< 1	1.7	1.618	26.46	21	13	79	5	3728	17	178
312		4	1.6	0.805	13.48	22	34	59	7	843	42	327
313		815	1.2	2.06	27.84	49	29	88	33	2401	222	234
314	3	9*	2.2	0.864	7.17	44	17	76	26	736	42	443
315		5	2.1	1.105	12.03	51	41	83	29	733	118	723
316		2	1.6	1.331	13.76	18	25	46	25	2669	23	253
317		2	1.7	0.708	6.86	36	14	51	13	713	< 5	371
318	4	4*	1.2	1.666	12.86	21	34	98	8	4805	21	309
319		1	0.6	0.548	6.43	10	21	27	5	1265	14	188
320		7700	1.6	0.577	6.23	30	7	55	17	622	6	337
321		2	0.7	0.929	9.8	19	15	75	10	3004	17	199
322	3	2*	0.4	0.525	12.18	13	6	32	6	743	25	199
323		29	0.8	1.048	17.34	29	27	69	16	1545	67	322
324		1	0.4	0.895	2.98	10	14	31	2	4429	5	1121
325		< 1	0.7	0.869	5.34	15	3	36	2	1805	< 5	294
326		27	1	0.91	17.29	44	24	63	7	634	109	452
327		3	2.4	1.065	25.12	32	71	72	6	1211	150	311
328	2	10*	0.7	0.75	10.81	10	24	26	7	2112	20	376
329	1	1*	1	1.285	14.26	25	13	45	12	1247	9	171
330		90	0.8	1.27	13.42	19	11	123	2	1591	9	252
331		936	0.9	5.257	39.85	64	31	146	24	8511	18	-
332		127	2.6	8.525	34.55	83	31	127	6	2889	18	-
333		13	1.1	0.344	6.1	19	7	30	9	210	< 5	283
334		12	1.3	1.587	9.61	26	13	92	35	3139	14	227

Fe_2O_3* = total iron expressed as Fe_2O_3; * gold determined after grain extraction; - not determined

Table 2 Additional elements in larger drainage concentrate samples determined by ICP-ES after aqua regia attack

Sample PTP	Al*	P*	V*	Cr*	Mn*	Co*	Ga*	Se	Sr*	Mo	Ag*	Sb	La*	Hg*	Tl	Pb	Bi*	Th*
306	2.45	460	46	63	407	22	7.2	<0.3	16	0.5	56	1	36	56	0.2	38	0.1	5
311	1.17	180	227	110	156	14	2.5	<0.3	13	1.6	<30	0.9	20	58	<0.1	81	0.1	7
313	0.84	240	303	148	150	28	2.8	<0.3	23	3.3	169	10.6	22	285	<0.1	177	0.7	9
317.	0.87	190	63	75	405	11	2.7	<0.3	11	0.8	<30	0.7	14	44	0.1	21	0.1	9
318	0.48	180	158	84	711	11	2.1	<0.3	14	1.1	67	2.4	19	67	0.4	670	0.3	11
320	0.88	150	46	75	323	11	3.1	<0.3	8	0.9	656	1.5	15	12	0.1	15	0.1	9
323	0.52	150	172	113	984	16	1.9	<0.3	17	1.9	40	4.1	14	81	<0.1	60	0.5	14
326	0.59	220	161	107	117	29	3.1	<0.3	25	2	67	14.2	18	52	0.1	91	0.4	11
327	0.87	240	250	129	125	18	3.0	<0.3	21	1.7	70	6.5	22	36	0.5	667	0.3	6
328	0.42	140	130	62	745	11	1.2	0.4	13	0.9	274	2.7	16	589	<0.1	221	0.9	8
330	0.39	190	169	92	887	16	1.8	<0.3	18	1.4	194	13.1	21	68	0.6	123	0.3	11
332	0.89	490	463	214	165	36	5.6	<0.3	35	2.3	168	0.9	24	93	<0.1	98	0.4	18
333	0.53	130	55	35	570	8	1.8	<0.3	8	1.3	<30	1	10	14	0.1	20	0.1	6
334	0.59	130	104	84	507	10	2.3	0.3	10	1.7	32	2.9	37	19	<0.1	42	0.3	29

* partial leach: values in ppm except Al in % and Ag and Hg in ppb

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 microscopically in detail 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. The results of the quantitative microprobe determinations are given in Table 3. In addition, microchemical mapping of segments of 5 grains was carried out using the Cameca SX 50 automated electron microprobe as described in Leake et al. (1991). Microchemical mapping was carried out on grains which showed evidence of internal chemical heterogeneity from reflected light microscopy or visible inclusions to determine its extent and to assist in the identification of microscopic inclusions.

DRAINAGE GEOCHEMISTRY

Distribution of gold

The distribution of gold in the concentrate samples is shown in Figure 3. The highest amplitude gold anomaly is derived from Cample Cleugh, about 500 m below the faulted contact between the Permian red sandstones and the Lower Palaeozoic rocks. Other high amplitude anomalies (> 500 ppb by analysis or > 2 gold grains extracted) comprise, from south to north, Crichope Linn, the main Carron Water, Column Burn, Shiel Burn, Kirk Burn and the north–west flowing tributary of Kirk Burn near Durisdeer. With the exception of the last site (PTP 314), which drains the Lower Palaeozoic rocks just east of their contact with the Permian volcanics, all the anomalies are situated on the outcrop of the Permian red sandstones, usually with the outcrop of the Permian alkali basalts just upstream. In addition, the anomalies are generally confined to the eastern side of the Thornhill basin where the Permian rocks are in faulted contact with the Lower Palaeozoic rocks. In this part of the basin there are north–south to north–west-trending faults which control the outcrop of the Permian rocks and usually form the contacts between Permian and Lower Palaeozoic rocks. As the samples derived mostly from the alkali basalts are not richer in gold than others, it is concluded that the source of the

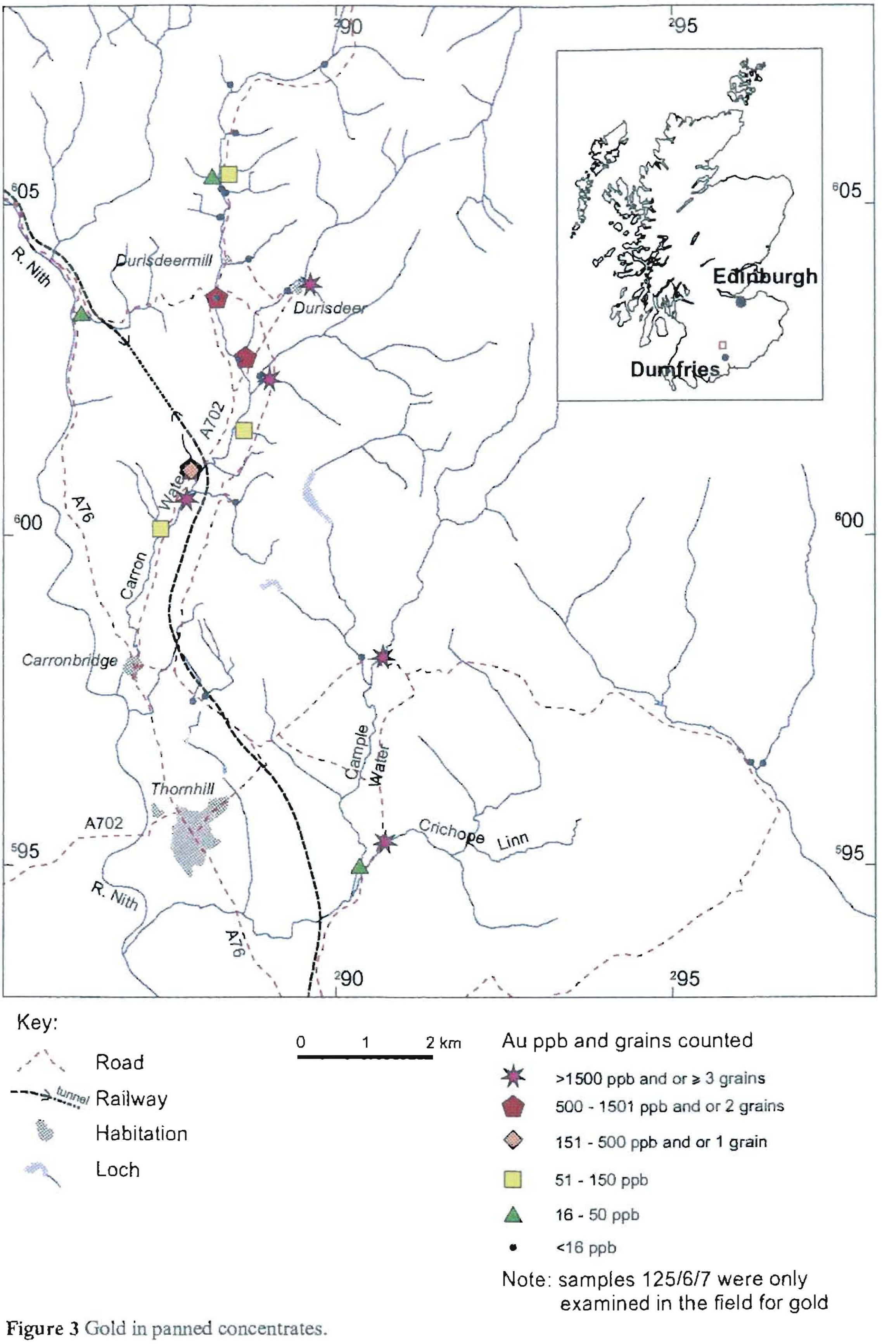


Figure 3 Gold in panned concentrates.

gold is not a fine dissemination in the lavas. Furthermore, the distribution of gold anomalies in the north of the basin (Figure 3) is not consistent with a fossil placer source within the sandstones overlying the basalts.

Samples obtained from sites draining Carboniferous rocks and Permian sandstones in contact with Carboniferous rocks apparently contain little gold, though further more detailed sampling is required to confirm this deduction. It is also worth noting that most of the anomalous sites are on streams which cut the boundary faults and other faults cutting the basin at high angles. Since detailed work on gold dispersion in the Leadhills area (BGS unpublished data) suggests that downstream dispersion of coarser gold particles is extremely limited where streams are eroding bedrock, detailed drainage sampling upstream of the anomalous sites may be effective in defining closely the source mineralisation. Similarly, anomalous levels of gold in drainage derived from a source cut at a high angle by the stream are likely to be more significant than similar amplitude anomalies in streams which follow potentially mineralised structures.

Distribution of other elements

Only the distribution of a few of the elements determined (Tables 1 and 2) are plotted in map form and discussed individually, since the majority of elements have no correlation with the distribution of gold and do not reflect significant amounts of other mineralisation.

Iron

The distribution of iron in the panned concentrate samples is shown in Figure 4. No simple correlation between Fe and Au is apparent and the most auriferous sample is low in iron. A general correlation between Fe and Ti, Ni, Zn, V and Cr is present in the data which probably reflects the abundance of material derived from the alkali basalts. The samples with the greatest proportion of this component occur just to the south of the northernmost outcrop of the Permian sandstones (Figures 2 and 4).

Copper

Copper concentrations in the panned concentrates from the Thornhill area are relatively low and the most anomalous samples are all from the northern part of the area (Figure 5). No general correlation between Cu and Au is apparent. The maximum Cu anomaly (PTP 307) coincides with the maxima of As and Sn and could reflect contamination, being downstream of a farm.

Arsenic

Apart from the possible anthropogenic anomaly at site PTP 307, the concentration of arsenic in the Thornhill samples is relatively low. The distribution of samples showing slight enhancement is shown in Figure 6. There is no evidence of any correlation between Au and As in the data.

Tin

The distribution of samples containing elevated concentrations of tin (Figure 7) probably reflects contamination from metallic waste associated with the various settlements and farms. Tin present in grains of the tin–mercury intermetallic compound is probably much subordinate to tin derived from metallic contamination, as there is no correlation evident between Sn and Hg evident in the data.

Silver

Only half of the samples were analysed for silver (Table 2). The maximum silver anomaly (Figure 8) correlates with the maximum gold anomaly, but at a level that suggests that most of the element is accommodated within gold grains. Some silver must exist in phases other than gold, as the next

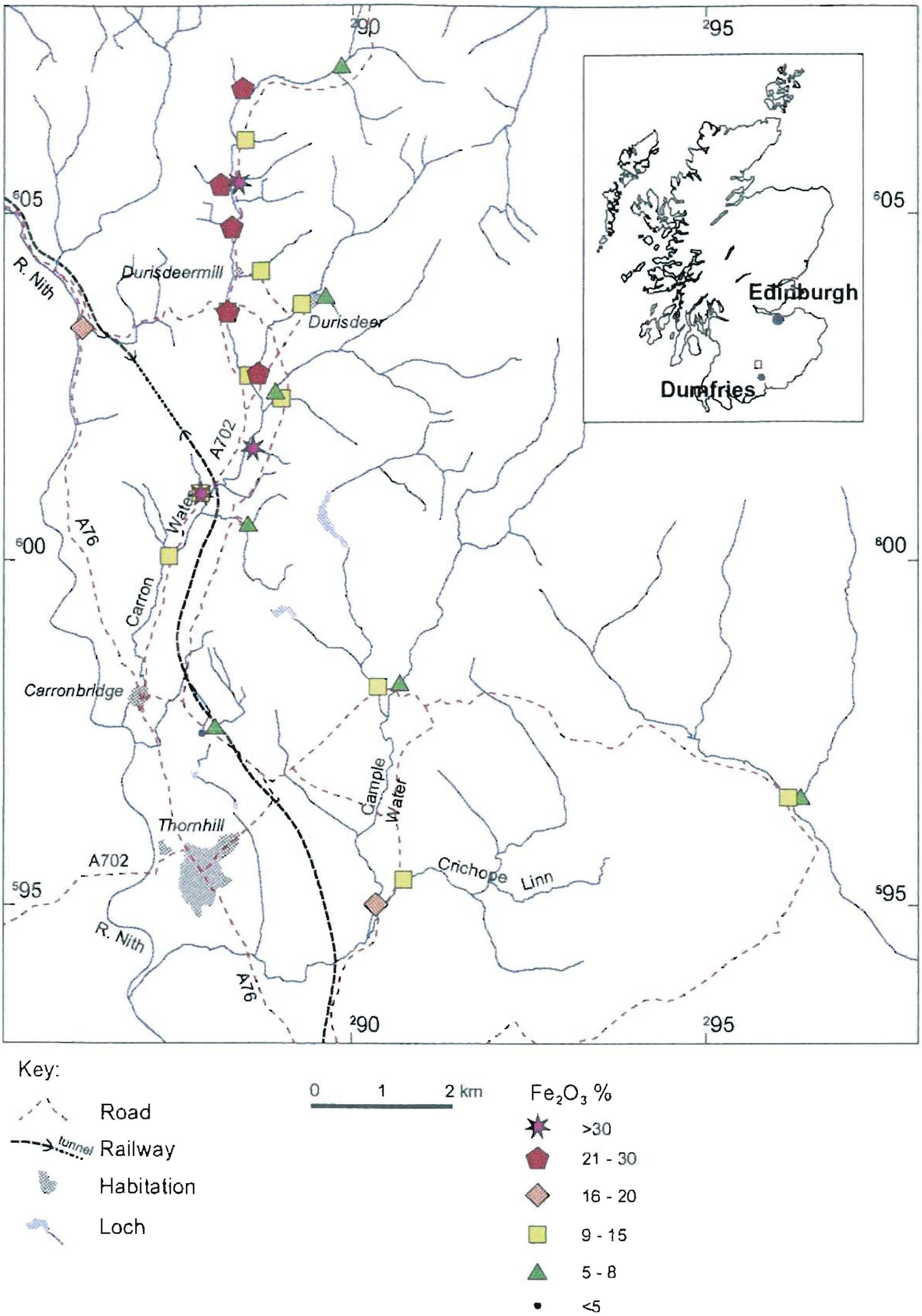


Figure 4 Iron in panned concentrates.

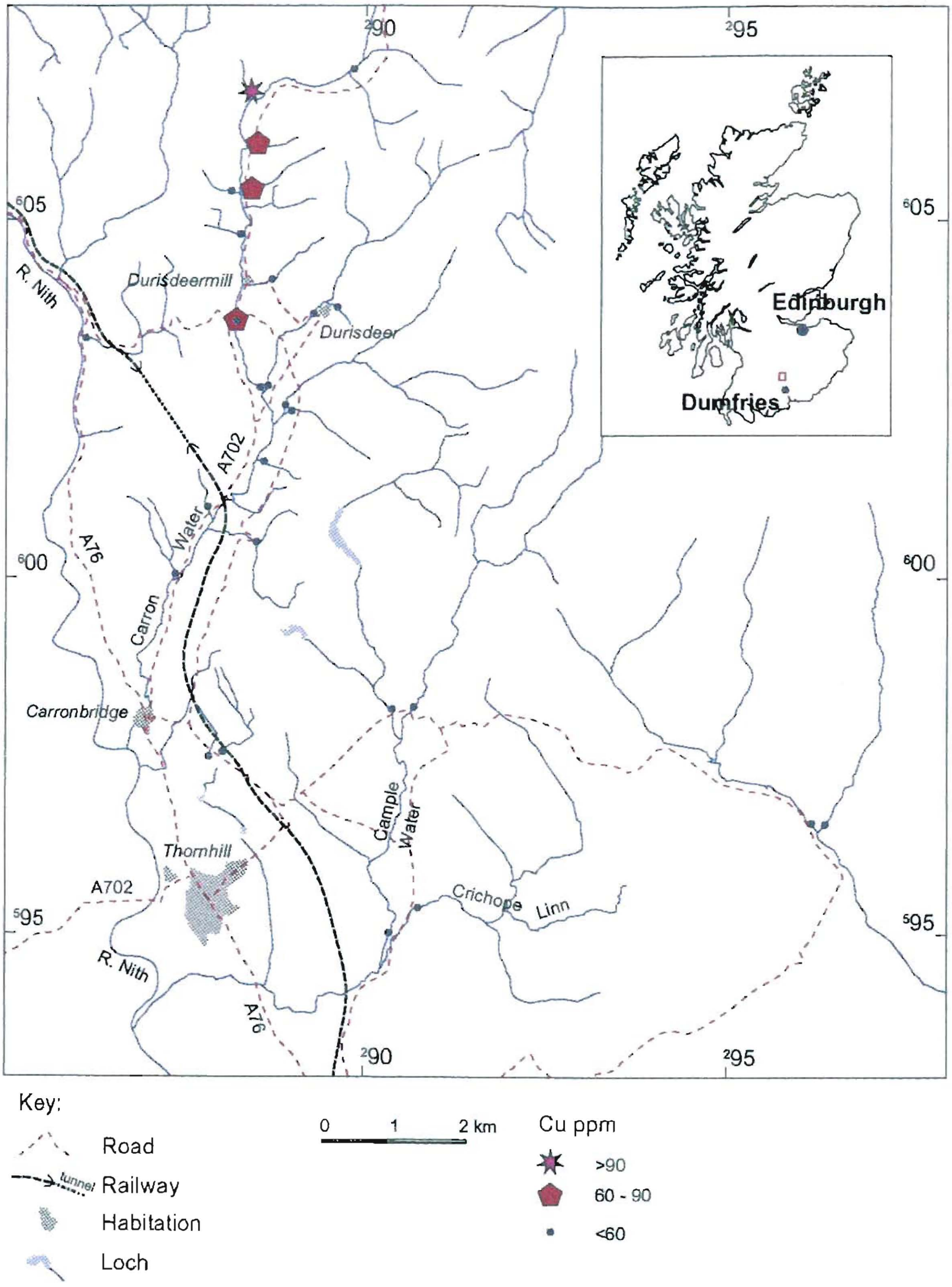


Figure 5 Copper in panned concentrates.

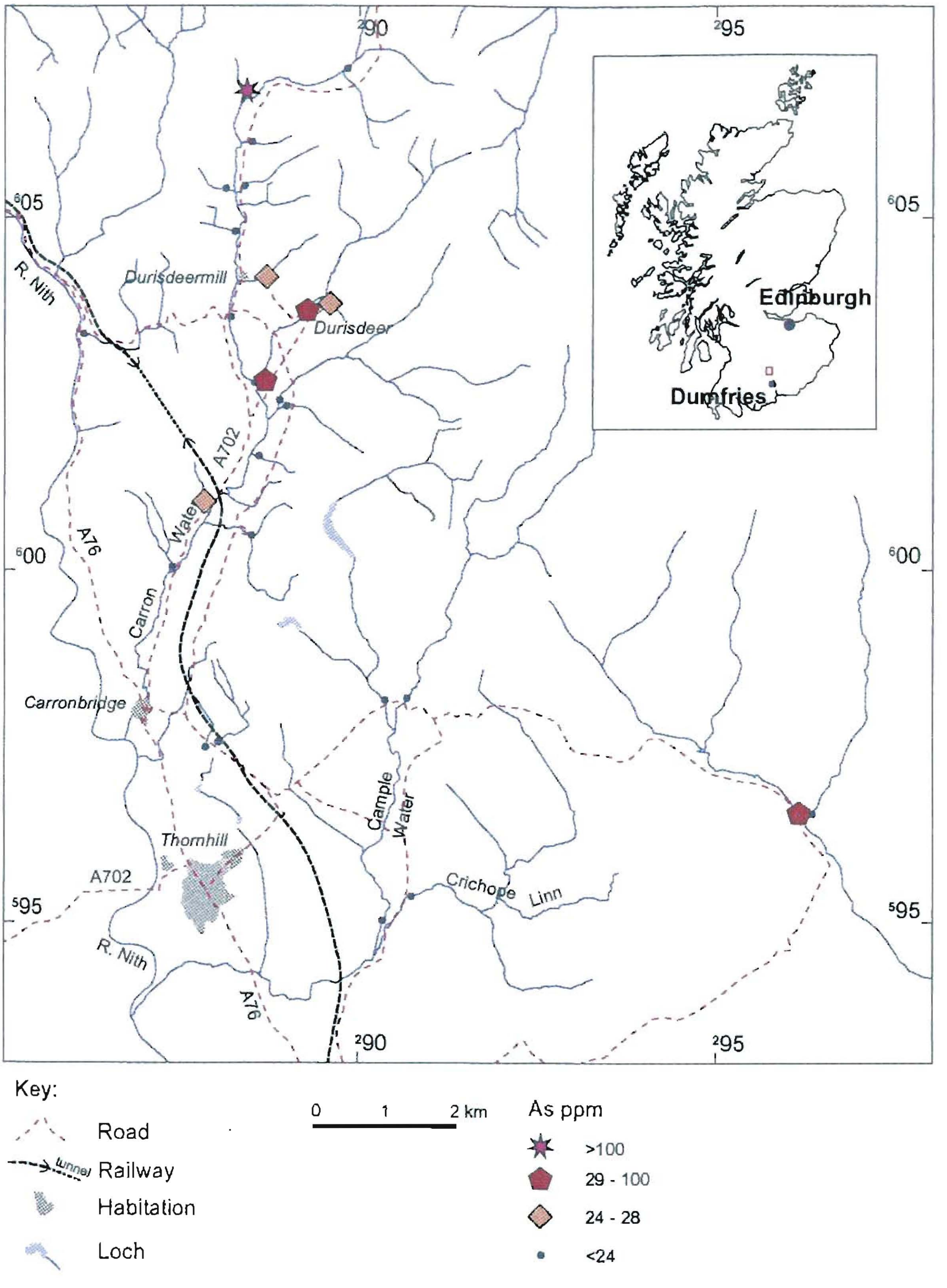


Figure 6 Arsenic in panned concentrates.

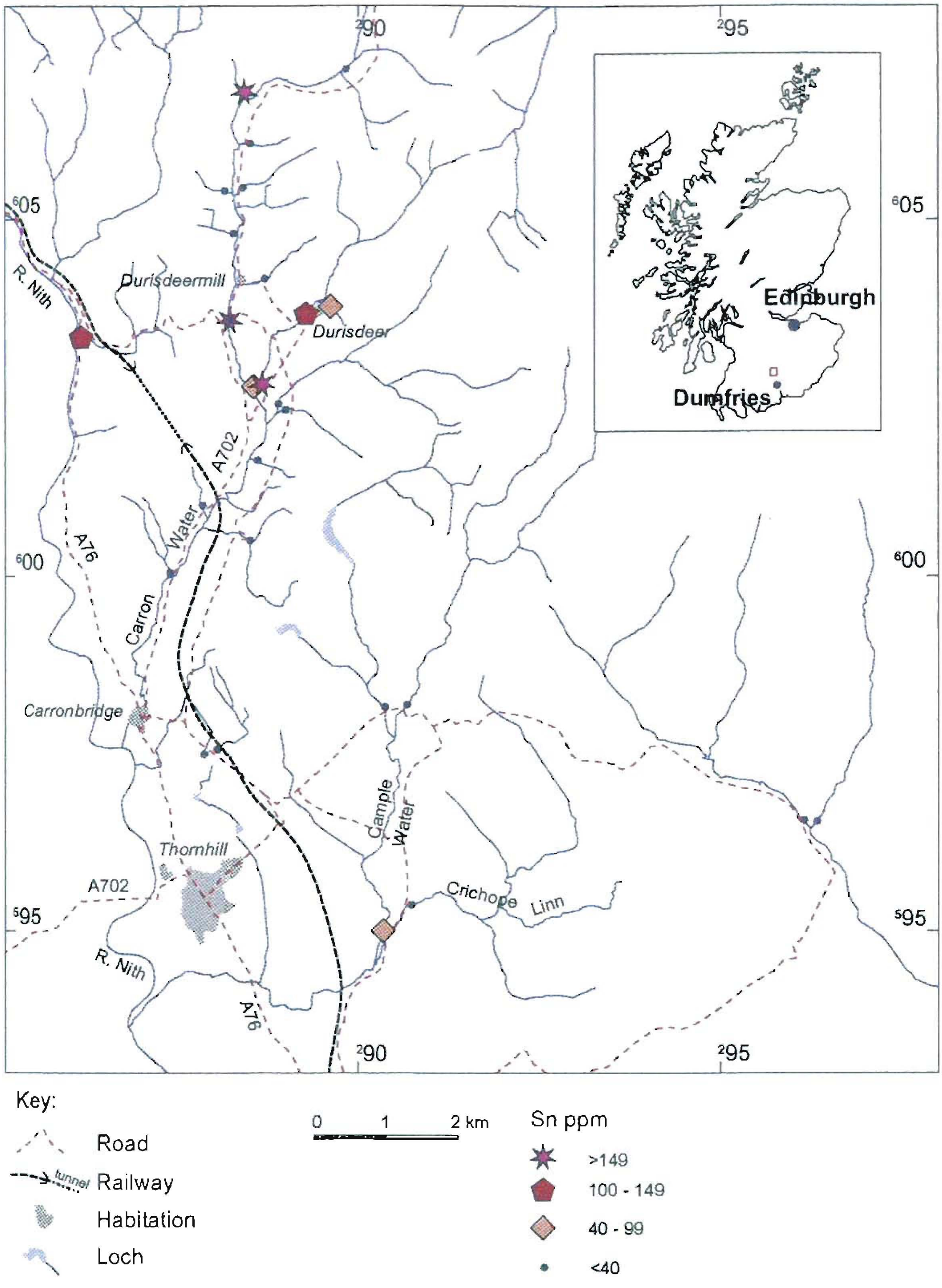


Figure 7 Tin in panned concentrates.

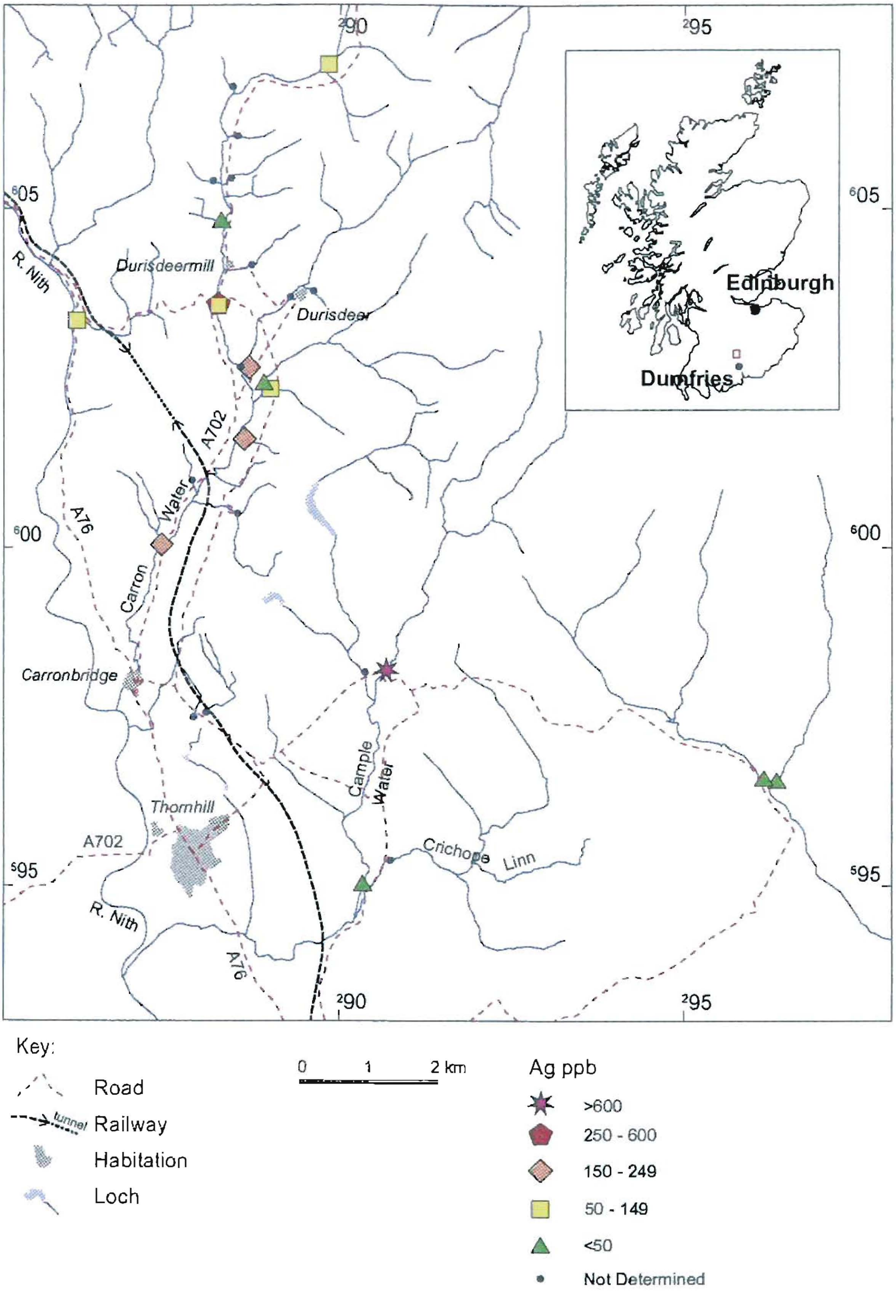


Figure 8 Silver in panned concentrate

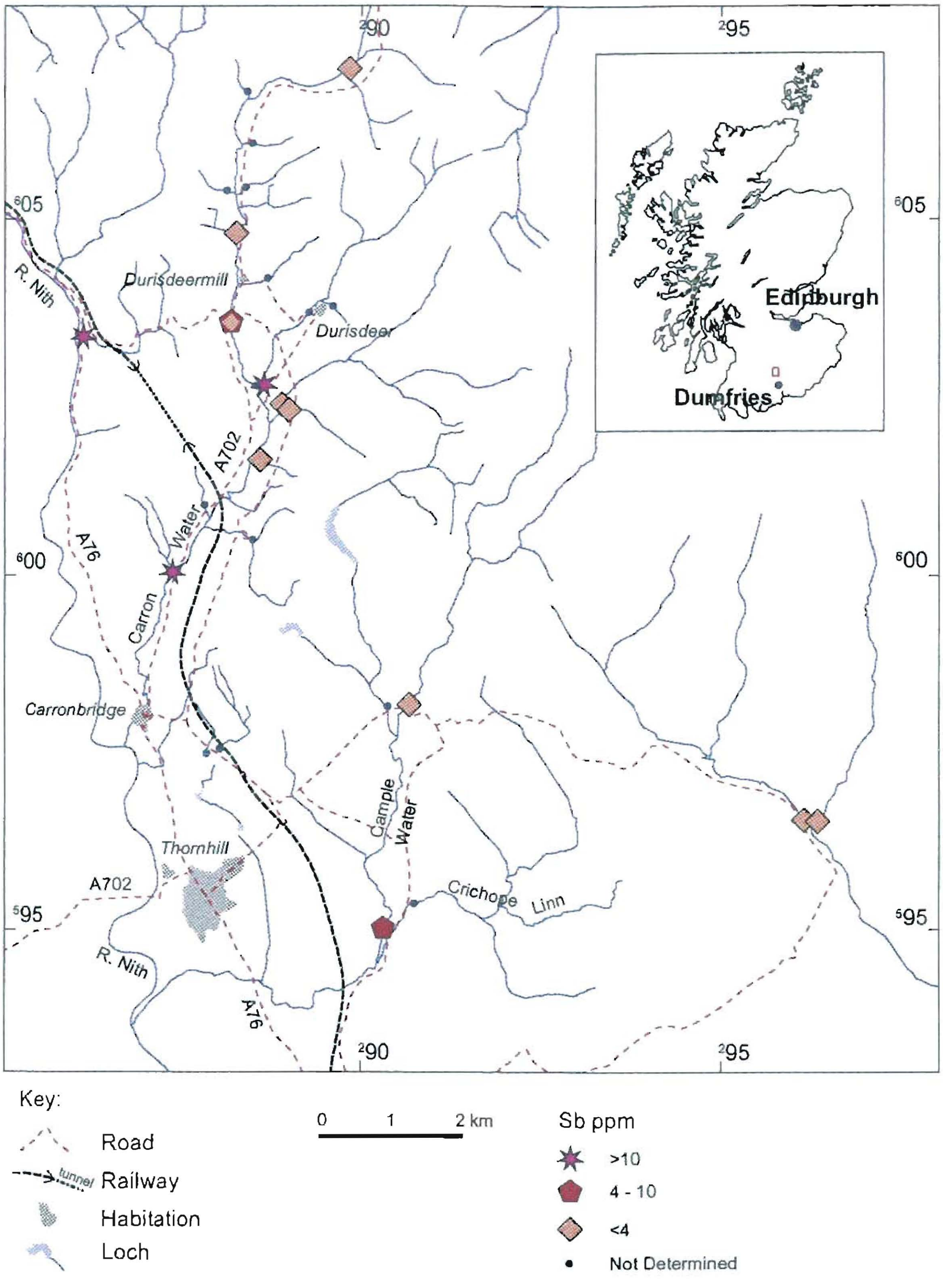


Figure 9 Antimony in panned concentrate

highest amplitude anomaly does not correspond with a gold-by-analysis anomaly. In general, the higher silver concentrations are associated with the centre of the area.

Antimony

Elevated antimony contents are associated with three samples, all from the eastern part of the basin (Figure 9). No correlation between Sb and either Au or As is evident.

Mercury

Only two of the samples analysed for mercury are anomalous (Table 2) and both of these are anomalous in gold. In contrast, the maximum gold anomaly is associated with the lowest concentration of mercury. Slightly enhanced levels of Hg are associated with samples from the centre of the area (Figure 10).

INTERNAL CHEMICAL CHARACTERISTICS OF GOLD AND OTHER GRAINS

Microchemical Maps

Microchemical maps of the distribution of the elements Au, Ag, Pd, As, Se, Cu, Bi, As, Pb, S, Sn, Te and Sb were produced for 5 of the grains, for three separate segments of the grain in the case of 314/2. Image processing was carried out on the raw images to accentuate the compositional differences present. Thus the relationship between colour and concentration varies from map to map. Maps which did not detect any variation in an element were not printed. Examples of the maps are given in plates 1 to 5 in the appendix.

Grain 314/1

There are three levels of silver apparent in the interior of grain 314/1 (Plate 1). Most of the grain consists of a network intergrowth of two compositional types of gold with differing silver, the predominant type with Ag 23–35% and the other with substantially higher amounts of silver. The boundaries between these two compositions are somewhat diffuse. This suggests deposition at relatively high temperature, but not high enough to promote complete diffusion between the two compositional types. In addition, there are small patches of pure gold or very low silver gold, and a smaller number of patches of gold showing enrichment in Pd.

Grain 314/2

This grain generally shows little variation in silver except for isolated marginal patches which are poor in silver (Plate 2) and a small patch in one segment of the grain with two lower levels of silver (Plate 3). The boundaries between the compositional types are distinctly diffuse, suggesting a relatively high temperature of crystallisation, as in the case of grain 314/1.

Grain 314/6

Grain 314/6 (Plate 3) is less silver-rich than the above grains, but shows a diffuse zone and patches with greater enrichment in gold, diffuse patches showing enrichment in Pd and a partial rim of an Sb–Pd mineral (probably stibiopalladinite Pd_5Sb_2). The grain shows clear evidence of outward concentric growth. The boundary between the gold and stibiopalladinite is relatively sharp.

Grain 318/3

This grain is composed of at least four different compositional types (Plate 4). Silver-poor gold (2.5% Ag) is traversed by a network of irregular masses and films of silver-rich gold (23% Ag). In addition, there are isolated elongate and more irregular patches of pure gold and separate patches of Pd-containing gold. The boundaries of the compositional types are somewhat diffuse, with the exception of the pure gold which has sharp boundaries, suggesting a later and lower temperature origin.

Grain 322/2

This grain (Plate 5) is an example of one of the grey grains which are associated with gold in the Thornhill drainage samples, and consists mostly of a Sn–Hg intermetallic compound with the approximate formula of Sn_9Hg. This composition is possibly equivalent to the γ phase in the Hg–Sn binary system and stable only below 220 °C. In addition, there is a partial rim of a more tin-rich phase which could represent the β phase in the Sn–Hg system, a marginal area of pure tin and another marginal area, possibly of tin oxide.

Table 3 Quantitative electron microprobe determinations of the composition of gold and other grains

grain	part	Au%	Ag%	Pd%	Hg%	Sn%	Sum
PTP127/1		95.6	3				98.6
127/2		102	0				102
127/3		96.5	2.4				98.9
127/4		100	0.8				100.8
127/5		88.9	8.7				97.6
314/1		**70.88**	**22.7**		**5.8**		**99.38**
314/1		**70.83**	**24.67**		**4.91**		**100.41**
314/1		**67.78**	**23.26**		**6.52**		**97.56**
314/1		**65.05**	**23.84**		**8.25**		**97.14**
314/2		**74.68**	**20.65**		**4.32**		**99.65**
314/2		**80.01**	**17.02**				**97.03**
314/2		**78.4**	**20.56**				**98.96**
314/6		**89.87**	**9.16**				**99.03**
318/1	right	99.56		3.7			103.26
318/1	right dark	97.16	5.86				103.02
318/1	more yellow	100.7		2.25			103
318/1	yellow	95.66	6.38	0.9			102.94
318/2		86.97	12.29				99.26
318/3	**dark patch**	**98.91**		**3.61**			**102.52**
318/3	**pale**	**75.12**	**23.37**		**2.51**		**101**
318/3	**yellow**	**100.4**	**2.52**				**102.94**
318/4		93.55	11.07				104.62
322/1		99.32	3.41				102.7
322/1		97.78	3.81				101.59
322/1		93.95	5.64				99.59
322/2					**17.81**	**82.76**	**100.57**
322/3					16.93	81.91	98.84
328/1		92.62	9.9				102.52
328/2		100.4	3.65				104.14
329/1		93.41	8.67				102.08

Grains for which microchemical maps produced shown in bold type.

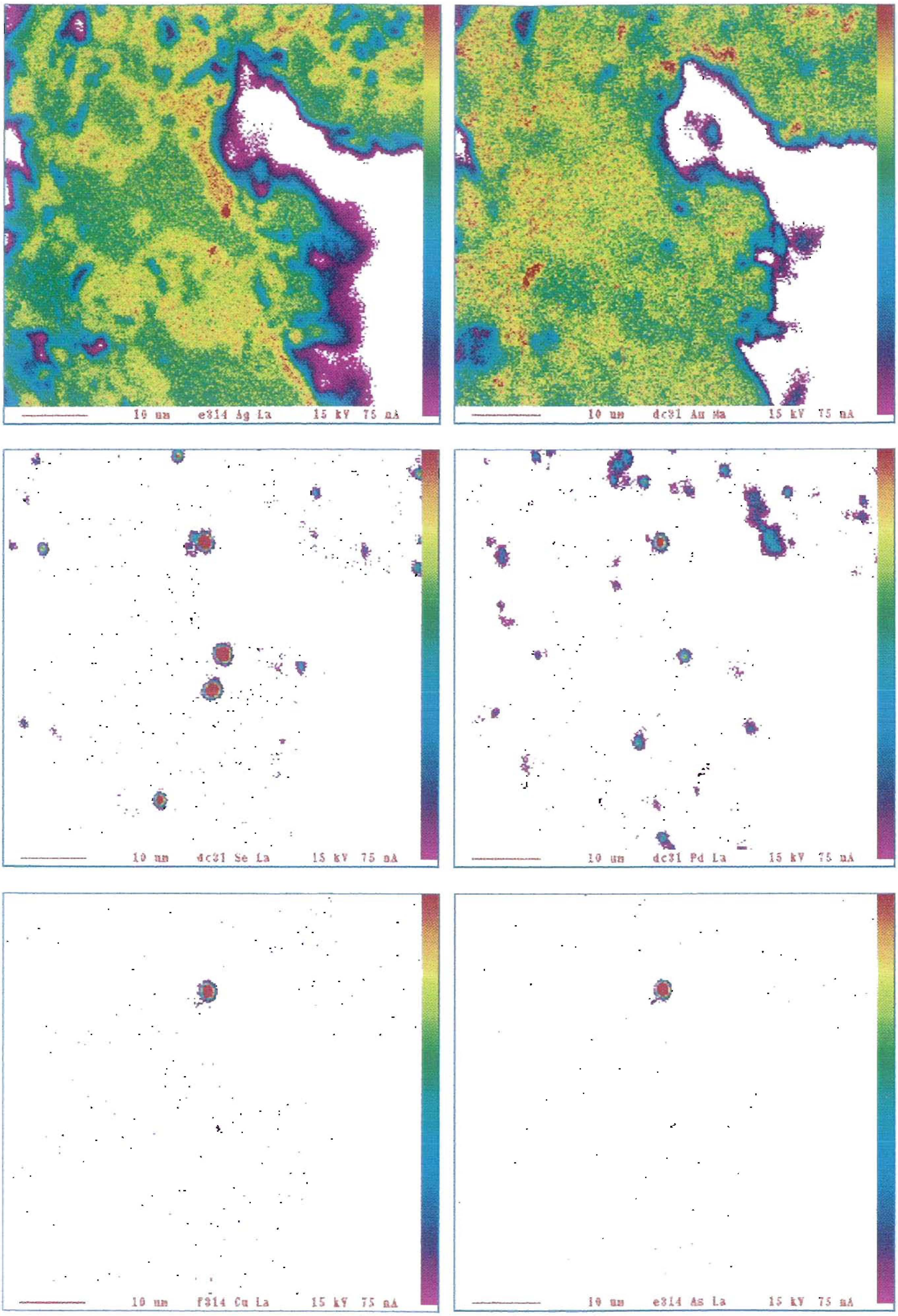


Plate 1 Sample PTP 314 Grain 1

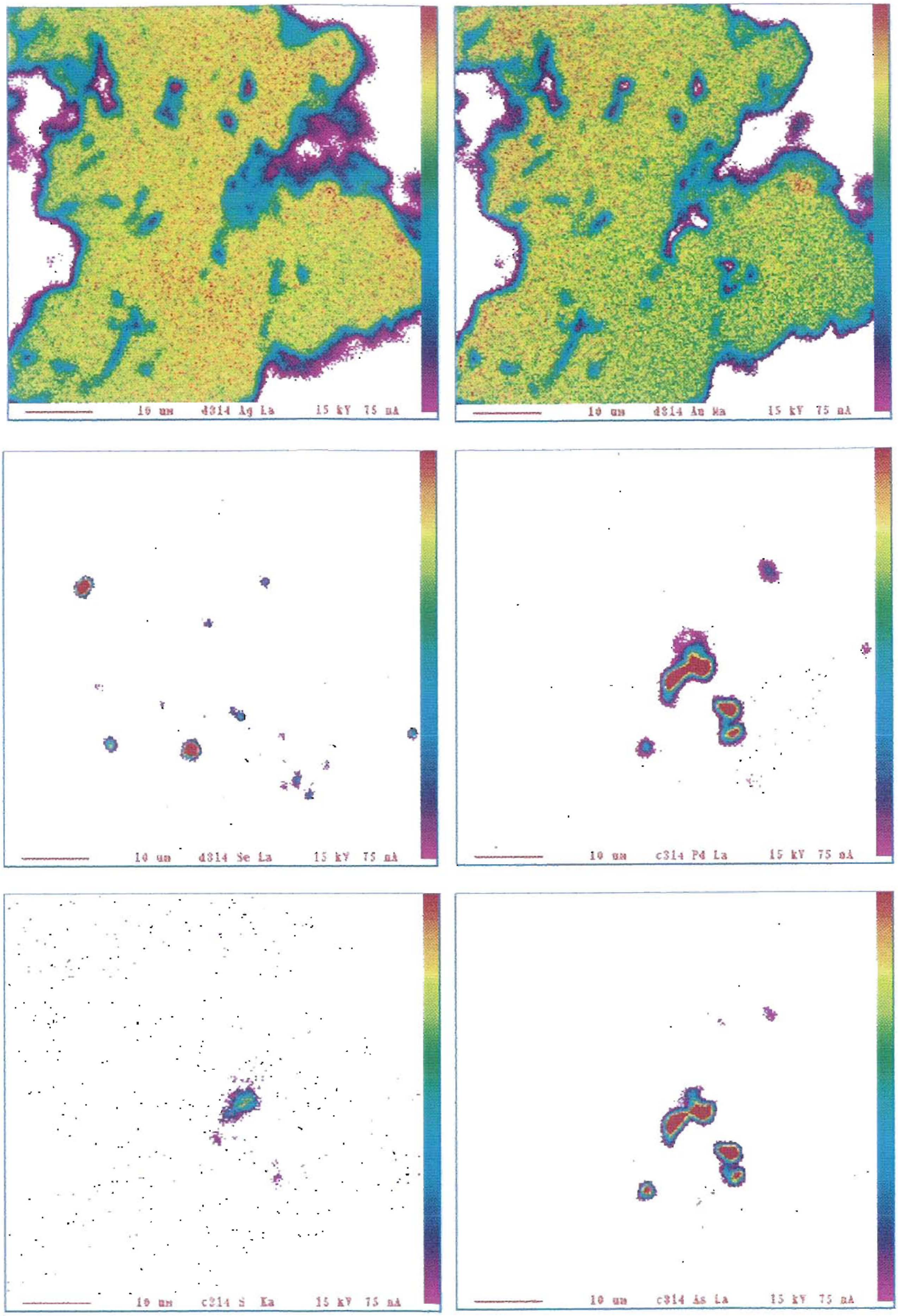
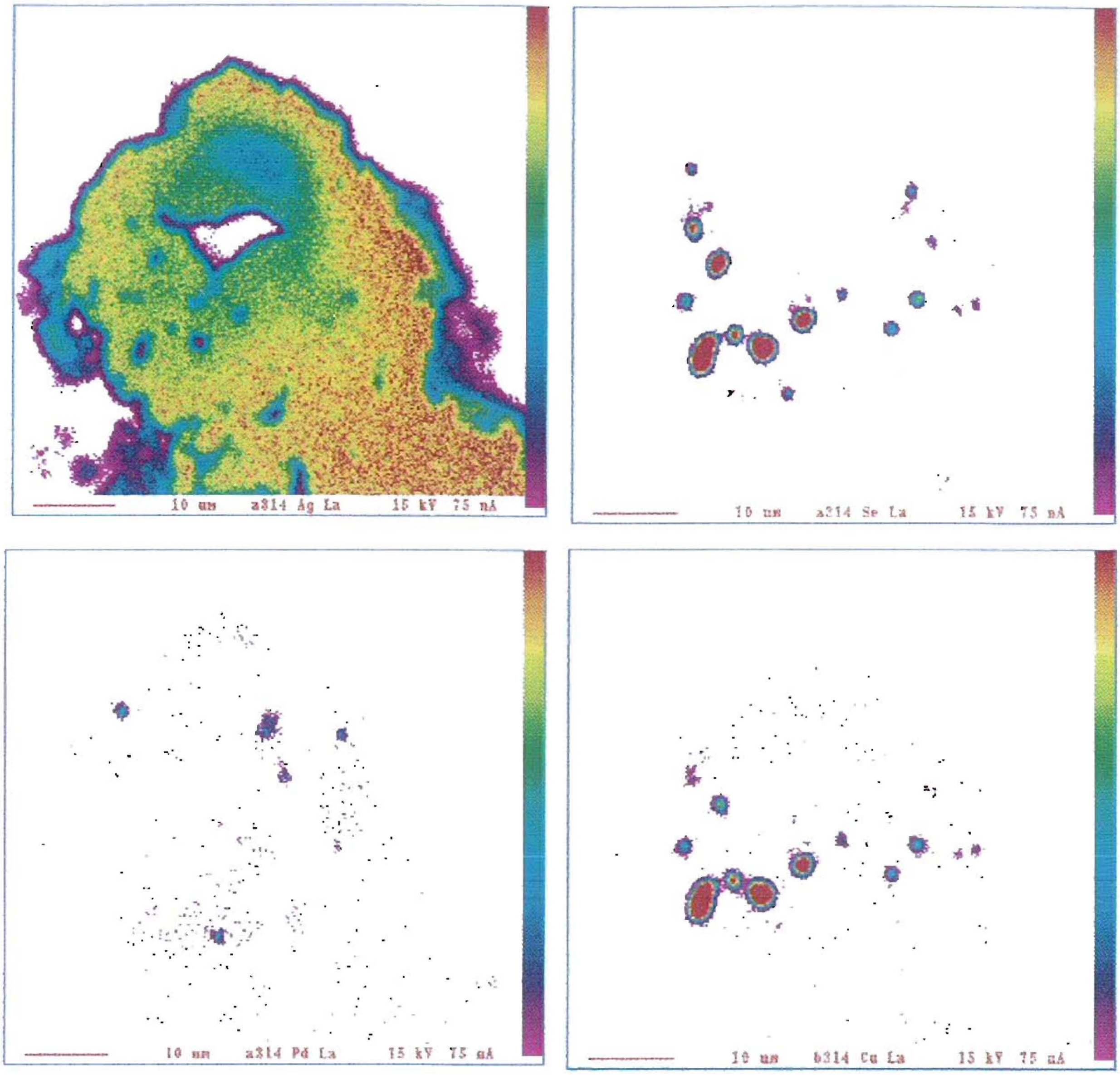


Plate 2 Sample PTP314 Grain 2 Part A



Sample PTP314 Grain 2 Part B

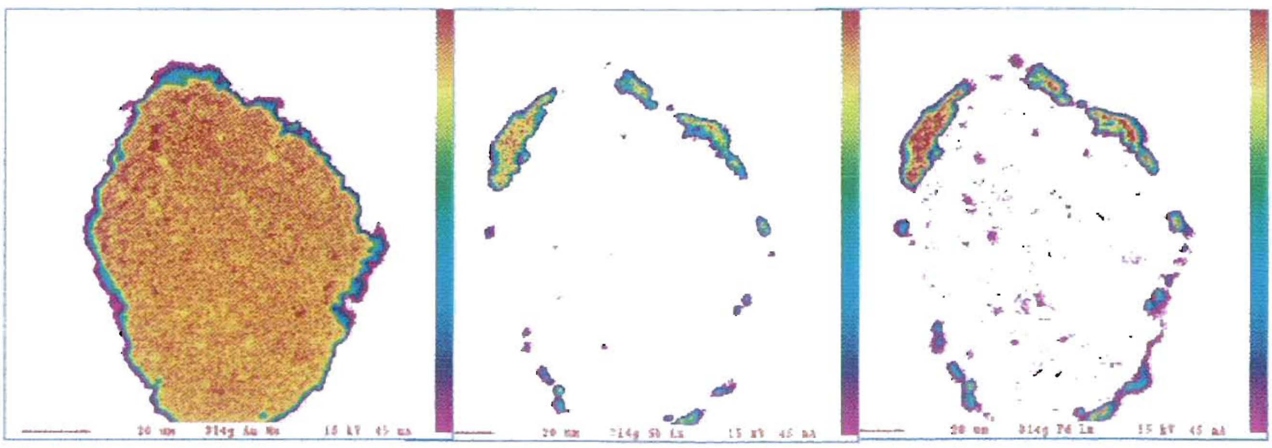


Plate 3 Sample PTP314 Grain 6

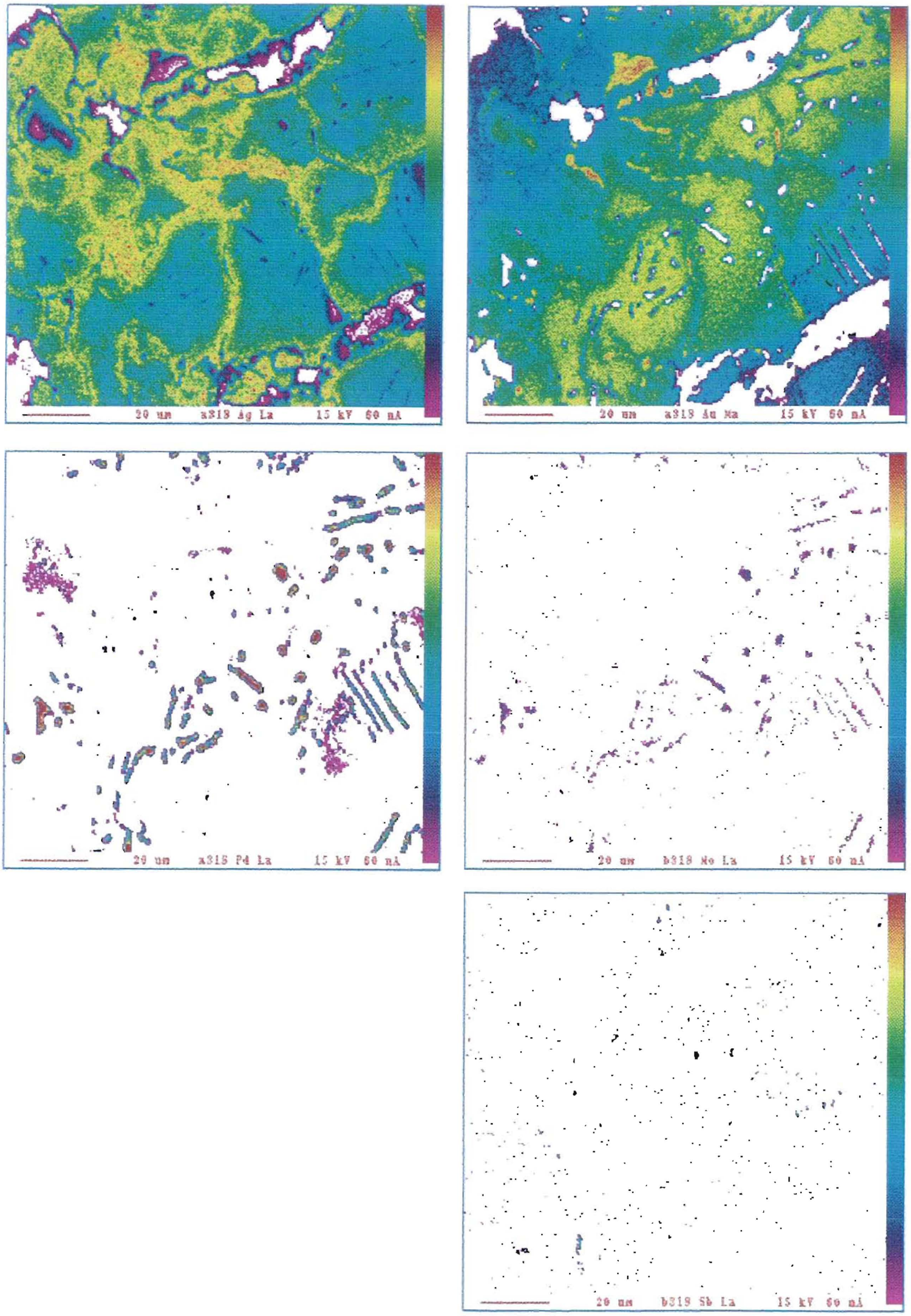


Plate 4 Sample PTP318 Grain 3

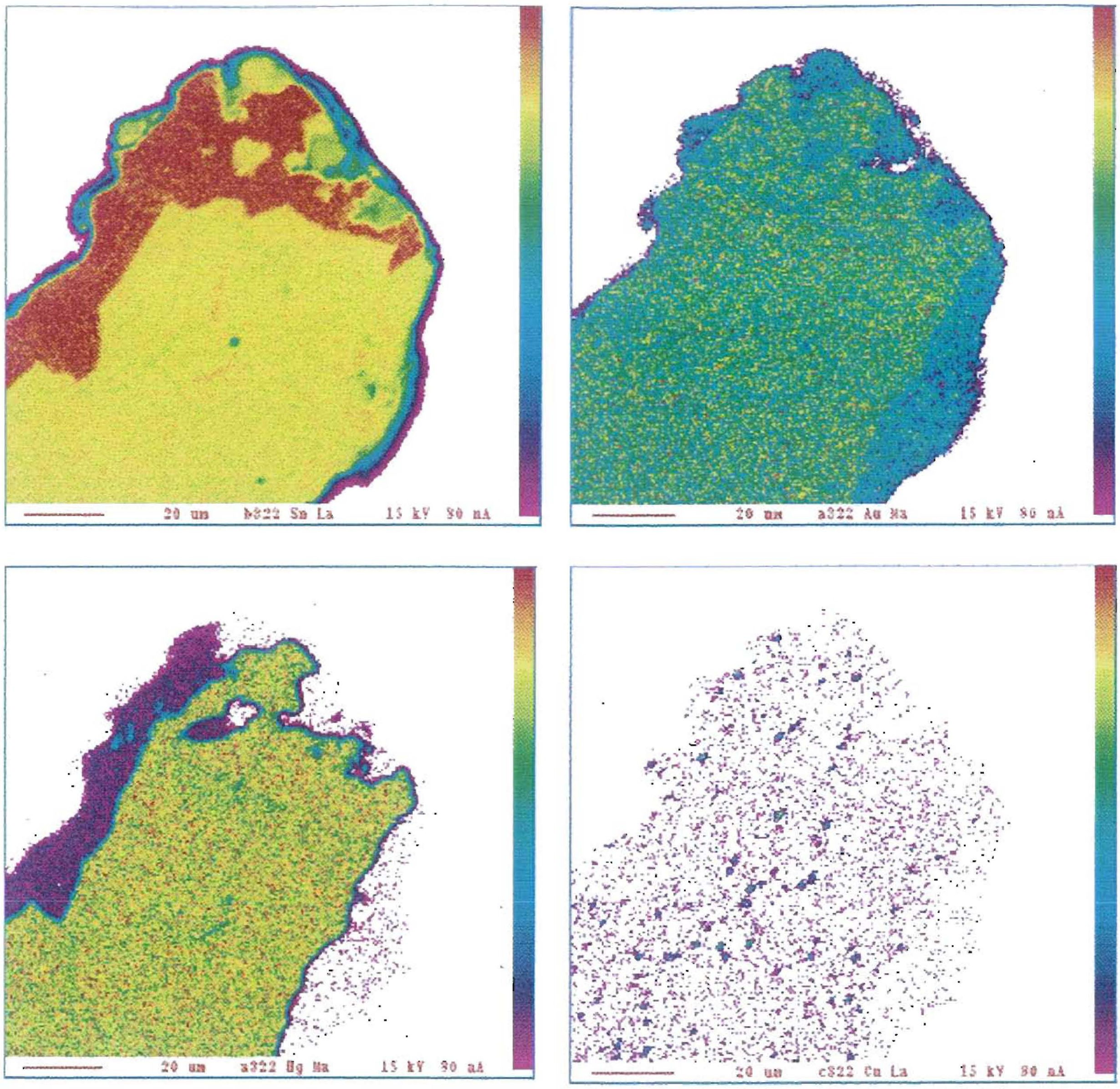


Plate 5 Sample PTP322 Grain 2

Overall composition

In view of the compositional complexity of the grains revealed by microchemical mapping it is probable that insufficient quantitative spot analyses of the grains have been carried out to characterise the full range of compositional types present. On the basis of the microchemical maps and the quantitative analyses, there would appear to be at least 5 gold compositions present in the grains from the area.

These comprise, in order of decreasing silver content

1) Ag 21–25% with which is associated mercury in the range 3–8% Hg

2) Ag 9–10%

3) Ag 2–6%

4) Ag < 2%

5) Ag < 0.5% with Pd 2–4%

Five grains consisting essentially of a Sn–Hg compound were also found from two sites. The origin of these grains is uncertain since such material has never been described in the scientific literature. A similar grain was found in a gold-bearing sample from South Devon but at the time was considered to be most likely an artefact. The presence of several grains of this material in the Thornhill area suggests that it may be of natural origin and associated with gold of the red bed type.

Inclusions.

Inclusions were found in three of the gold grains and also in one of the Sn–Hg grains. Most of the inclusions are of selenides, some of which have been identified while others remain uncertain. The nature of these inclusions are shown in Table 4

Table 4 Inclusions present in gold grains from Thornhill

314/1	314/2	318/3
Pd selenide	Cu selenide	Pd–Mo compound
naumannite (Ag_2Se)	Pd arsenide	Pd–Sb compound
Cu+Se+Pd+As	tiemannite (HgSe)	
	Pd–As–sulphide?	
	Cu–Pd selenide	
	Pd arsenide + S	

Inclusions shown in approximate order of abundance

The identification of many of the inclusions is uncertain. Many are extremely small (< 2μm), and a combination of very detailed mapping together with closely spaced quantitative analyses would be required to identify them more satisfactorily. Some inclusions with an apparent complex composition, e.g. Cu–Pd–Se–As, could comprise two separate inclusions which may only be resolvable from very detailed mapping to the limits of the resolving power of the electron microprobe. The inclusions in grain 318/3 appear to be intermetallic compounds, as no anionic components (e.g. Se, Te, As, S) were detected. The elongate shape of the inclusions and their parallel orientation may indicate very high temperature, perhaps in the magmatic range. As in the case of inclusions found in Devon gold, some of the Thornhill inclusions may represent minerals new to science.

Though exact identification of several of the inclusions remains uncertain, the abundance of selenides and the absence of simple sulphides is clearly evident. In this respect, the gold from the Thornhill basin is very similar to that from South Devon and the Crediton Trough. Tiemannite, naumannite, palladium selenide and Cu-Pd selenide are common inclusions found in the gold from the Crediton Trough and from parts of south Devon. In contrast, gold from other parts of the Southern Uplands usually contains inclusions of sulphide and sulpharsenide minerals, forming completely different assemblages. The nature of the Thornhill alluvial gold is thus a strong indication that it is sourced from the Permian red beds and their contacts with the underlying rocks.

ROCK GEOCHEMISTRY

No systematic rock sampling has been carried out. Six rock samples were collected as part of the initial reconnaissance survey (Table 5) and after pulverisation in a Tema disc mill with Cr-steel pot these were analysed by XRF at the BGS chemical laboratories. In addition, Au was determined by the same method as used for the drainage samples. The results are given in Table 6. In addition, friable samples of two of the rocks were also panned and the heavy mineral concentrate analysed for gold. Neither sample contained gold above the 2 ppb level.

Table 5 Locations and description of analysed rock samples.

Sample PTR	Grid reference	Description
225	288259 604802	red Permian conglomerate with large blocks of alkali basalt
226	288558 602647	red Permian conglomerate with blocks of alkali basalt
227	288640 604158	red purple Permian conglomerate with blocks of red sandstone and alkali basalt
228	290680 595482	red/orange poorly cemented sandstone with Mn oxide joint coating
229	290681 595322	purple oxidised shale
230	290685 595324	hematised layered mudstone

Table 6 Chemical analyses of rock samples (XRF)

Sample PTR	MgO	CaO	TiO_2	MnO	Fe_2O_3	Ni	Cu	Zn	As	Zr	Ba	Pb	Au
225	10.2	0.77	1.952	0.089	9.79	120	22	88	6	563	345	19	< 2
226	5.9	0.95	1.311	0.090	6.37	75	18	40	< 5	339	307	17	< 2
227	5.6	0.36	1.365	0.061	6.58	56	23	54	< 5	287	265	16	2
228	0.3	< 0.05	0.122	0.616	1.01	72	4	25	<5	121	853	10	<2
229	0.4	0.15	1.456	0.009	2.36	40	5	24	<5	240	212	3	2
230	1.0	0.19	0.766	0.079	7.69	28	9	33	<5	213	569	15	<2

MgO, CaO, TiO_2, MnO, Fe_2O_3 in %, Ni, Cu, Zn, As, Zr, Ba, Pb in ppm, Au in ppb

The composition of the conglomerates reflects the basaltic composition of the dominant clast lithology. The absence of gold above background levels in the three samples of conglomerate with alkali basalt blocks, may indicate that gold is not uniformly enriched in the basalt, but is more localised and probably structurally controlled.

CONCLUSIONS AND RECOMMENDATIONS

1. Alluvial gold, with characteristics very similar to gold from the Crediton Trough and the South Hams areas of Devon, has been discovered for the first time in association with Permian red beds of the Thornhill basin. This discovery strongly supports the model developed for the controls of gold transport and deposition within the red bed environment.

2. There is sufficient evidence from the distribution of gold in drainage samples and from the microchemical mapping and quantitative analyses of the gold grains to suggest that mineralised structures carrying gold occur at contacts between the Permian strata and the underlying Lower Palaeozoic rocks and possibly also in structures cutting the Permian rocks.

3. Follow-up exploration is recommended to locate and assess the economic potential of the mineralisation. Because of the limited dispersion of coarser particles of gold in those streams cutting bedrock in the area, detailed drainage sampling for gold may serve to locate cut-offs in streams which cut the presumed structures at high angles. In addition, overburden sampling by pitting could be used to establish if gold is concentrated in boundary structures. Drill holes through the contact zones will be the only means of establishing the extent of interaction between mineralising fluids circulating in the Permian red bed sequence and the underlying greywacke–shale sequence.

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