CHAPTER 4

THE IMPACT OF METAL MINING ON HEADWATER TRIBUTARIES OF THE RIVER SWALE:

THE GUNNERSIDE BECK CATCHMENT

4.1. INTRODUCTION

Previous investigations have demonstrated that historic metal mining can have a major and lasting effect on river catchments where such activities have taken place (*e.g*. Lewin *et al.*, 1977; Macklin *et al.*, 1997; Miller, 1997). A number of studies have focussed on the large-scale impacts of mining activities, and have identified patterns of contamination at a catchment scale. Although the potential importance of mined tributaries as sources of contaminated sediment to the main fluvial system has been recognised, few investigations have focussed on the impacts of mining within individual tributaries (*e.g.* Boult *et al.*, 1994; Rowan *et al.*, 1995). In the U.K., mining activities are frequently concentrated in the upland headwater tributaries of a river system (typically first and second order streams, *cf*. Strahler, 1952), where the impacts may be proportionally far more severe than in a larger catchment that can better adjust to the introduction of large volumes of mining waste. Furthermore, many formerly mined tributaries contain significant sinks and sources of contaminated sediment in the form of extensive spoil tips and contaminated floodplains.

This chapter aims to evaluate the impact of mining and processing activities on contamination and the geomorphology of Gunnerside Beck, in upper Swaledale. This small tributary has been severely contaminated by mining and processing activities dating back to the Roman occupation of Britain (Raistrick and Jennings, 1965). Large quantities of highly contaminated sediment are stored within the catchment, on spoil tips and in the floodplain. Patterns of metal transport and storage in Gunnerside Beck will be identified, and the geomorphological factors that influence these patterns will be considered. Finally, the likely significance of contaminated sediment storage in tributaries will be evaluated.

4.2. STUDY AREA: GUNNERSIDE BECK

4.2.1. General characteristics

Gunnerside Beck is a small upland tributary (*c.* 13.8 km^2), located in the headwaters of the River Swale (Figure 4.1). Maximum elevation is approximately 665 m in the north of the catchment, on a relatively flat upland plateau, with a minimum elevation of 220 m close to the confluence with the River Swale. The 7 km long channel flows through a narrow, steep-sided valley which bisects the upland plateau. The predominant land cover is open moorland, which is managed as grouse habitat and used as rough pasture for sheep grazing. Higher quality grazing land is found in the lower reaches of the catchment, adjacent to the River Swale. The only urban area within the catchment is the village of Gunnerside, which is located approximately 500 m upstream of the confluence with the Swale.

4.2.2. Catchment geology and mineralisation

Gunnerside Beck is underlain by a series of Carboniferous strata. The sandstones, limestones and cherts of the Stainmore Group (formerly classified as the Millstone Grit Formation) outcrop in upland areas of the catchment, and fluvial erosion has exposed the limestones and sandstones of the Wensleydale Group (formerly known as the Yoredales) in lower-lying areas (Dunham and Wilson, 1985).

The rocks of the Gunnerside catchment are heavily mineralised, with most veins trending in an east-west direction (Figure 4.2). The primary metal sulphide ore found within the catchment is galena, although small amounts of sphalerite are also encountered (Dunham and Wilson, 1985). The principal gangue minerals are witherite and baryte, although calcite and barytocalcite are locally abundant. The veins in the Gunnerside catchment are notable for their low fluorite content in comparison with other ore bodies in the region (Dunham and Wilson, 1985). The most continuously mineralised vein in the catchment, and possibly the entire Northern Pennine Orefield, is the Friarfold Vein, which outcrops in

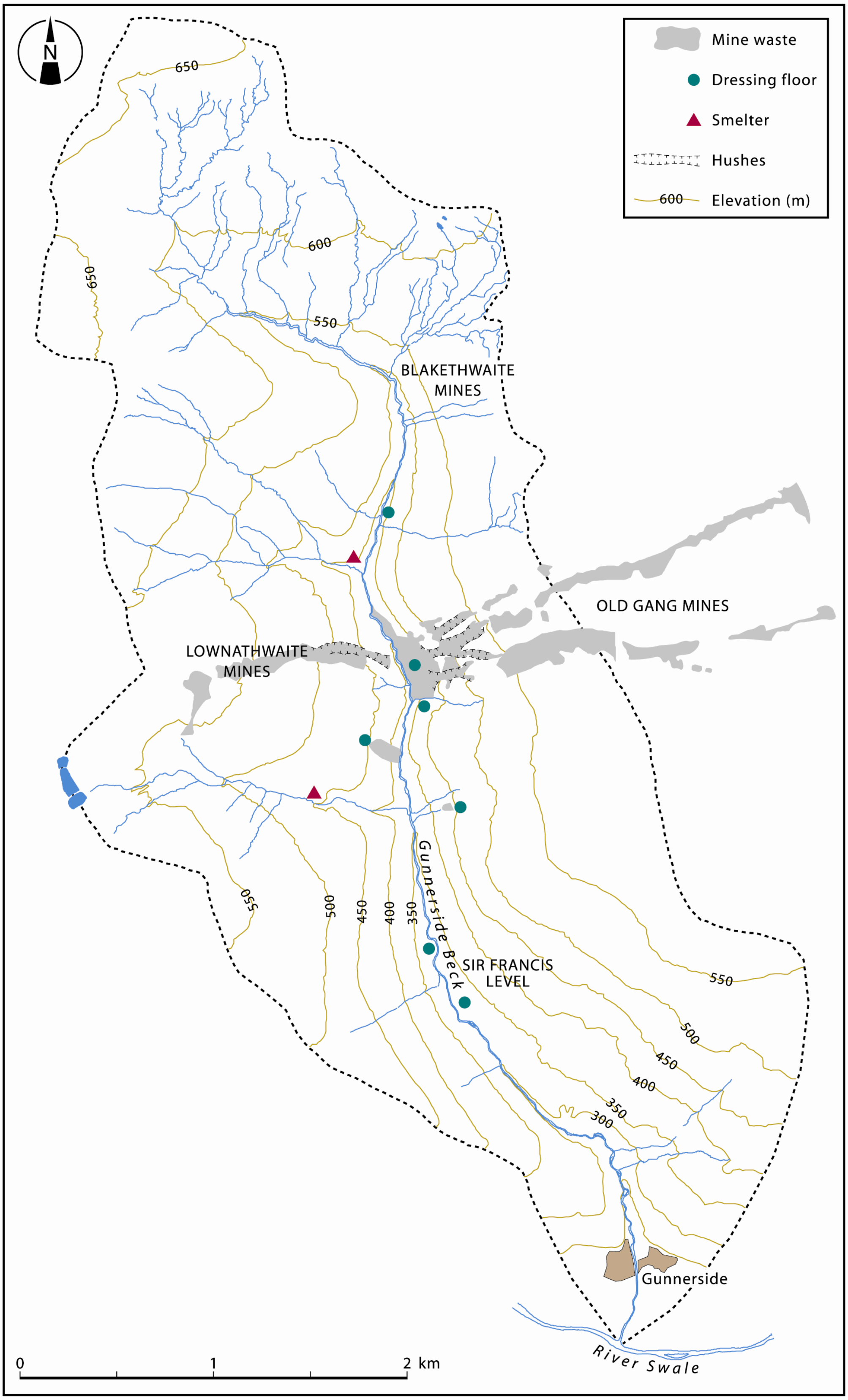

Figure 4.1: Map of the Gunnerside Beck catchment, showing drainage network, relief, and location of mines, dressing floors and smelters

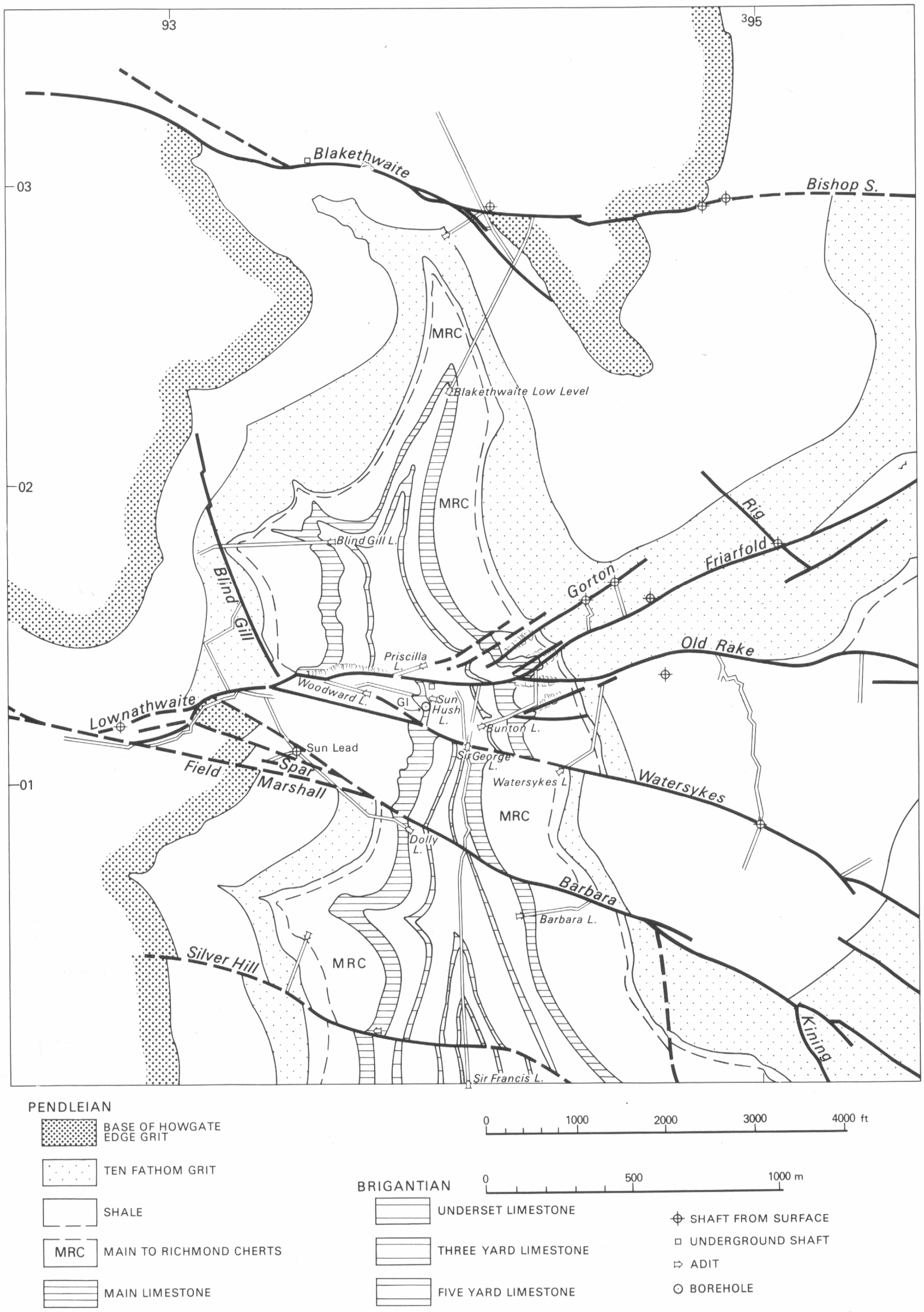

Figure 4.2: Major mineral veins in the Gunnerside catchment (from Dunham and Wilson, 1985)

the middle reaches of Gunnerside Beck (Dunham and Wilson, 1985). A number of smaller, but still substantial, ore bodies are associated with this vein, notably the Old Rake, Gorton, Bunton and Lownathwaite Veins, all of which have been extensively mined by hushing and deeper excavations (Section 4.3). Other veins such as Watersikes, Barbara and Kining Veins, which are orientated in a south east-north west direction, outcrop to the immediate south, eventually linking with the Friarfold complex to the west of Gunnerside Beck (Dunham and Wilson, 1985). The northern part of the catchment is crossed by Blakethwaite Vein, another large ore body.

4.2.3. Fluvial geomorphology

The Gunnerside Beck catchment can be subdivided into three broad geomorphological zones; a steep sided narrow valley with small areas of discontinuous floodplain development in the upper reaches, a wider valley with more extensive floodplain development punctuated by two gorges in the middle and lower reaches, and an alluvial fan where the tributary enters the main Swale valley (Figure 4.3).

In the upper reaches of the catchment, the gently meandering single-thread channel is well constrained by the steep valley sides (Plate 4.1). Large volumes of extremely coarse sediment (cobble-boulder size) can be observed as bedload within the channel and in the form of small lateral bars. Large limestone exposures, attributed to glacial activity (Pounder, 1979), are prominent features on the middle and upper valley slopes, frequently with coarse colluvial deposits at the base. Smaller bedrock exposures can also be observed within and adjacent to the channel. Small, discontinuous floodplain units have developed in places, with finer sediment partially covering coarse basal material. Floodplain development begins to become more pronounced at the lower end of the reach, and the channel bifurcates around a large, partially vegetated medial bar. The large hushes on both sides of the valley, operated as part of the Lownathwaite and Old Gang mines (Sections 4.3.3 and 4.3.4), are prominent features at the end of this reach (Figure 4.1).

Larger areas of floodplain have developed in the middle reach, downstream of the Lownathwaite and Old Gang hushes (Plate 4.2). This may reflect the large volumes of sediment released from the hushes and dressing floors while they were operational, and from the extensive unvegetated spoil tips that adjoin the river. The valley sides remain steep, but the valley is wider than in the upper reaches of the catchment. Much of the

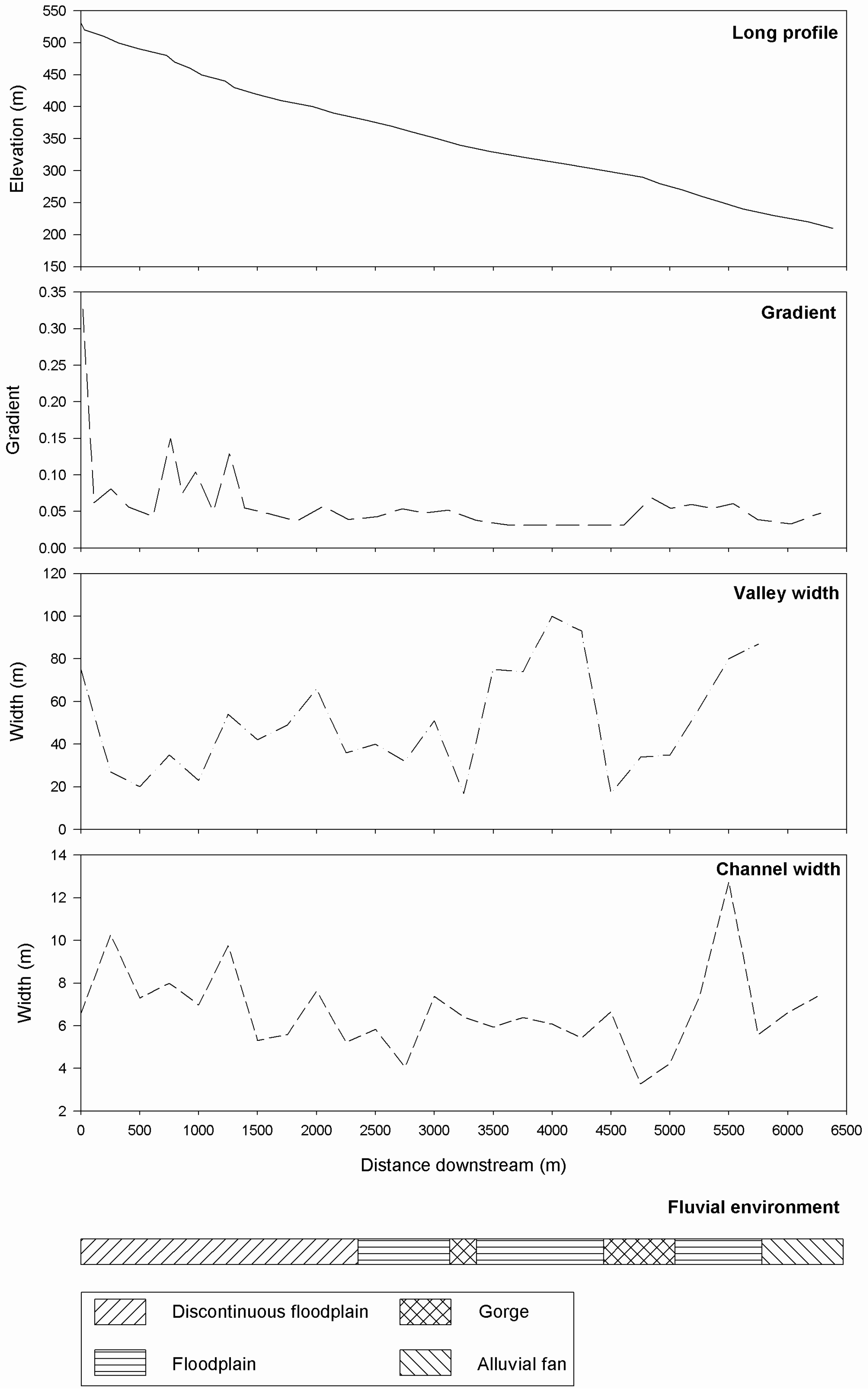

Figure 4.3: Geomorphological characteristics of Gunnerside Beck (measured from OS 1:10,000 scale Landline data)

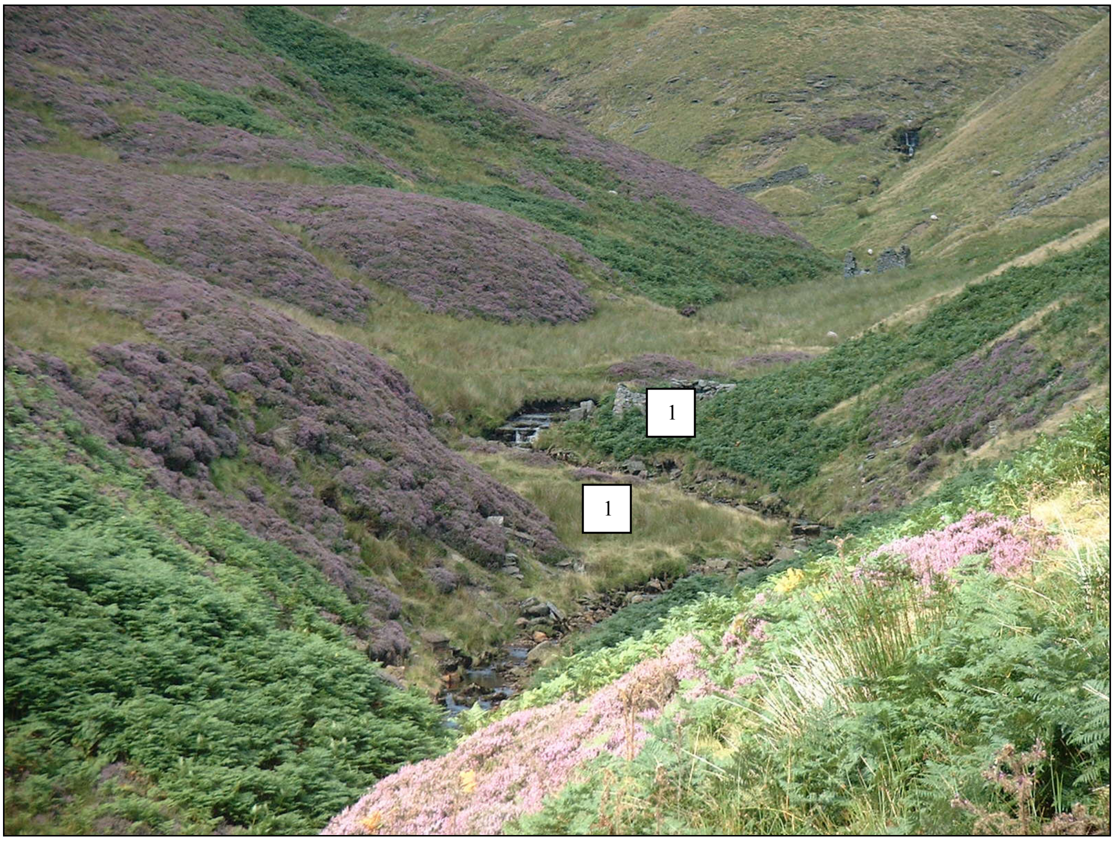

Plate 4.1: Small floodplain units (1) in the upper reaches of Gunnerside Beck

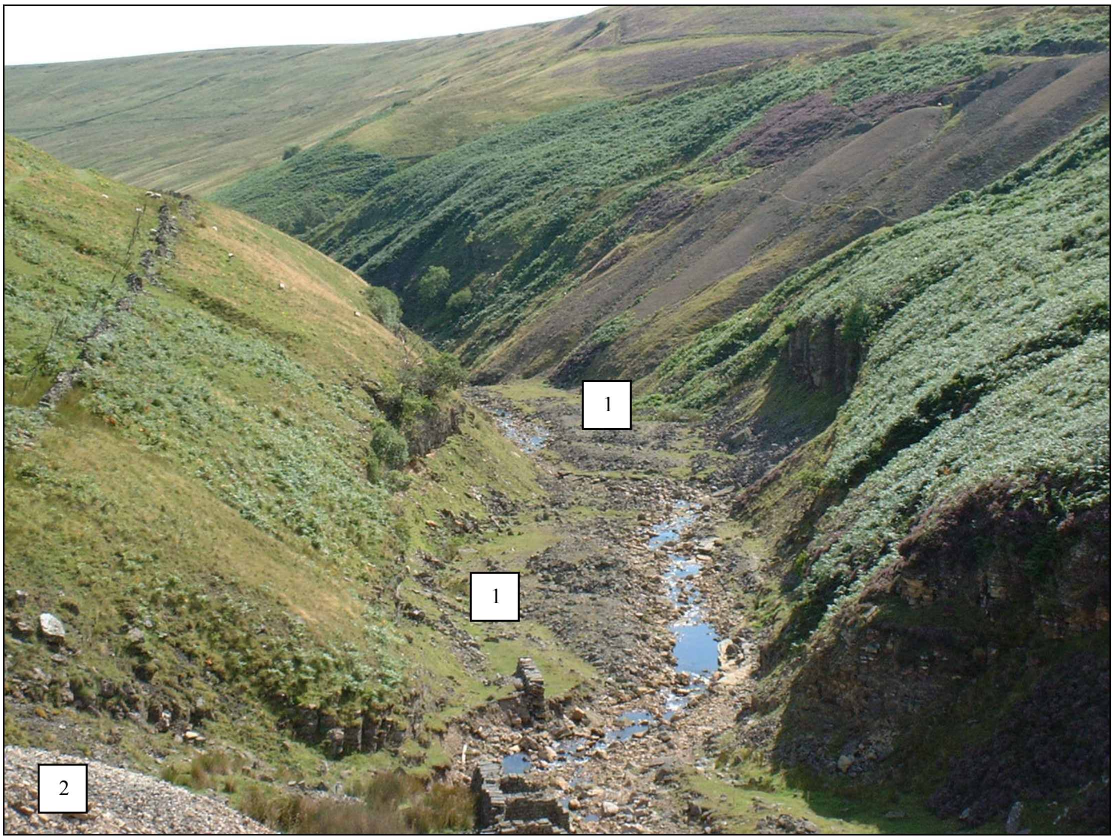

Plate 4.2: Floodplain deposits (1) downstream of the Old Gang (2) and Lownathwaite mines

sediment on the channel bed and adjacent bars is very coarse (predominantly cobble-sized), and similar material can be observed on top of and within floodplain deposits. This reach is terminated by a narrow bedrock controlled gorge (NY 939003) downstream of Botcher Gill.

Downstream of the gorge, the valley opens out into a wider reach (Plate 4.3). Extensive areas of floodplain have developed, on which are located the abandoned Sir Francis Level mine workings (Section 4.3.5). A series of small terraces have formed on the floodplain (Pounder, 1989), although the large amounts of mining waste on the floodplain surface obscure several of these features. Both bedload and channel bars remain coarse, although the proportion of boulder-sized material is smaller than further upstream. The channel in this reach follows a gently meandering pattern, with a number of braided sections. Several of the larger spoil tips are being actively eroded by the channel (for example on the AD Company dressing floor at SD 940999), and erosion of the valley side at the end of the reach has led to the development of a large scar (SD 942994). This major alluvial reach is

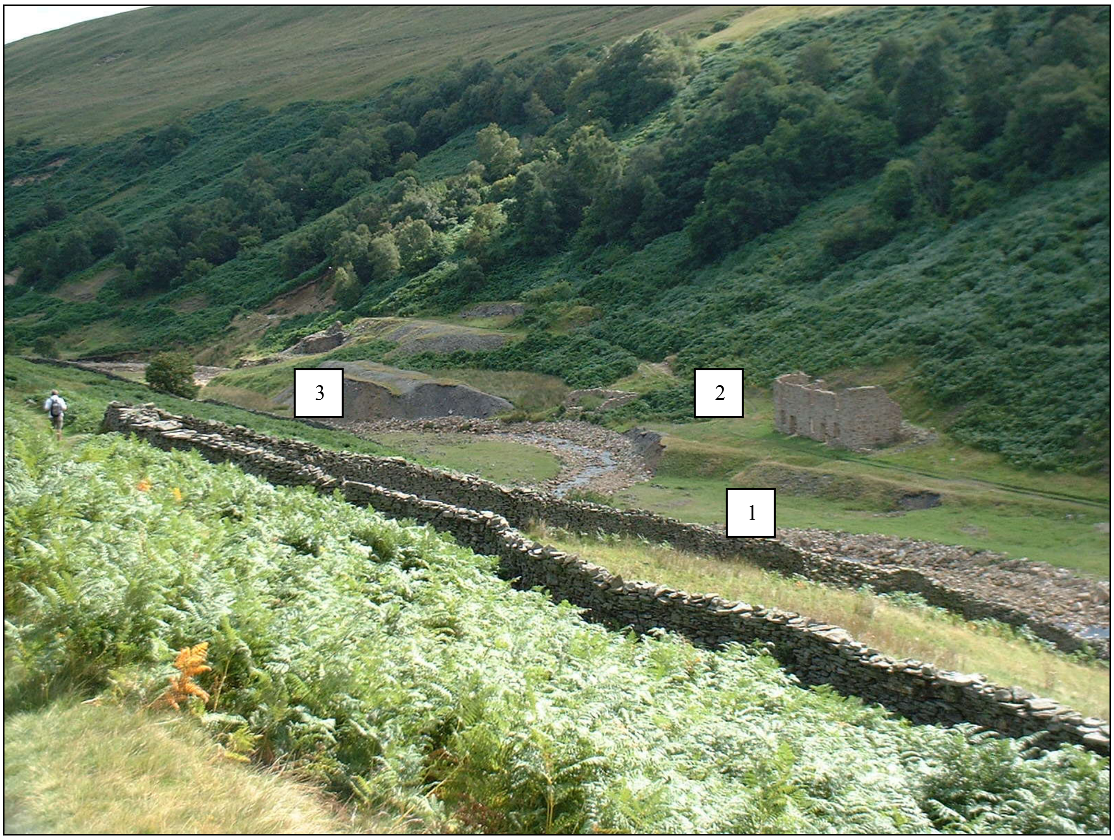

Plate 4.3: Floodplain deposits (1) and the AD Company dressing floor (2) at Sir Francis Level. Note the large spoil tip that is currently being eroded by the river (3)

terminated by a bedrock gorge (SD 945991) approximately 100 m downstream of this feature.

The second gorge, located within Birkbeck Wood, is approximately 450 m in length. The channel is bounded by bedrock for much of this distance, although small areas of both fine and coarse sediment deposition can be observed within the gorge. The valley opens out downstream of the gorge, where a series of fragmented terraces have developed. The channel divides around several large medial bars, comprised of coarse material partly overlain by finer sediments. Much of the sediment transported in the river and deposited on adjacent terrace fragments and bar surfaces is extremely coarse, with many boulders exceeding 1 m in diameter (Pounder, 1979). It is likely that much of this material is sourced from the unvegetated spoil tips further upstream, transported through the gorge section during periods of high flow, and redeposited on the bars and terraces in this lower gradient reach (Pounder, 1979).

Detailed investigations by Merrett (2001) have identified sixty-six distinct coarse-grained flood units in the alluvial reaches downstream of the Old Gang and Lownathwaite hushes. These have been dated by lichenometry to between 1783 and 1995, although the majority were formed between 1822 and 1908 (Merrett, 2001). The number and surface area of these boulder berm deposits peaks in the 1850s, when sediment supply from mining was at its greatest (Merrett, 2001). The cessation of mining activities in the catchment in the early twentieth century significantly reduced sediment supply, leading to a decline in the number of flood units and the gradual incision of the river channel (Merrett, 2001). It is likely that many of the terraces observed in the alluvial reaches were formed as a result of this incision, which has continued throughout the twentieth century (Merrett, 2001).

Channel gradient steepens sharply at the end of the alluvial reach, as the river enters the main Swale valley. A large alluvial fan has developed on the floodplain at this point, possibly as a result of high sediment transport by meltwaters at the end of the last glaciation (Pounder, 1989). The surface of the fan is covered by a series of abandoned distributary channels and associated depositional lobes (Pounder, 1979). These features become larger with distance downstream. The lowest terrace surfaces described by Pounder (1979) grade into the surface of the fan at its most upstream extent. Documentary evidence suggests that the large fan remains an active feature during large flood events.

Pre-existing channels have been scoured by receding flood waters, and changes to the surface morphology of depositional features is also apparent (Pounder, 1979).

A small contemporary alluvial fan, comprised of predominantly coarse-grained sediment, can be observed at the confluence with the River Swale. The position of the stream channel and morphology of the fan appear to have varied considerably over a short time scale, being altered during periods of high flow. Boulders greater than 80 cm in diameter were moved during the floods associated with Hurricane Charley during August 1986 (Pounder, 1989), showing that the fan is susceptible to change during such events.

4.3. MINING IN GUNNERSIDE BECK

4.3.1. Mining history

The Gunnerside Beck catchment has a long history of lead mining and processing. These activities have had a major impact on the catchment, and have left behind a large body of physical evidence in the form of extensive spoil tips and large hushes. It is unclear when the mineral resources of the catchment were first exploited, but many eighteenth and nineteenth century attempts at extraction were frustrated by '*Old Man*' workings, which could have been made at any time after the Roman occupation of Britain (Raistrick and Jennings, 1965; Dunham and Wilson, 1985). Mining records are incomplete, but evidence suggests that mines in Gunnerside Beck were already yielding 750 tonnes of lead concentrates per year by 1696 (Dunham and Wilson, 1985). Lead extraction increased markedly during the mid 1700s, peaked in the mid 1800s, and ceased at the beginning of the twentieth century. There are four principal groups of mines in the catchment; Blakethwaite in the north, the Lownathwaite mines in the west, the Old Gang mines in the east and Sir Francis Level to the south.

4.3.2. The Blakethwaite mines

The Blakethwaite mines are located in the northern headwaters of Gunnerside Beck (Figure 4.4). Lead ore was first extracted near Little Punchard Gill in 1710, but the inaccessibility of the site meant that large scale exploitation did not occur for another 87 years (Gill, 2001). Several deep shafts were sunk from the moor to the north of Gunnerside Beck, and Lonsdale's Level, an old level driven into the valley side, was

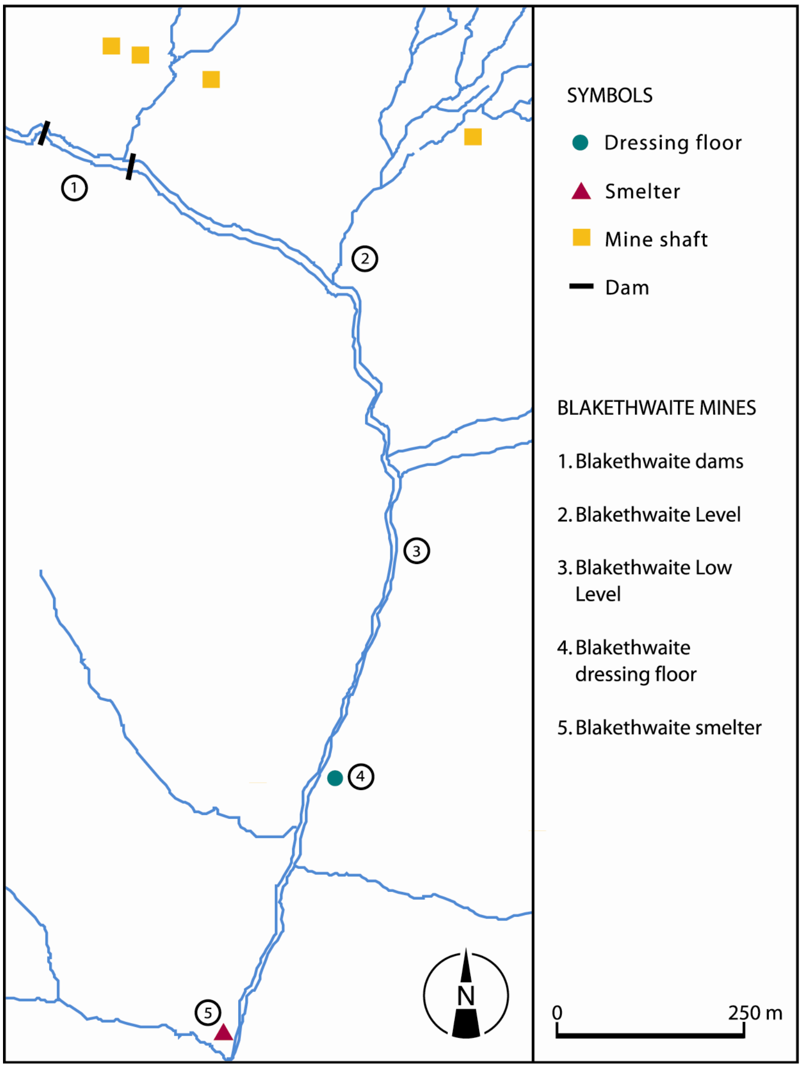

Figure 4.4: The Blakethwaite lead mines

reopened. Work started on the driving of two new levels in 1812 and 1814, respectively. The latter, Blakethwaite Low Level (NY 939027), proved unproductive and was abandoned in 1818 (Gill, 2001). A major ore-bearing vein was finally reached from the former, Blakethwaite Level (NY 939028), in 1821 (Raistrick, 1975b). A smelter (NY 937018), with a stamp mill to crush hard slags, and dressing floor (NY 938021), with water-powered ore crushers, were constructed to process the ore raised from the Blakethwaite levels and shafts in 1820 (Raistrick, 1975a) (Plate 4.4). Output from this dressing floor averaged 383 tonnes of lead per year until 1831. However, a major slump in the lead market in the early 1830s caused a sharp decline in production (Gill, 2001).

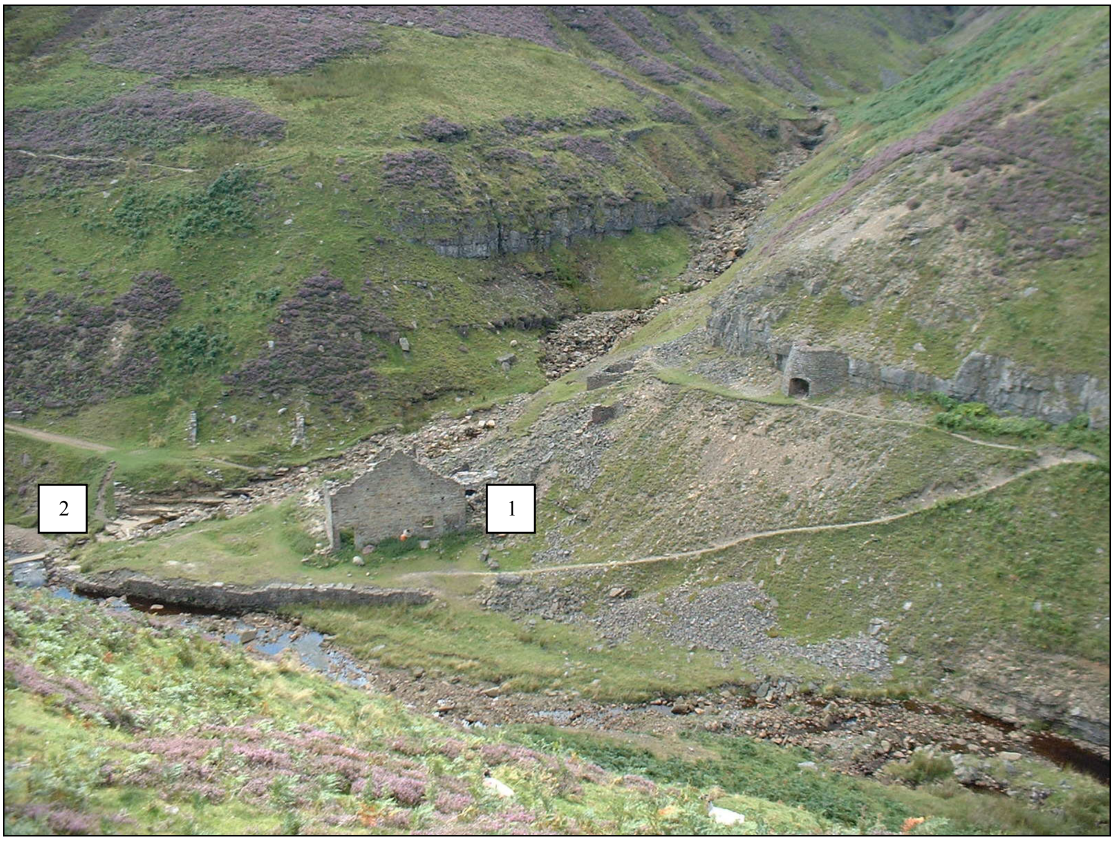

Plate 4.4: Blakethwaite smelter (1) and the Blind Gill - Gunnerside Beck confluence (2)

Extraction recommenced in 1837, and between 1839 and 1847 production exceeded that of the mines prior to the closure. Blakethwaite Level was extended considerably in the early 1840s, and a water-pressure engine was installed to raise ore from the deeper sections (Gill, 2001). This was driven by water fed from the Blakethwaite dams (NY 935029), through underground workings and down a 50 m deep shaft. This was extremely productive, and records suggest that ore worth £100,000 was raised (Dunham and Wilson, 1985). Production declined during the late 1860s, and is likely to have ceased altogether by the early 1870s (Gill, 2001). Smelting continued at Blakethwaite until 1878, although the smelter was idle between 1870 and 1873. Total output at the mine may have reached 20000 tonnes of lead concentrates (Dunham and Wilson, 1985), with output between 1817 and 1874 estimated as 13205 tonnes (Fieldhouse and Jennings, 1978).

4.3.3. The Lownathwaite mines

The Lownathwaite mines are situated on the western side of Gunnerside Beck, and are marked by a series of prominent hushes and spoil tips on the valley side (Figure 4.5). These mines, which extend westwards until they meet Swinner Gill, were in production prior to 1670 (Raistrick, 1975b), although detailed production figures are scant. It is likely

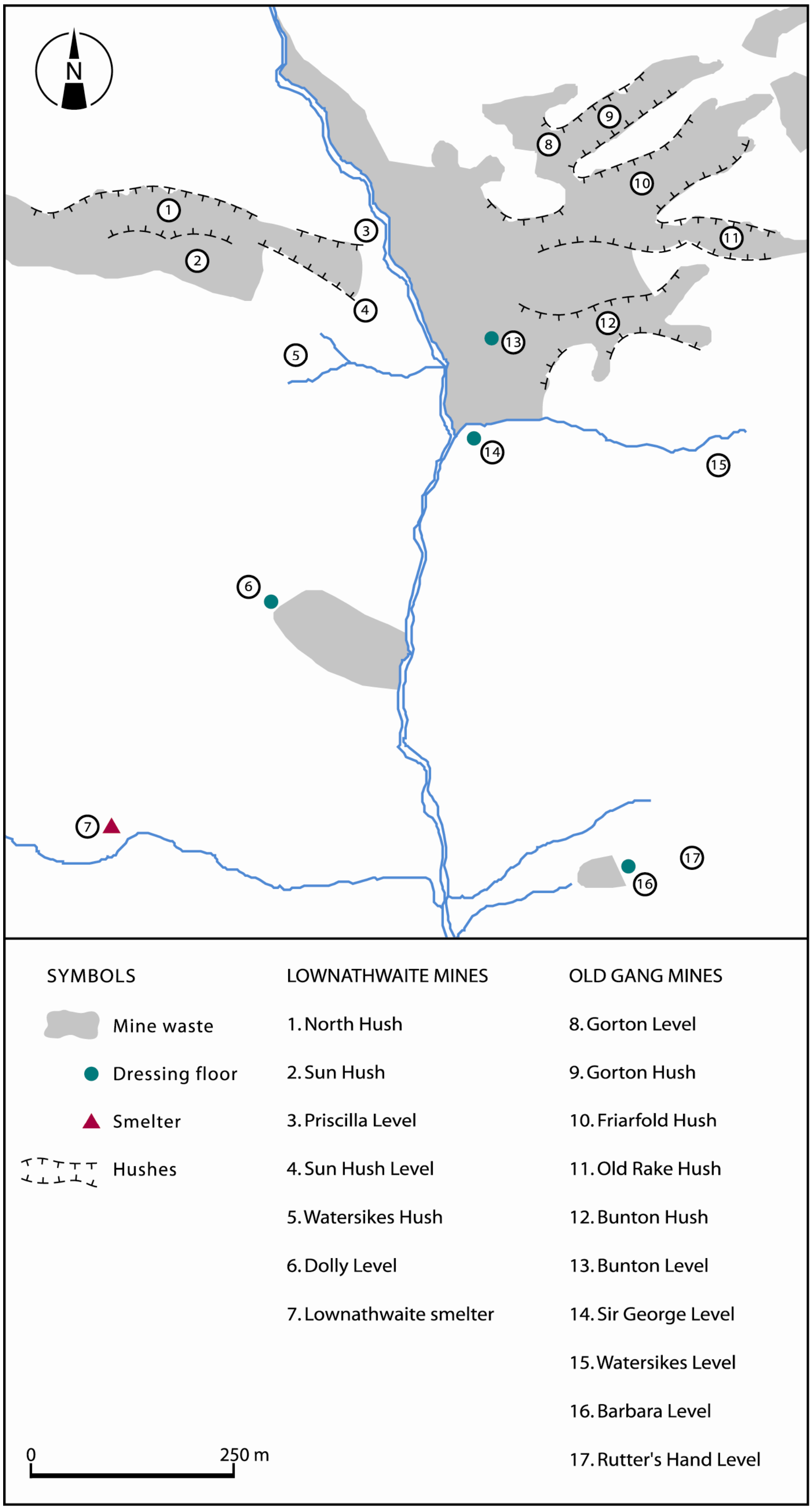

Figure 4.5: The Lownathwaite and Old Gang mines

that work started in North, Sun and Watersikes hushes prior to 1676 (Raistrick and Jennings, 1965; Dunham and Wilson, 1985) (Plate 4.5). Activities became more intensive during the late seventeenth century, and a series of shafts were sunk to gain access to ore bodies that could not be exploited through hushing. These mines proved extremely productive, making a profit of £5117 over an eighteen month period, despite problems caused by extensive '*Old Man*' workings (Raistrick and Jennings, 1965). Small scale extraction continued throughout the eighteenth century, and by 1769, lead output had risen sufficiently for a smelter to be constructed on the northern bank of Botcher Gill (NY 934006) (Raistrick, 1975a; Gill, 2001). It is likely that production up to and including this period was focussed on North Hush (NY 935014). A series of new levels were driven during the early nineteenth century. The most productive of these was Dolly Level (NY 938009), which was equipped with its own dressing floor and water-powered crusher. Again, however, the slump in lead prices in the early 1830s led to a rapid decline in output.

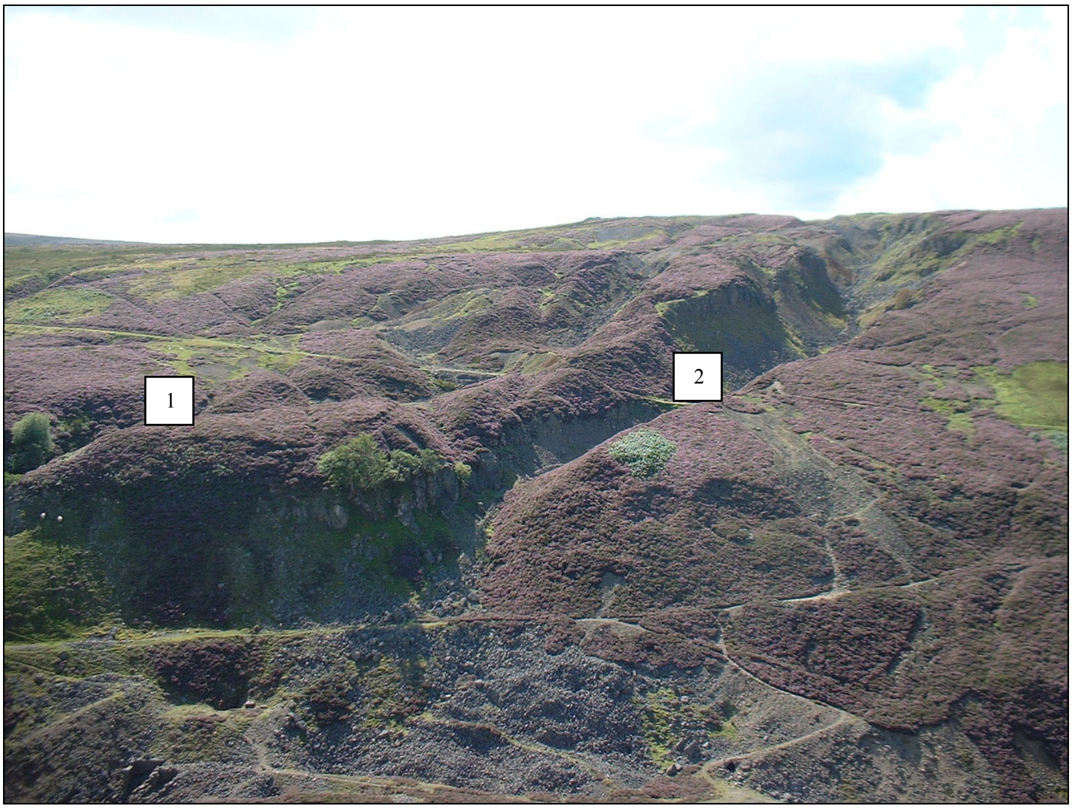

Plate 4.5: Sun Hush (1) and North Hush (2), divided by a narrow ridge

This decline was relatively short lived, and a number of new levels were driven during the 1840s. Blind Gill Level (NY 935018) was situated to the north of the main complex, on the southern bank of Blind Gill. This was highly productive for a short time, but became waterlogged and was closed down (Dunham and Wilson, 1985; Gill, 2001). Work on Sun Hush and Priscilla Levels, both located in Sun Hush (NY 938012), also began at this time. These levels proved more productive, and work continued until the 1860s. The dressing floor was located within the hush, but this has now been largely eroded away (Gill, 2001). Priscilla, Sun Hush and Dolly Levels were reopened in 1874, and good quality ore was raised in 1876. Mining at Lownathwaite effectively ended at this time, since the underlying veins were accessed through new workings at Sir Francis Level (Section 4.3.5).

4.3.4. The Old Gang mines

The Old Gang mines are located on the eastern side of Gunnerside Beck, opposite the Lownathwaite complex (Figure 4.5). These mines extend eastwards into Barney Beck, and are marked by a series of large hushes. It is likely that large quantities of lead ore were extracted from Gorton, Friarfold, Old Rake and Bunton (or Bunting) hushes from before 1670 until after 1770 (Raistrick, 1975b; Dunham and Wilson, 1985). The practice of hushing had largely been abandoned by the early nineteenth century, however, and a series of shafts and levels were driven to gain access to deeper ore bodies. Gorton Level (NY 942015) was driven at some point shortly before 1800, but had been abandoned for some time by 1824 (Gill, 2001). Extraction was difficult, but sufficient ore was raised to necessitate the construction of a dressing floor at what became known as Bunton Level (NY 940012) (Plate 4.6). Bunton Level was the main focus of activity in the Old Gang mining area. Work may have commenced as early as 1802, and ore was extracted until at least 1814. However, waterlogging and trouble with '*Old Man*' workings forced the closure of the level, which was abandoned by 1824 (Gill, 2001). Bunton Level was reopened in 1828, and the dressed ore was taken back through the level to be smelted at the Old Gang smelt mills in Barney Beck. The dressing floor was refurbished in the mid 1850s to enhance the processing of poor quality ore from the Friarfold vein. A particularly rich oreshoot was reached in 1866, however, and worked until the early 1870s. Ore continued to be raised until 1884, and all workings were abandoned in 1887 (Gill, 2001).

Work began on Watersikes (NY 943011) and Barbara (NY 942006) Levels during the 1820s, but these trials were generally abortive and little ore was raised. Kinning Level (NY 955993) was opened on the hills above the village of Gunnerside in the 1840s, and

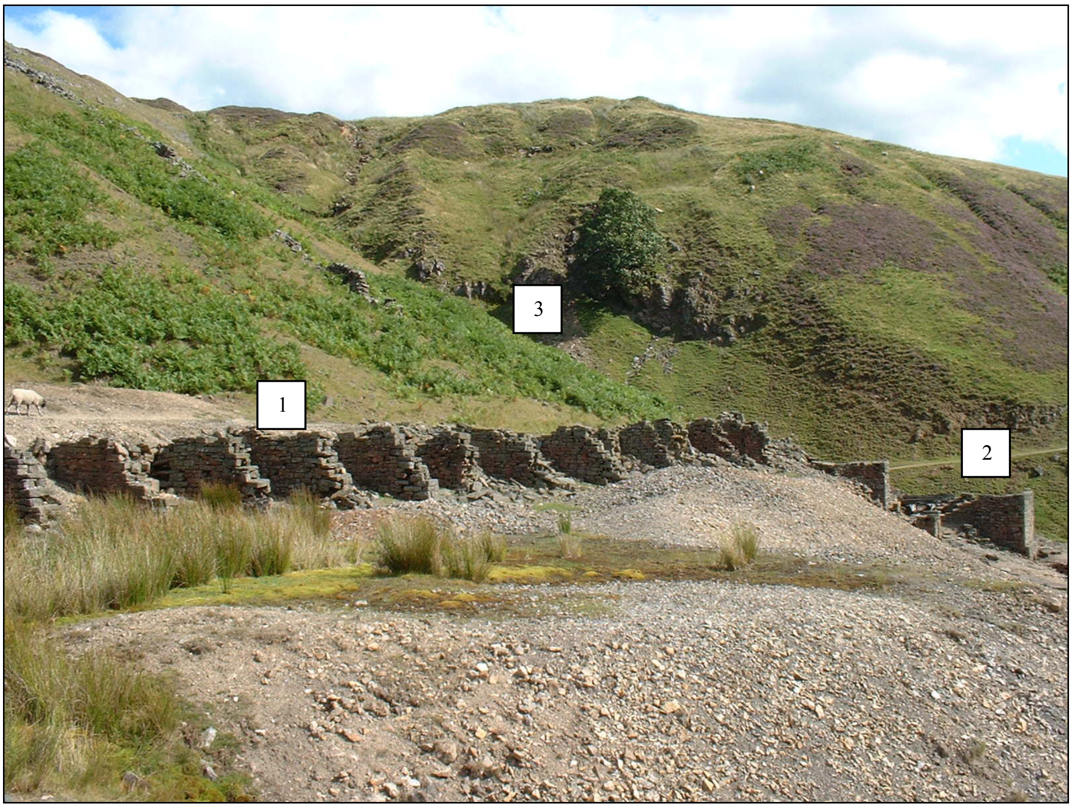

Plate 4.6: Bouse teams (1) and the remains of a crushing mill (2) at Bunton Level dressing floor. The entrance of Bunton Hush can be seen in the background (3)

some ore was dressed close to the level entrance in the 1850s and early 1860s. The level was not a major producer of ore, however, and was closed at some time after 1862 (Gill, 2001). Sir George Level (NY 940011) was driven during the early 1850s to give access to mineral veins too deep to be exploited from Bunton Level (Dunham and Wilson, 1985). Sir George and Barbara Levels were reopened during the early 1860s, and a dressing floor, now destroyed by landslips, was built at the former (Gill, 2001). Bunton Level was reopened in 1889, and ore was raised from this and Rutter's Hand Level, behind Barbara Level, during the early 1890s. However, output began to fall by the middle of the decade, and the workings were finally closed in 1898 (Gill, 2001).

4.3.5. Sir Francis Level

Sir Francis Level is located to the south of the other major mines in the Gunnerside Beck catchment (NY 940001) (Figure 4.1). Work commenced in 1864, but the hard rocks into which the level was cut made progress slow (Gill, 2001). Compressed air drills were introduced in 1870, to be replaced by dynamite blasting in 1873. This greatly increased the rate of progress, and the first ore was raised in 1877 (Raistrick, 1975b). The veins were extremely productive, and dressing floors were built by the AD Company (SD 940998) (Plate 4.3) and Old Gang Company (SD 942996) to process the ore. Records suggest that the AD Company had produced £32,000 worth of ore by 1880 (Raistrick, 1975b). However, production ceased in 1882 due to a slump in the lead market. Small amounts of ore were raised in the late 1890s, but this quickly became uneconomical and the mines closed by the end of the century (Gill, 2001).

4.3.6. Summary: The legacy of mining in Gunnerside Beck

The extensive mining operations described in this section have greatly increased the supply of sediment to the Gunnerside Beck system. Mining activities such as hushing periodically released large volumes of sediment into the river over a short time, including many cobble- and boulder-sized clasts. This is likely to have had a major geomorphic impact on the Gunnerside catchment (Merrett, 2001), resulting in the 'active transformation' of the fluvial system downstream of the input (Lewin and Macklin, 1987) and ultimately leading to the creation of the coarse-grained depositional features described in Section 4.2.3. The techniques employed to process the lead ore, particularly crushing and sorting, produced large volumes of fine-grained, metal-rich sediment (Sections 2.2.2 and 2.3.1). Much of this material was stored on the extensive spoil tips that are clearly in evidence on and around all the principal dressing floors. However, large quantities of this highly contaminated sediment were discharged directly into the river channel, in the form of particles suspended in waste water from crushing mills and ore sorting apparatus. These fine sediments are likely to have been transported alongside the uncontaminated natural suspended load with minimal impact on the geomorphology of the river (Lewin and Macklin, 1987), and would eventually become incorporated within depositional features such as bars, boulder berms and floodplains. This has caused the severe contamination of alluvial units within the catchment.

Mining has therefore had two principal impacts on the Gunnerside catchment. First, the episodic input of large volumes of coarse sediment from hushing into the river system is likely to have caused considerable geomorphological adjustment and the widespread formation of coarse depositional features. Second, the introduction of metal-rich, fine grained sediment directly from mineral processing while the mines were operational and indirectly through the erosion of spoil tips during high flows is likely to have severely contaminated floodplain soils and channel sediments throughout the Gunnerside Beck catchment. The nature and extent of contamination and changes to fluvial geomorphology will be evaluated in the subsequent sections.

4.4. THE IMPACT OF MINING ON CATCHMENT GEOCHEMISTRY

4.4.1. Introduction

The extensive mining operations described in Section 4.3 have left a lasting legacy of metal contamination in the Gunnerside Beck catchment. Contaminated sediment released by mining activities is stored in three principal sinks: abandoned spoil tips, floodplain soils and active channel sediments. The distribution of metals within each of these primary sinks will be assessed in turn, and particular 'hotspots' of contamination will be identified.

4.4.2. Methods

In order to evaluate the extent and severity of contamination within the Gunnerside Beck study catchment, a high-resolution geochemical investigation was undertaken in a 6.5 km long study reach, from the upper Blakethwaite dam to the confluence with the River Swale (Figure 4.6). Active channel sediments, collected using a stainless steel trowel, were sampled during low flow conditions at intervals of between 50 and 100 metres. Floodplain cores were collected at similar intervals, depending on the availability of suitable sedimentary units, using a stainless steel Edelmann auger. Samples of mine spoil were collected from waste tips located close to the river channel, using a stainless steel trowel. The 2000-63 μm and <63 μm size fractions from each sample were digested in HNO_3 for one hour at 100°C prior to comprehensive geochemical analysis using ICP-MS. Full details of sample collection, preparation and analysis can be found in Chapter 3. Full data are presented in Appendix 1. All geochemical results were incorporated into a GIS of the Gunnerside Beck catchment to allow spatial patterns of contamination to be easily identified.

4.4.3. Patterns of metal dispersal in mine waste

Samples of mine spoil collected from sites adjacent to the river channel display a significant degree of contamination, with extremely elevated metal concentrations

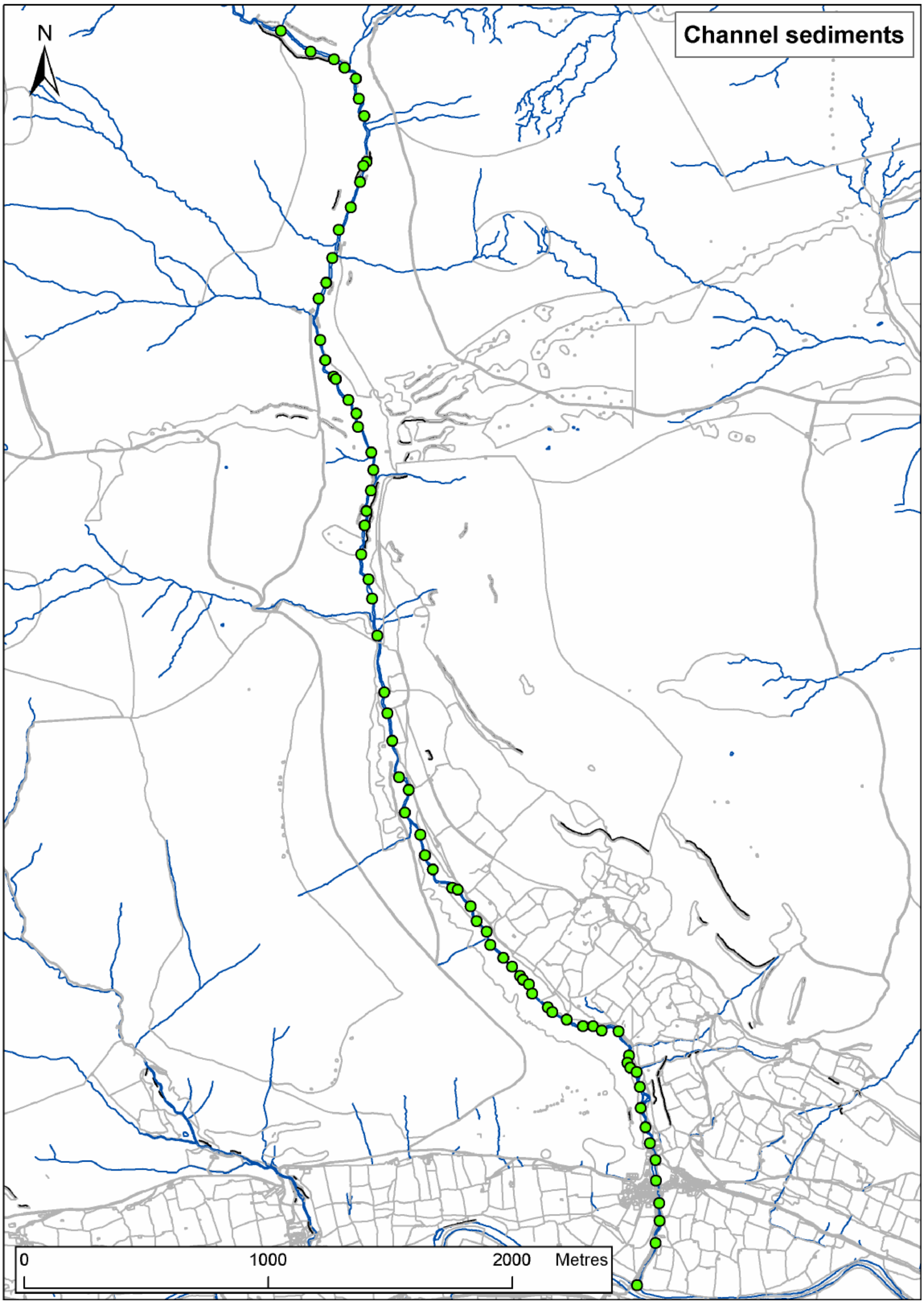

Figure 4.6 (a): Channel sediment sample sites (green circles) in Gunnerside Beck

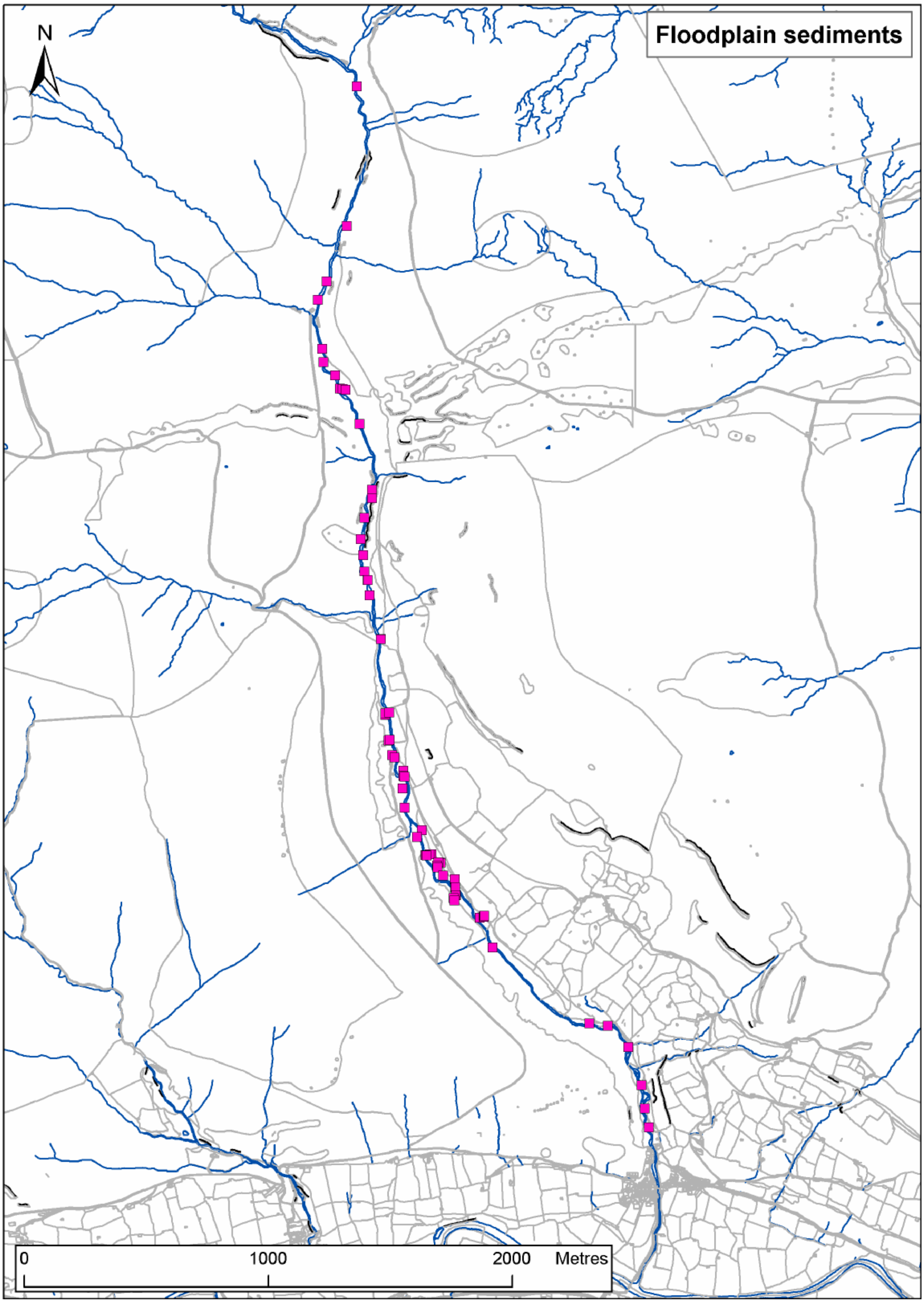

Figure 4.6 (b): Floodplain sediment sample sites (purple squares) in Gunnerside Beck

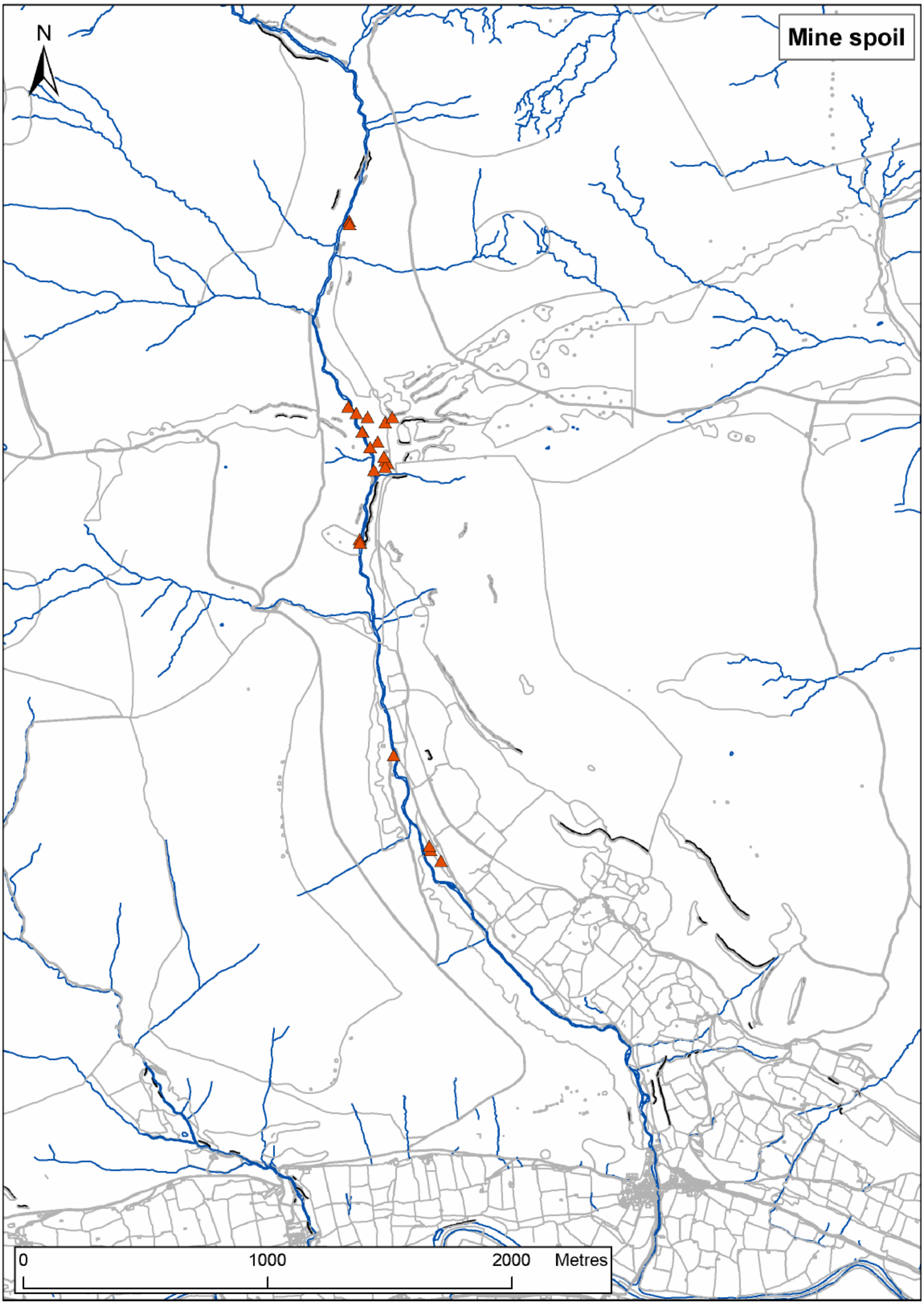

Figure 4.6 (c): Mine spoil sample sites (red triangles) in Gunnerside Beck

observed in spoil tips throughout the catchment (Figures 4.7 and 4.8). The highest metal concentrations (65,000 mg kg^{-1} Pb in both the silt and clay and sand size fractions) are recorded in samples collected from the Blakethwaite dressing floor. Further downstream, the extensive spoil tips surrounding the Old Gang and Lownathwaite workings contain Pb in concentrations of up to 45,000 mg kg^{-1}. Metals such as Zn, Cd, Ba, Ni, Cu and As are also found in high concentrations (up to 7800 mg kg^{-1}, 203 mg kg^{-1}, 5400 mg kg^{-1}, 93 mg kg^{-1}, 500 mg kg^{-1} and 46 mg kg^{-1}, respectively). The waste tips on Sir Francis Level also exhibit high concentrations of a variety of metals (up to 18,000 mg kg^{-1} Pb, 5600 mg kg^{-1} Zn, 460 mg kg^{-1} Cd, 10,300 mg kg^{-1} Ba, 115 mg kg^{-1} Ni, 140 mg kg^{-1} Cu and 64 mg kg^{-1} As). Several waste tips, notably adjacent to Priscilla Level and on the Old Gang dressing floor at Sir Francis Level, contain only background metal concentrations.

This shows that mine spoil samples collected from Gunnerside Beck are extremely rich in metals, with particular enrichment observed on the Blakethwaite and Bunton Level dressing floors. The 'background' metal concentrations observed on several spoil tips, however, suggest that there is some differentiation between types of mine spoil in the catchment. Waste dumps fall into two broad categories: relatively uncontaminated waste tips comprised of large, angular fragments of bedrock, and highly contaminated spoil tips containing the detritus from the latter stages of ore processing (*cf.* Benvenuti *et al.*, 1997). It is the fine-grained sediment stored within the latter that is likely to have a significant impact on the chemistry of the wider Gunnerside Beck catchment.

4.4.4. Patterns of metal dispersal in floodplain sediments

Metal concentrations in floodplain sediments from the Gunnerside Beck catchment display a distinct downstream trend (Figures 4.9 and 4.10). Pb, Zn and Cd concentrations increase downstream of the primary inputs of metal to the system, *e.g.* downstream of Blakethwaite dressing floor, the Old Gang and Lownathwaite hushes and dressing floors, and the dressing floors at Sir Francis Level. The most contaminated floodplain sites are located immediately downstream of the Old Gang and Lownathwaite workings and on Sir Francis Level (22,400 mg kg^{-1} and 21,500 mg kg^{-1} Pb in the 2000-63 μm fraction and 11,000 mg kg^{-1} and 14,500 mg kg^{-1} Pb in the <63 μm fraction, respectively), although an exceptionally large peak associated with a flattened spoil tip can be observed upstream of the hushes. The larger peaks in metal concentrations rapidly attenuate downstream of

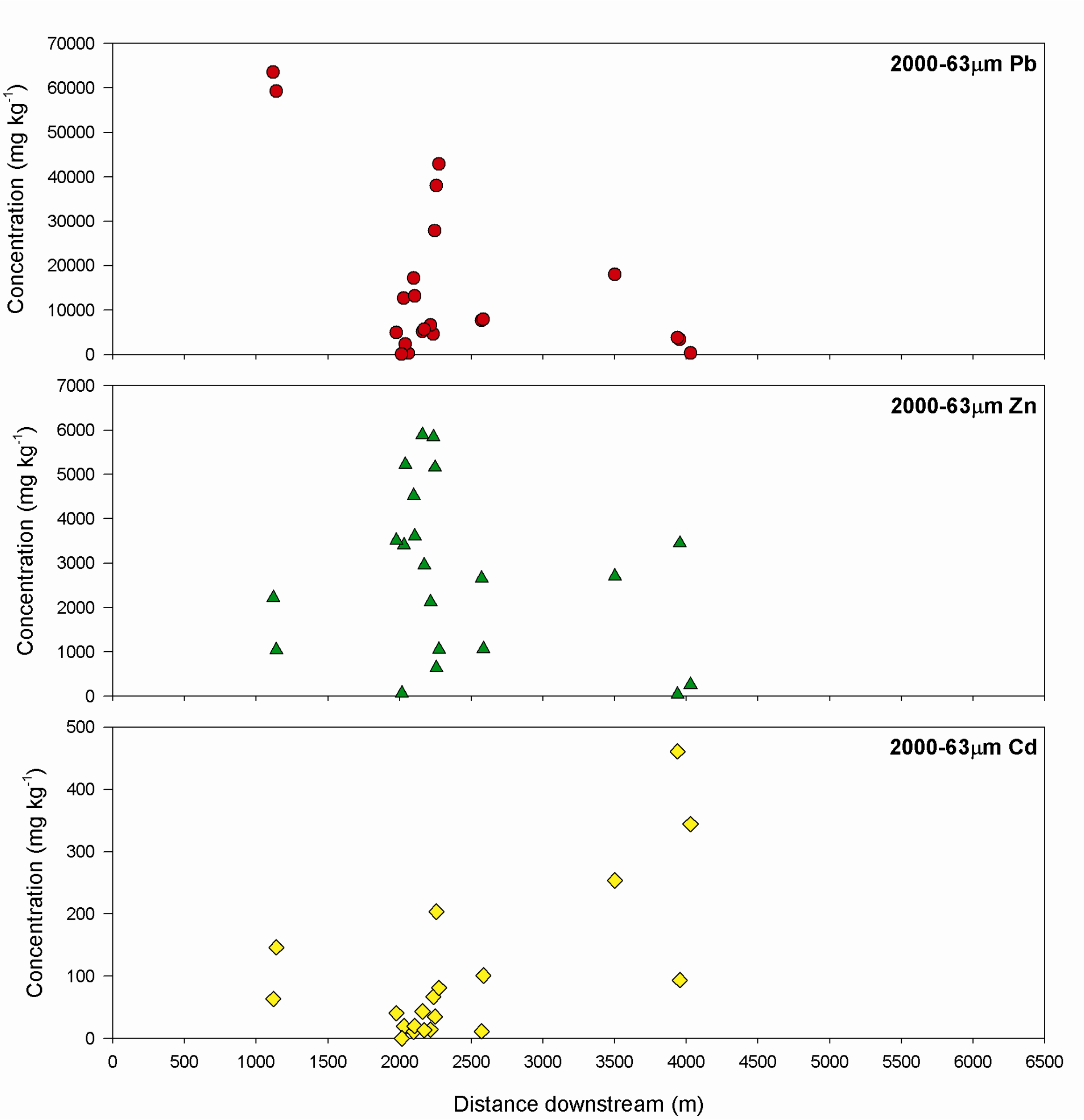

Figure 4.7: Pb, Zn and Cd concentrations in 2000-63 μm Gunnerside Beck mine spoil. Samples with low concentrations were derived from bedrock tips from the earlier stages of ore processing

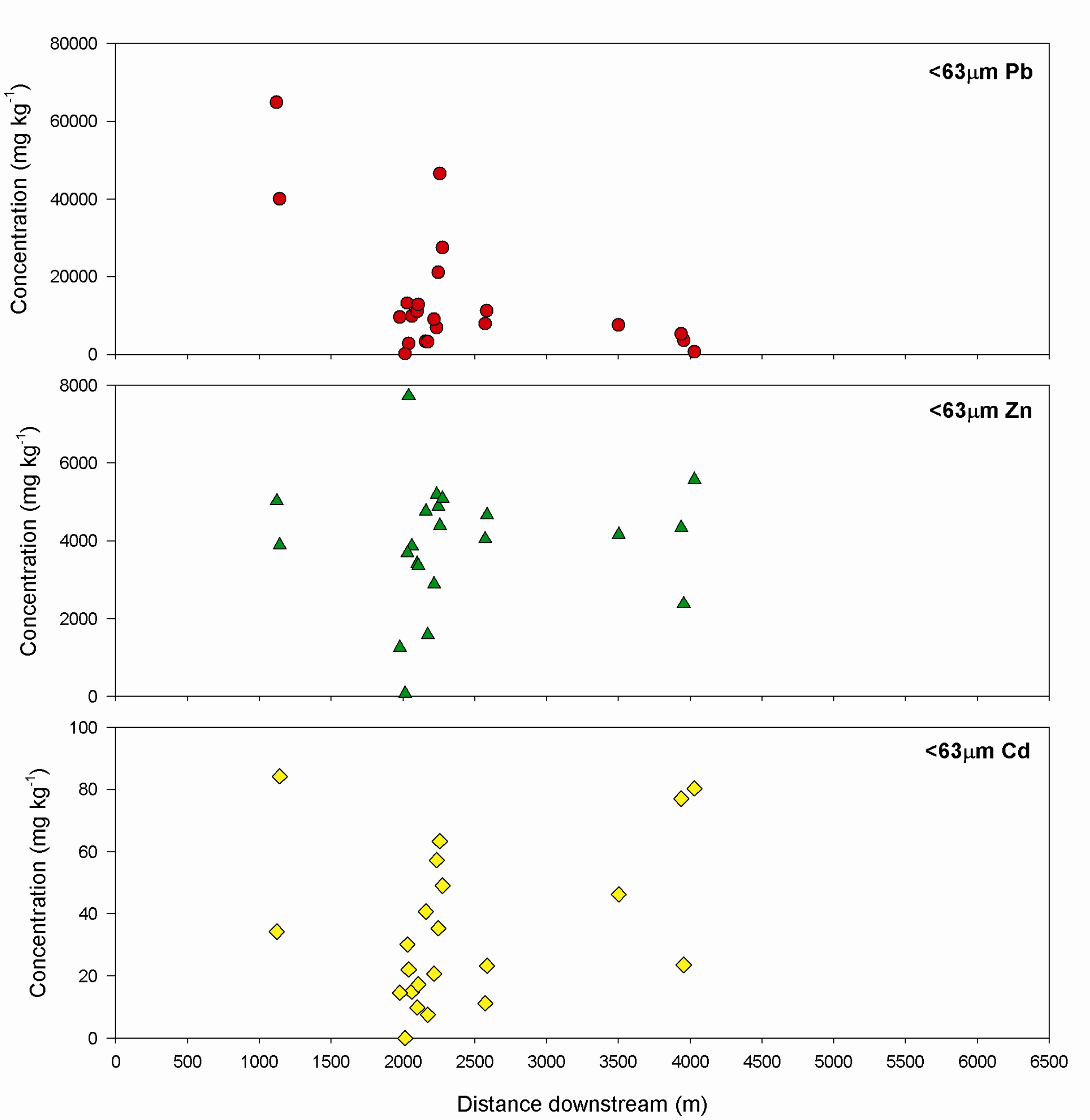

Figure 4.8: Pb, Zn and Cd in <63 μm Gunnerside Beck mine spoil. Samples with low concentrations were derived from bedrock tips from the earlier stages of ore processing

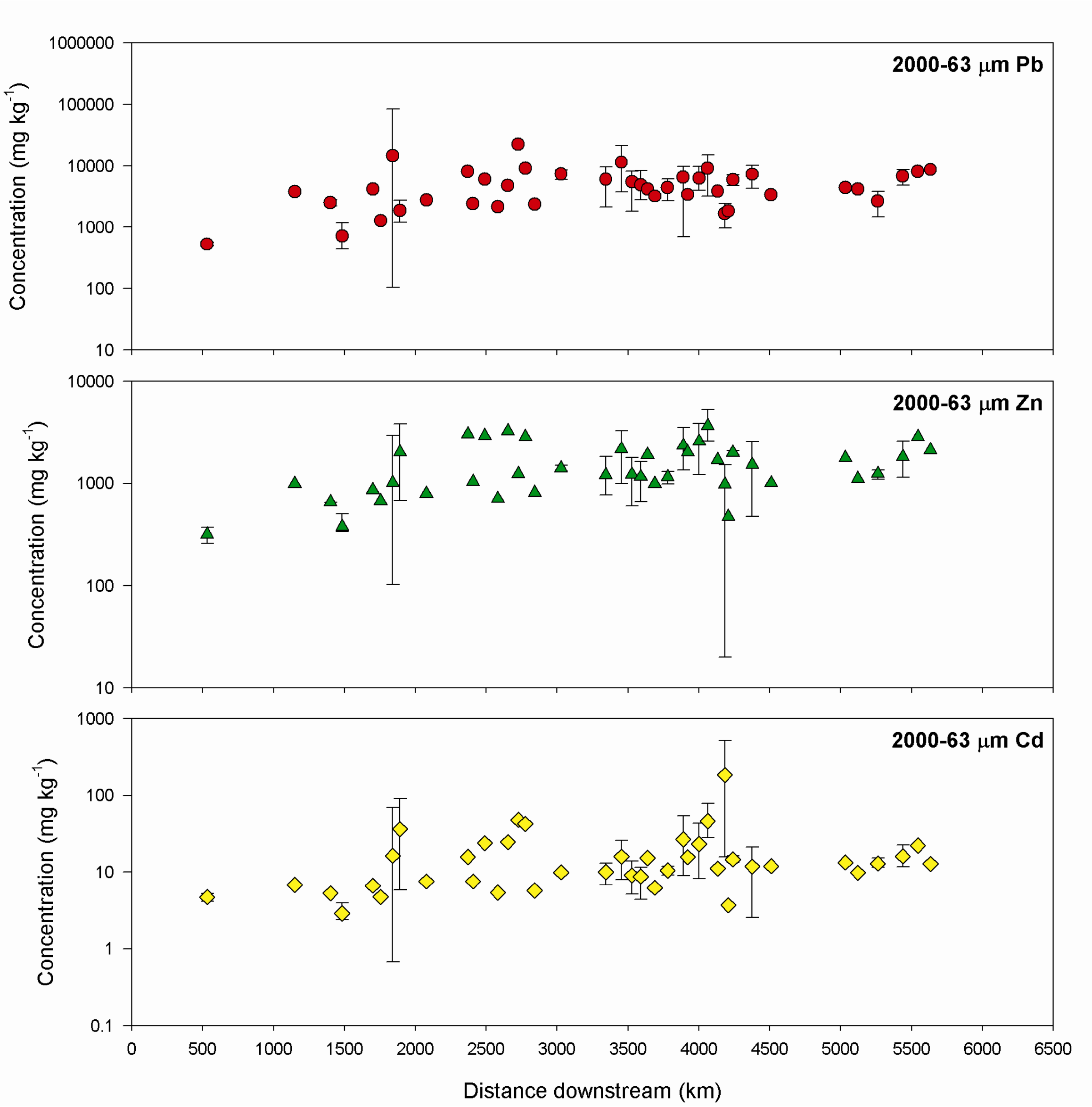

Figure 4.9: Pb, Zn and Cd concentrations in 2000-63 μm Gunnerside Beck floodplain sediments. Points without range bars indicate results for single samples, and points with range bars represent results from floodplain cores (mean, minimum and maximum concentrations are shown)

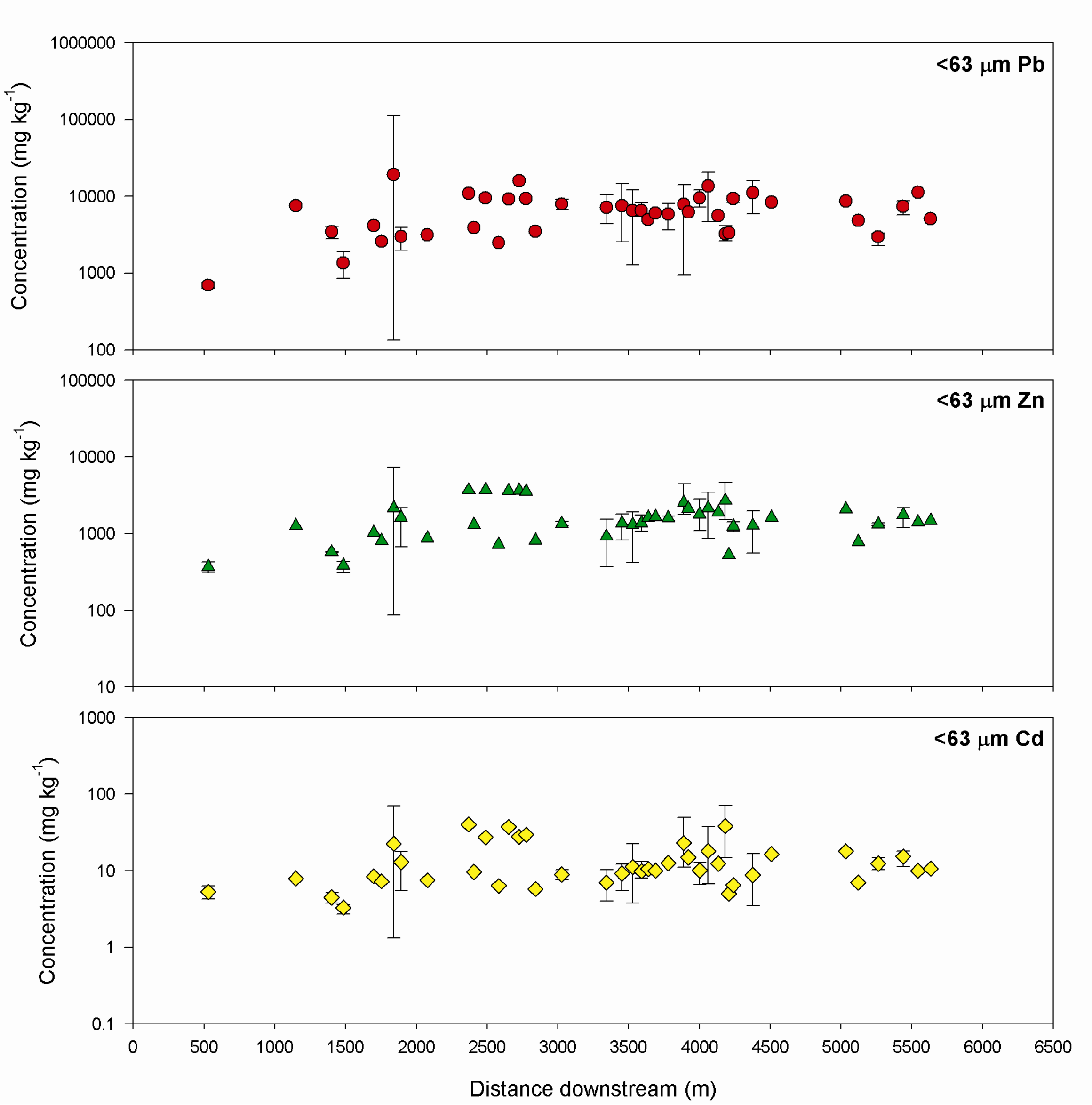

Figure 4.10: Pb, Zn and Cd concentrations in <63 µm Gunnerside Beck floodplain sediments. Points without range bars indicate results for single samples, and points with range bars represent results from floodplain cores (mean, minimum and maximum concentrations are shown)

each input of metal-rich material, although this trend is less marked in the lower reaches, particularly in the alluvial reach downstream of Sir Francis Level. Metal concentrations in the lower reaches of the catchment, downstream of the mines, are generally greater than those recorded upstream of the principal mining zone. Concentrations appear to be greatest in areas with a wide valley floor, possibly reflecting the preferential accumulation of sediment in these reaches (Macklin and Lewin, 1989; Marron, 1989). However, this signal may be partially masked by localised peaks in floodplain metal concentrations immediately downstream of mine waste inputs, and in zones of channel narrowing, immediately upstream of an obstacle to flow such as a bedrock gorge.

This suggests that geomorphological factors such as gradient, channel width and valley floor width may play an important role in controlling the downstream distribution of metals in floodplain sediments in Gunnerside Beck. However, regression analysis suggests that variations in these parameters do not explain a large proportion of the variation observed in metal concentrations (Table 4.1). Furthermore, the weak relationships suggested by the regression analysis are not statistically significant (p = >0.05). It may generally be expected that metal accumulation would be at its greatest in wide, low gradient 'storage' reaches (*cf.* Macklin, 1996). However, there is insufficiently strong evidence to suggest that any of these factors, with the possible exception of gradient, play a major role in determining downstream metal dispersal patterns in floodplain sediments. The results of the regression analysis therefore imply that metal dispersal in floodplain sediments is not solely a function of simple relationships between geomorphological parameters. Other factors, including the location of sediment inputs, variations in metal and sediment load, historical flood discharge and floodplain inundation patterns, are likely to play an important role in determining downstream metal dispersal.

Metal concentrations are generally elevated throughout the depth profile, although considerable variation can be observed. In reaches with thin floodplain soils, concentrations of Pb, Zn and Cd are generally greatest in surface sediments (0-20 cm depth). Subsurface sediments also contain high concentrations of metals, although observed levels are lower than in surface deposits. In reaches with greater accumulations of floodplain sediment (greater than 60 cm), metal concentrations are greatest in surface sediments and in subsurface deposits between 60 and 80 cm deep. Evidence from cut bank profiles upstream of the Old Gang and Lownathwaite mines indicates that metal

Table 4.1: Multiple regression results: The relationship between metal concentrations and geomorphological parameters in Gunnerside Beck floodplain sediments

Sediment	r^2	Significance level (p)	Individual parameters	
<63 μm	0.111	0.221	Gradient	0.106 (-)
			Channel width	0.002 (-)
			Valley width	0.045 (+)
2000-63 μm	0.027	0.796	Gradient	0.026 (-)
			Channel width	0.000
			Valley width	0.005 (+)

concentrations are greatest in fine sandy-gravel layers within the floodplain (up to 9000 mg kg^{-1} Pb, 3000 mg kg^{-1} Zn and 25 mg kg^{-1} Cd in 2000-63 μm sediments and 1200 mg kg^{-1} Pb, 4400 mg kg^{-1} Zn and 54 mg kg^{-1} Cd in <63 μm sediments), which are likely to be the remains of mining-era gravel splays incorporated into the floodplain. In the thick floodplain at Sir Francis Level, however, these gravel splays are less prominent features and highest metal concentrations are observed in fine-grained vertical accretion deposits (reaching a maximum of 9600 mg kg^{-1} Pb, 2500 mg kg^{-1} Zn and 54 mg kg^{-1} Cd in 2000-63 μm sediments and 14,000 mg kg^{-1} Pb, 4500 mg kg^{-1} Zn and 50 mg kg^{-1} Cd in <63 μm sediments).

Metal concentrations display a marked lateral variation across floodplain units. The highest metal concentrations are frequently found within fine sediments incorporated into the numerous coarse-grained flood deposits on the floodplain surface (reaching a maximum of 23,000 mg kg^{-1} Pb, 4000 mg kg^{-1} Zn and 45 mg kg^{-1} Cd in the 2000-63 μm size fraction and 16,000 mg kg^{-1} Pb, 3600 mg kg^{-1} Zn and 38 mg kg^{-1} Cd in the <63 μm size fraction), which are likely to have been formed during the peak of mining operations between 1822 and 1908 (Merrett, 2001). In addition, features such as palaeochannels on the terrace surface also act as foci for the accumulation of metals (Lewin *et al.*, 1977; Marron, 1992; Brewer and Taylor, 1997). Besides these deposits, Pb, Zn and Cd concentrations are generally greatest on the lowest terrace surfaces and, where they are present, on the highest terrace fragments. Intermediate terraces are, almost without exception, the least contaminated areas of the floodplain. This pattern is likely to be attributable to variations in the relative proportions of contaminated and uncontaminated sediments delivered to different parts of the floodplain. The low-lying terraces which border the channel are likely to be regularly inundated during lower overbank flows, when the ratio of easily erodible contaminated sediment, for example from unvegetated spoil tips, to uncontaminated sediment, for example from vegetated slopes, is greater (Leenaers, 1989; Graf *et al.*, 1991). This means that these surfaces receive large volumes of relatively undiluted metal rich sediment, and, as such, become the primary focus of metal accumulation. In contrast, the intermediate terraces are more likely to be inundated during periods of higher flow, and therefore metals stored in this zone may become diluted with uncontaminated material (*cf.* Alloway and Davies, 1971; Rowan *et al.*, 1995). It is likely that the highest terraces were formed during the peak of mining operations, where flood magnitude was high and the system was strongly influenced by activities such as hushing (Merrett, 2001). Subsequent channel incision has stranded these features above the level of frequent inundation, so metals stored within them are not significantly diluted with less contaminated sediment (*cf.* Rowan *et al.*, 1995) (Figure 4.11). These lateral trends are less marked in the silt and clay size fraction than in the sand size fraction, reflecting the greater ease with which the finer particles are transported across the floodplain surface during periods of inundation (Macklin, 1996).

4.4.5. Patterns of metal dispersal in channel sediments

Metal concentrations in active channel sediments collected within Gunnerside Beck display a distinct downstream trend, with a series of rapidly attenuating peaks observed downstream of sites of mining activity (*cf.* Lewin *et al.*, 1977; Wolfenden and Lewin, 1978; Axtmann and Luoma, 1991; Macklin, 1996) (Figures 4.12 and 4.13). A number of moderate peaks in metal concentrations can be observed in the upper reaches of the stream (up to 2500 mg kg^{-1} Pb, 3000 mg kg^{-1} Zn and 25 mg kg^{-1} Cd in 2000-63 μm sediments and 2600 mg kg^{-1} Pb, 850 mg kg^{-1} Zn and 6 mg kg^{-1} Cd in <63 μm sediments), principally downstream of the Blakethwaite dressing floor and, to a lesser extent, the Blakethwaite smelter and Blind Gill Level. Highest concentrations are observed downstream of the most intensively worked zone, where the Old Gang and Lownathwaite mining operations were focussed (reaching a maximum of 48,500 mg kg^{-1} Pb, 3300 mg kg^{-1} Zn and 50 mg kg^{-1} Cd in the 2000-63 μm size fraction and 22,000 mg kg^{-1} Pb, 3300 mg kg^{-1} Zn and 30 mg kg^{-1} Cd in the <63 μm size fraction). Elevated concentrations can also be observed

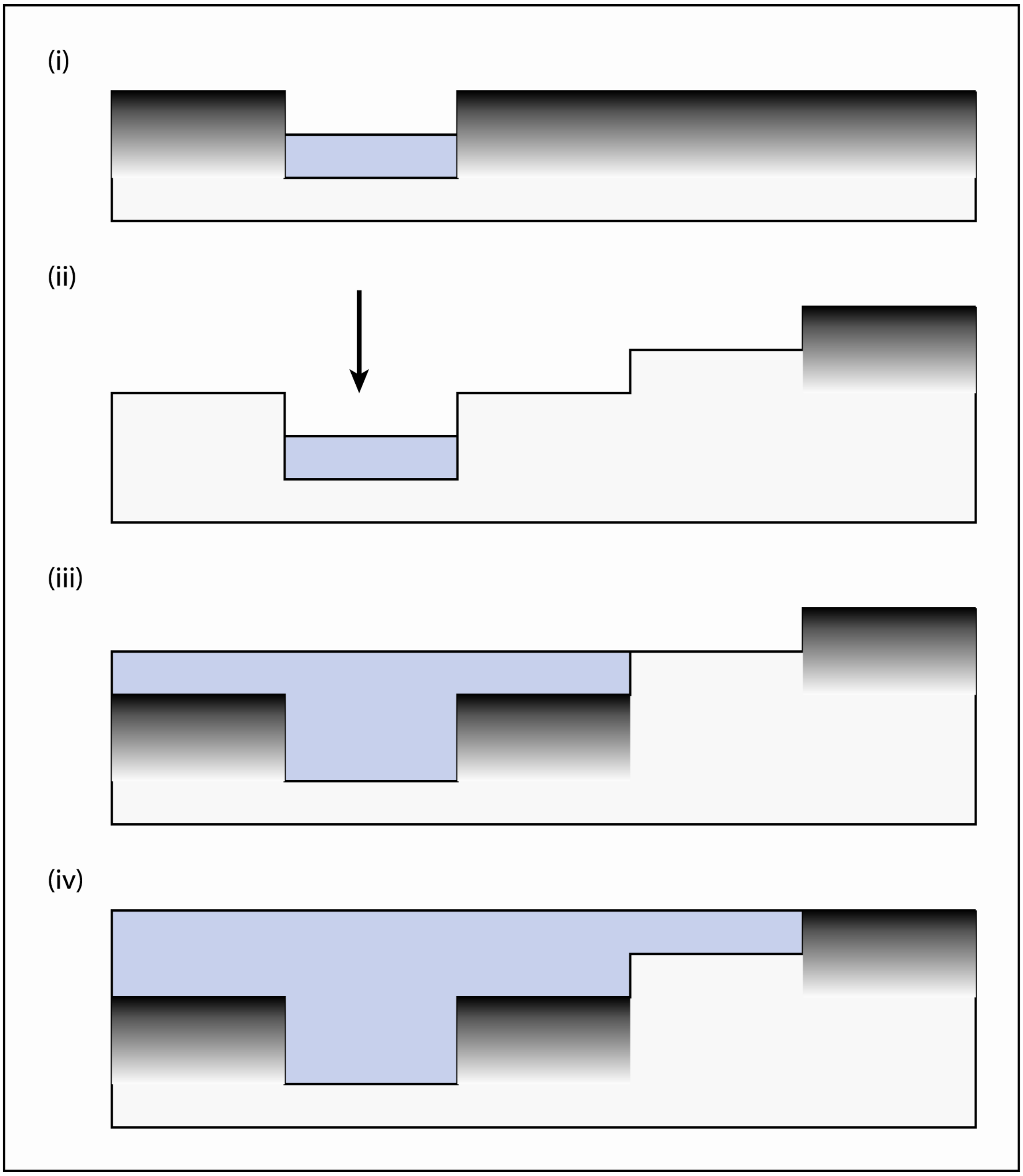

Figure 4.11: Floodplain contamination schematic

- *(i)* *Contaminated sediment distributed over floodplain surface*
- *(ii)* *Period of incision creates terraces and leaves old surface above the level of flooding*
- *(iii)* *Lower terrace surfaces inundated during moderate floods, when contaminants are not diluted*
- *(iv)* *Intermediate surfaces only inundated during large floods, when contaminants are considerably diluted*

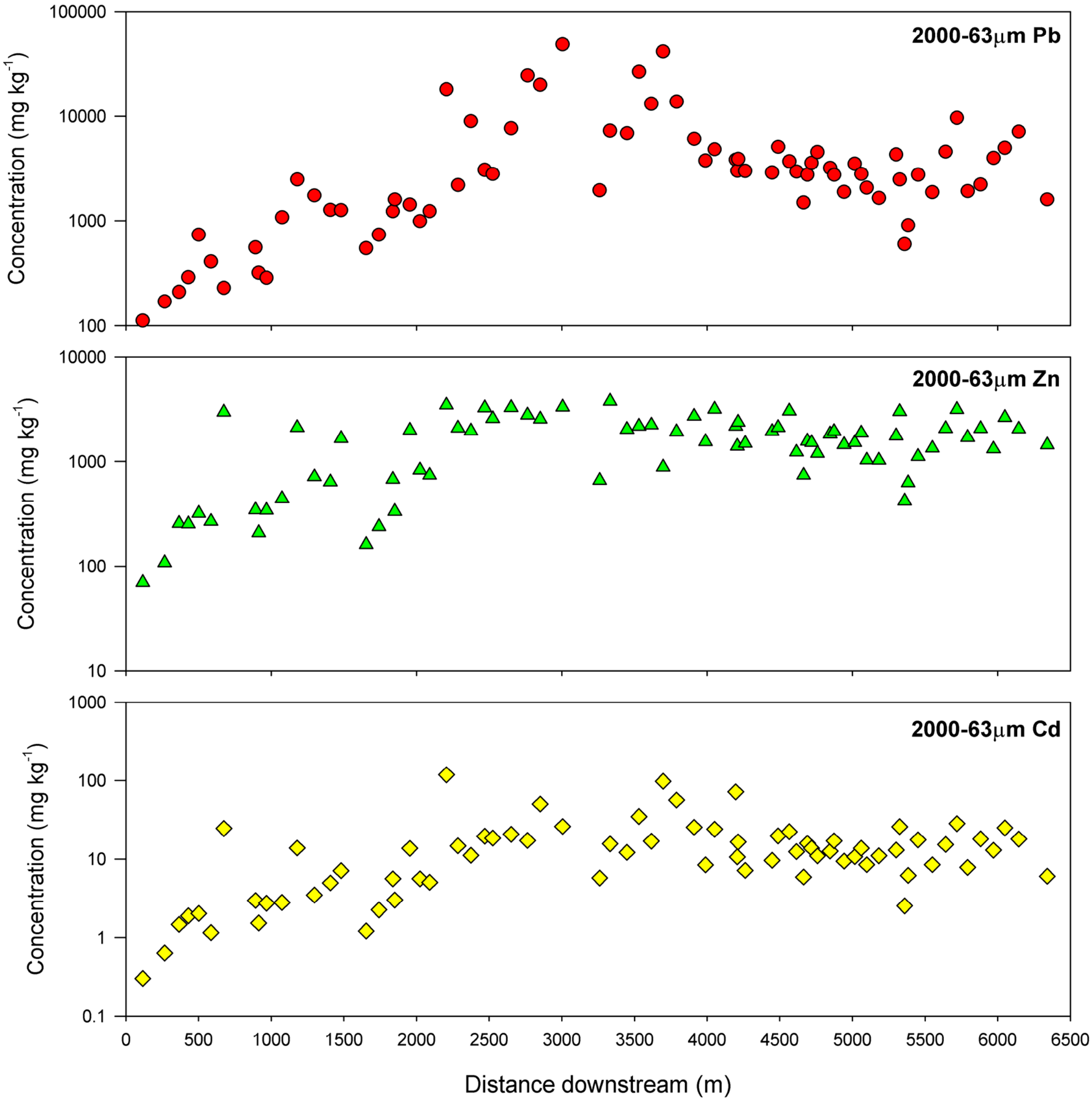

Figure 4.12: Pb, Zn and Cd concentrations in 2000-63 μm Gunnerside Beck channel sediments

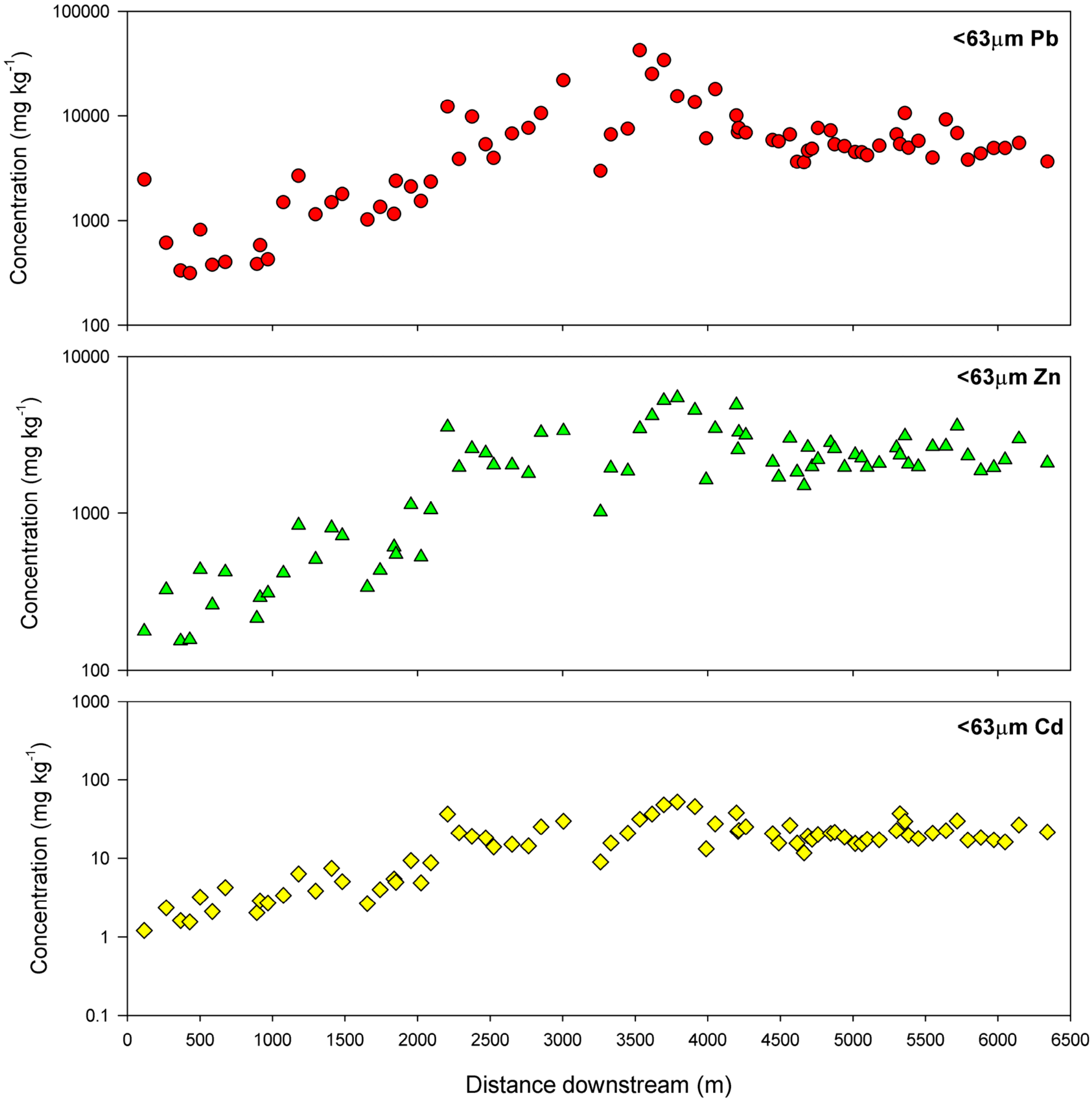

Figure 4.13 Pb, Zn and Cd concentrations in <63 μm Gunnerside Beck channel sediments

further downstream, where the channel flows through a wide alluvial reach on which were located the dressing floors of Sir Francis Level (41,500 mg kg^{-1} Pb, 2200 mg kg^{-1} Zn and 98 mg kg^{-1} Cd in the 2000-63 μm fraction and 42,000 mg kg^{-1} Pb, 5500 mg kg^{-1} Zn and 52 mg kg^{-1} Cd in the <63 μm fraction).

Metal concentrations remain elevated for a considerable distance downstream of the mine workings, reflecting the continued transport of contaminated sediment from spoil tips and floodplain sources (*e.g.* Leenaers, 1989; Miller, 1997). The decline in metal concentrations with distance from the source area is less marked than that observed in other catchments (*e.g*. Lewin *et al.*, 1977; Wolfenden and Lewin, 1978; Macklin, 1996; Bird *et al.*, 2003). This is partly attributable to the small size of the catchment and the distribution of mine waste inputs within it; there is not sufficient distance or inputs of 'clean' material for contaminated sediment to become diluted before the river reaches its confluence with the Swale. Secondly, the gradual downstream decline of contaminants is generally associated with systems where passive dispersal is dominant (Lewin and Macklin, 1987; Miller, 1997), and may not apply to actively transformed systems. Metal concentrations display a wave-like pattern that is most pronounced in the lower reaches of the catchment. This is likely to be attributable to the movement of contaminated sediment as a wave or 'slug' over the channel bed (Lewin and Macklin, 1987; Merefield, 1987; Nicholas *et al.*, 1995).

Geomorphological factors such as channel gradient, channel width and valley width are also likely to have an influence on downstream metal concentrations in channel sediments. Multiple regression analysis suggests that variation in these factors accounts for 42 % of the variation in metal concentrations in <63 μm channel sediments, and 29 % of the variation observed in 2000-63 μm channel sediments (Table 4.2). In both cases, these relationships are highly significant (p = <0.001). Each of these geomorphological factors is therefore likely to have a strong influence on the depositional conditions within a particular reach. The results of the regression analysis suggest that gradient has the strongest influence, with metal concentrations increasing with decreasing channel gradient. Gradient is likely to affect metal deposition primarily through influencing stream power, a measure of the potential energy of the river per unit length, area or weight of water (*e.g*. Richards, 1982). The physical properties of sediment particles interact with

Table 4.2: Multiple regression results: The relationship between metal concentrations and geomorphological parameters in Gunnerside Beck channel sediments

Sediment	r^2	Significance level (p)	Individual parameters	
<63 µm	0.422	<0.001	Gradient	0.242 (-)
			Channel width	0.188 (-)
			Valley width	0.128 (+)
2000-63 µm	0.293	<0.001	Gradient	0.138 (-)
			Channel width	0.129 (-)
			Valley width	0.112 (+)

stream power to determine rates of sediment transport; a decline in stream power can therefore lead to the initiation of sediment deposition. Metal concentrations are therefore greater in low-gradient reaches than in higher gradient reaches. The regression analysis suggests that valley width has a positive relationship with metal concentrations in channel sediments. This may reflect a degree of interdependence between valley width and gradient, since it is unlikely that valley width itself would strongly influence metal concentrations in channel sediments. Instead, this suggest that reaches with a wide valley floor (*i.e.* storage zones) generally have a low channel gradient, low stream power and large sediment storage capacity, leading to the preferential accumulation of metals in these sites. Conversely, narrow reaches (*i.e.* transport zones) generally have higher channel gradients, high stream power and more limited sediment storage capacity, and therefore exhibit much lower metal concentrations (Macklin and Dowsett, 1989; Macklin and Lewin, 1989; Macklin, 1996).

Perhaps unexpectedly, channel width has a negative relationship with metal concentrations. Given the likely importance of gradient in controlling metal deposition, it might be expected that metal concentrations would be higher in wider, low-gradient reaches than in adjacent narrower reaches. There are several possible explanations for this apparent discrepancy. For example, a decline in stream power in wider reaches may lead to the accumulation of uncontaminated sediments in the river channel, diluting metals in those areas. Alternatively, the increased metal concentrations in reaches with a narrow channel may be a reflection of the physical concentration of metal particles in a proportionally smaller area. This is likely to be particularly important in areas where metal-rich sediment is moving within a wave of bed-material. Furthermore, concentrations are frequently elevated in zones of channel and valley narrowing downstream of wider reaches, which may serve to effectively mask any trends to the contrary.

4.4.6. Grain size partitioning

Floodplain and channel sediments and fine-grained mine spoil samples from the Gunnerside Beck catchment are dominated by sand-sized material (2000-63 μm) (Figure 4.14). Proportions of silt and clay-sized material (<63 μm) are generally low, ranging between 2 and 28 % of floodplain sediments, 0.2 and 12 % of channel sediments, and 7 and 26 % of mine spoil samples. The proportion of fine sediment in floodplain deposits is greatest in the wide alluvial units at Sir Francis Level, but displays no clear downstream trend. Channel sediments show no clear downstream trend, although the variation appears to be greatest in the upper reaches of the catchment. Each of the major spoil tips sampled appears to display a similar degree of variation, suggesting that processing techniques were similar on each dressing floor.

In accordance with many other investigations, metal concentrations are generally at their greatest in the silt and clay size fraction (*e.g.* Brandvold *et al.*, 1995; Macklin, 1996). This is apparent in floodplain sediments and mine spoil samples throughout the catchment, and in channel sediments is most marked in the lower reaches of Gunnerside Beck, downstream of Sir Francis Level. However, several of the largest peaks in Pb and Cd concentrations are observed in the sand size fraction. This is particularly apparent in channel sediments, where, with the exception of a single large peak associated with the AD dressing floor at Sir Francis Level, concentrations immediately downstream of mine workings are generally greatest in the sand size fraction. The reasons for this pattern are twofold. First, metals display a high affinity for fine sediments, and concentrations are frequently greatest in the <63 μm size fraction (Gibbs, 1973; Förstner and Wittmann, 1979; Salomons and Förstner, 1984). Second, the crushing and grinding of lead ore is likely to have produced large quantities of sand-sized waste material, which was abandoned on spoil tips (Section 4.4.3). These coarse, dense, lead-rich particles are more difficult to transport during periods of low flow and as such are more likely to accumulate in channel and floodplain sediments downstream of mine workings. Conversely, finer particles are more readily transported in the suspended sediment load of the river, and are more likely to have been washed away from their point of origin and deposited further downstream.

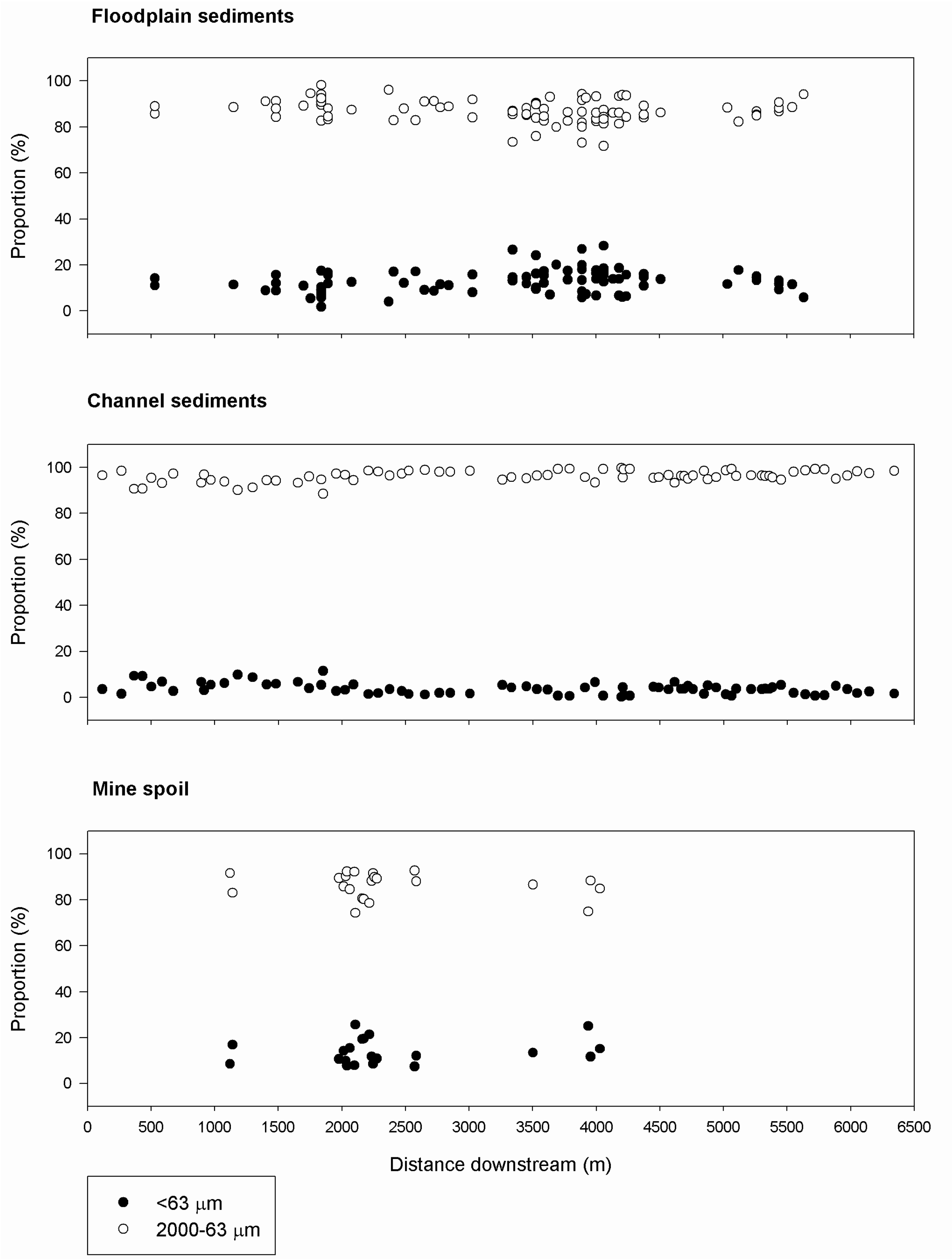

Figure 4.14: Grain size characteristics of Gunnerside Beck floodplain sediments, channel sediments and mine spoil

4.4.7. Summary: The geochemical legacy of mining in Gunnerside Beck

The results of the detailed geochemical investigation described above clearly show that the Gunnerside Beck catchment has been severely affected by historic mining activities. Both floodplain and active channel sediments contain high concentrations of metals such as Pb, Zn and Cd, as do the large mine waste tips which continue to supply contaminated sediment to the river system (summarised for Pb in Figures 4.15 and 4.16).

The highest metal concentrations in the floodplain are observed within mining-era flood deposits such as boulder berms and gravel splays. However, even greater metal concentrations are observed in active channel sediments downstream of the principal dressing floors. This does not necessarily suggest that contemporary sediments are more contaminated than mining-era deposits. Instead, it is more likely that the active channel sediments, collected during a period of low flow, represent a temporary accumulation and concentration of metals (*cf.* Ciszewski, 2001), which cannot be directly compared to mining-era flood deposits. It is important to note, however, that levels of contamination in contemporary sediments have not decreased greatly from those found in mining-era sediments, and that metal-rich material from abandoned mine workings continues to be supplied to the river in appreciable quantities.

The distribution of metal contaminated sediment within floodplain and active channel sediments in the Gunnerside Beck catchment is likely to be strongly influenced by both the location of mine waste inputs and the fluvial geomorphology of the catchment. Metal concentrations in floodplain and channel sediments increase markedly downstream of mine waste inputs such as dressing floors and hushes (Figures 4.15 and 4.16). These peaks attenuate rapidly, but concentrations remain elevated even at the confluence between Gunnerside Beck and the River Swale. Geomorphological factors such as gradient, valley width and channel width also have a strong influence on metal concentrations, particularly in channel sediments, probably through controlling depositional conditions within the river system.

It is clear that metal-rich sediment released from lead mining and processing operations has had a major impact on the geochemistry of floodplain and channel sediments in the Gunnerside Beck catchment, and that the distribution of contaminated sediments is strongly influenced by the geomorphology of the catchment. Equally, it is also highly

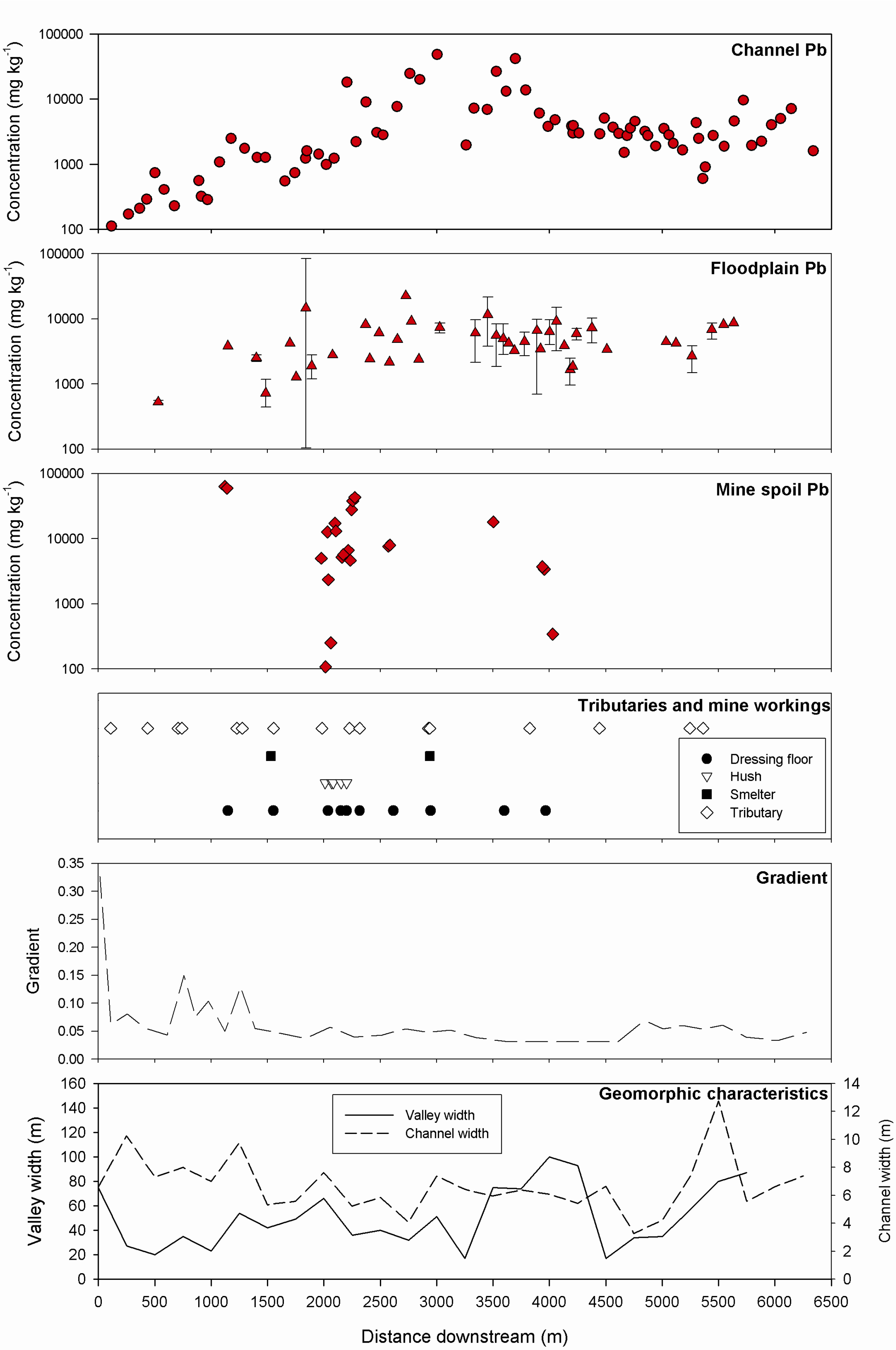

Figure 4.15: Gunnerside Beck 2000-63 µm Pb concentrations, waste inputs and catchment characteristics

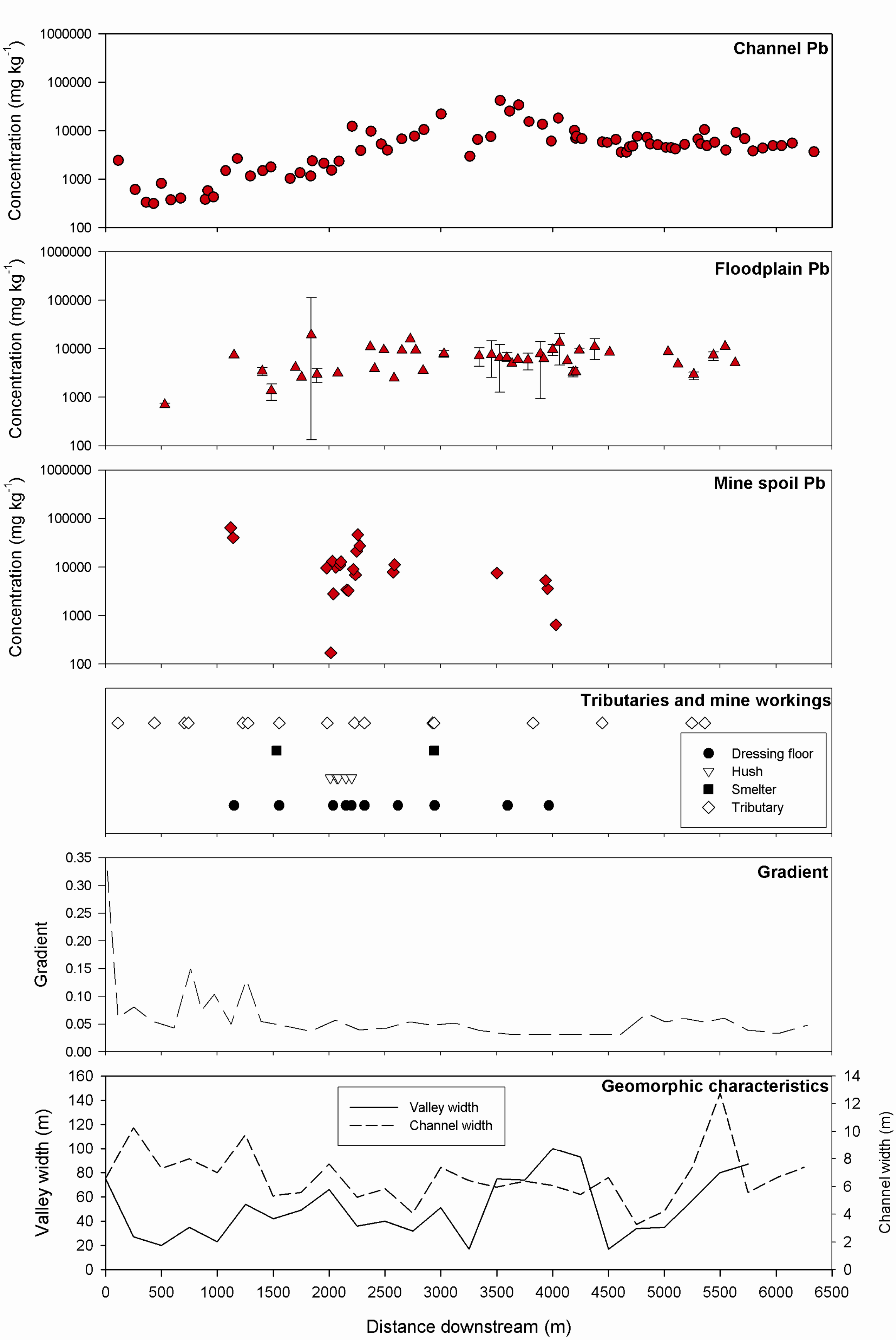

Figure 4.16: Gunnerside Beck <63 μm Pb concentrations, waste inputs and catchment characteristics

likely that these sediments themselves influenced the geomorphic characteristics of Gunnerside Beck. Mining is likely to have greatly increased sediment supply, leading to marked morphological changes and alterations in the catchment. The impact of historic metal mining and processing on the fluvial geomorphology of Gunnerside Beck will be considered in the following section.

4.5. THE IMPACT OF MINING ON FLUVIAL GEOMORPHOLOGY

4.5.1. Introduction

The mining activities described in Section 4.3 have had a significant impact not only on the geochemistry of channel and floodplain sediments within the Gunnerside Beck catchment, but also on the fluvial geomorphology of the catchment. Mining activities, principally hushing and the dressing of galena, greatly increased the supply of sediment to the river system. Hushing led to the periodic introduction of large quantities of coarse-grained sediment into the river channel, while the dressing floors contributed large volumes of fine-grained sediment directly into the river channel when they were operational. In addition to this, coarser waste material from the dressing process was discarded on spoil tips that continue to act as secondary sources of sediment to the fluvial system. The greatly enhanced supply of sediment as a result of metal mining has caused a number of responses in the Gunnerside Beck system that are compatible with the concept of ‘active transformation’ (Lewin and Macklin, 1987), including the formation of a large number of highly contaminated, coarse-grained boulder berms on floodplain deposits downstream of the hushes (Merrett, 2001), the initiation of channel braiding (*cf.* Lewin *et al.*, 1983; Knighton, 1989, 1991; Rowan and Franks, 2002), a likely increase in floodplain development through vertical accretion (*cf.* Macklin, 1985; Macklin and Lewin, 1989; Marron, 1992; Rowan and Franks, 2002), and gradual channel incision after the cessation of mining (Lewin *et al.*, 1983; Lewin and Macklin, 1987; Macklin and Lewin, 1989).

4.5.2. Morphological changes attributable to mining

The increase in sediment supply as a result of metal mining resulted in a number of major geomorphic changes in Gunnerside Beck. An important response to the influx of mining-related sediment was the initiation of channel braiding in several reaches downstream of the major mining zones. This is demonstrated by a series of bars and chutes indicative of a formerly braided channel that are preserved on the floodplain surface. These deposits are most apparent in the small alluvial reach upstream of the hushes (Plate 4.7) and in the wider alluvial reaches downstream of the hushes (Plate 4.8). The coarse and angular nature of the braid bars, flood deposits and active channel bars in Gunnerside Beck (Section 4.2.3) strongly suggests that much of the material transported in the channel was initially derived from both hushing and erosion of the unvegetated spoil tips that can be observed adjacent to the river (in contrast to Lewin *et al.*, 1983). It is unclear, however, whether the initiation of braiding is attributable to the excess supply of sediment from hushes or spoil tips. The positioning of the braided reaches suggests that the introduction of large volumes of sediment from dressing floors has had at least as great an impact on catchment morphology as the input of material derived from the hushes.

The channel patterns in the uppermost reach must be attributable to the supply of sediment from the Blakethwaite dressing floor and smelter, since they are the only major sources of mining-related sediment upstream of the braided reach. Further downstream, the close proximity of hushes and dressing floors in the Lownathwaite-Old Gang complex make it difficult to determine which has had the greater impact on fluvial geomorphology. It is evident that the hushes formerly contained large volumes of material; also that extremely large quantities of coarse-grained sediment were produced on the dressing floors and subsequently discarded on the hillsides adjacent to the river channel.

Lead mining has also had a major impact on floodplain development in the Gunnerside catchment. The coarse-grained flood deposits on the floodplain surface described by Merrett (2001) (Section 4.2.3) are likely to be comprised of mining-related sediment from hushes and spoil tips, although their formation is also closely related to flood frequency and magnitude. Much of fine-grained sediment released from the dressing floors (Section 4.3.6) was deposited during high flows in reaches with a wide valley floor, leading to extensive floodplain development in these areas (*cf.* Macklin and Lewin, 1989; Marron, 1989). In these reaches, coarse basal sediments have been overlain by a sequence of dark horizons of silt and sand, interspersed with beds of angular sandy gravels (Plate 4.9). Metal concentrations in these deposits are extremely elevated, reaching their maximum in finer sediments within the gravel layers. It is likely that the highly contaminated coarse layers represent the bedload of the river, deposited across the floodplain surface during large floods in the form of gravel splays, and subsequently incorporated into the floodplain by further accretion of both fine and coarse sediments (*cf.* Bradley and Cox, 1986, 1987).

Plate 4.7: Channel braiding upstream of the Old Gang and Lownathwaite hushes (white arrow indicates direction of flow)

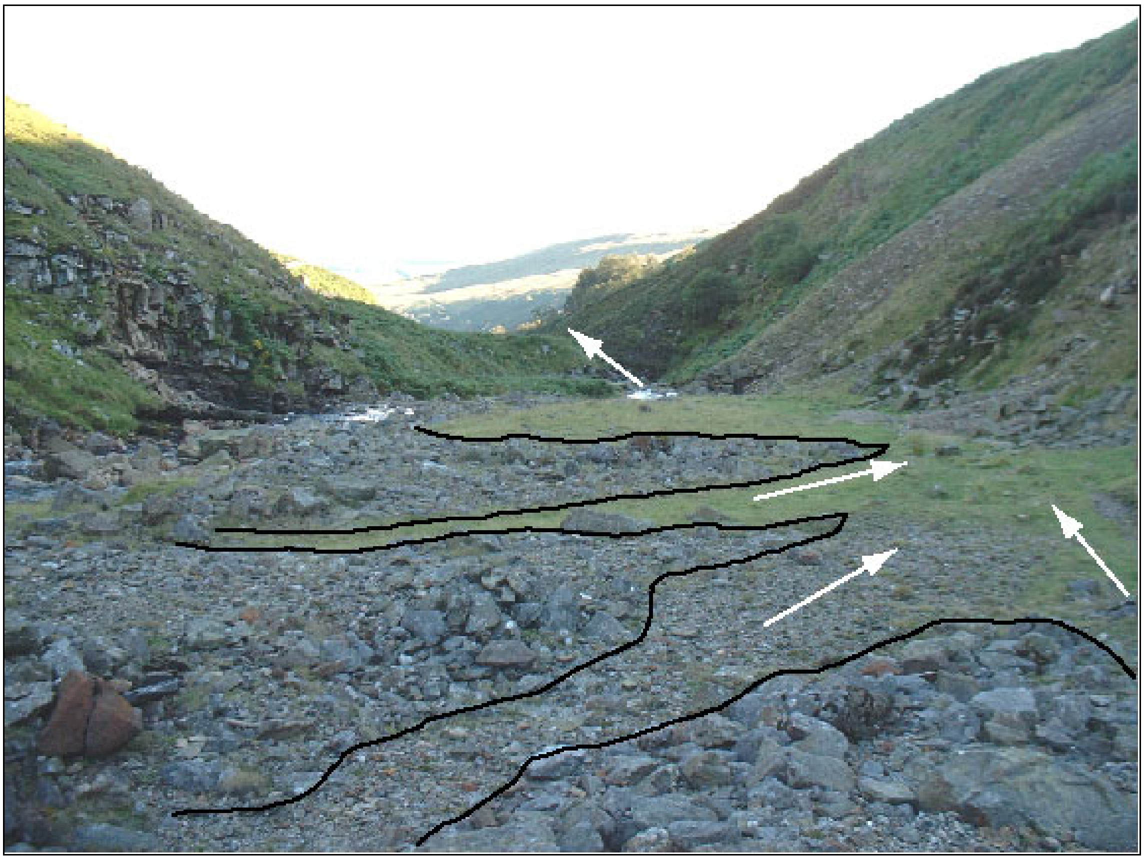

Plate 4.8: Braid bars and chutes downstream of the Old Gang and Lownathwaite hushes (white arrows indicate direction of flow). Note the angular nature of the coarse sediment

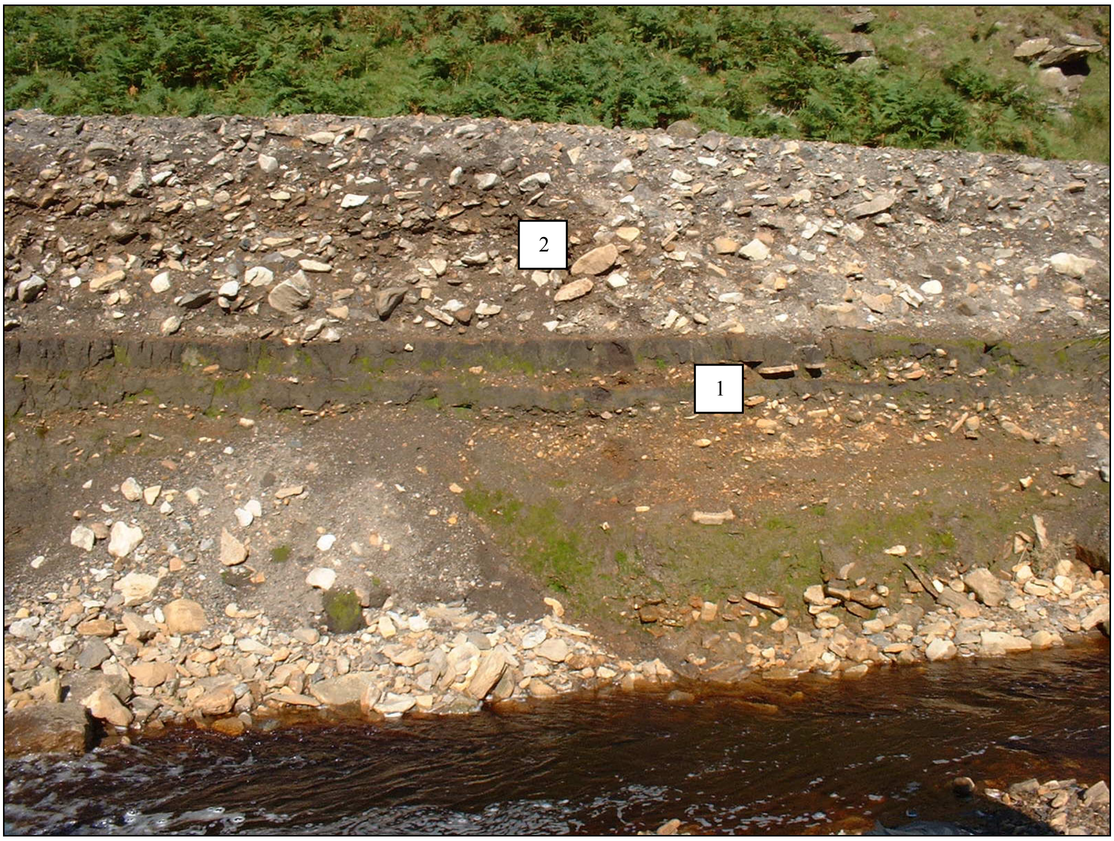

Plate 4.9: Eroding bank section showing mining-related floodplain development. Note the coarse gravel splays which represent flood deposits in the middle of the section (1). The coarse undifferentiated deposits at the top of the section represent the remains of a spoil tip that has been flattened out on the floodplain surface (2)

4.5.3. Morphological changes since the cessation of mining

The cessation of mining in the early twentieth century considerably reduced the amount of sediment supplied to the Gunnerside catchment, resulting in a further period of geomorphic adjustment. A major response to the reduction in sediment supply has been the gradual incision of the channel into its mining-era floodplain and bed (*cf*. Gilbert, 1917; Lewin *et al*., 1983; Lewin and Macklin, 1987; James, 1989; Macklin and Lewin, 1989; James, 1991; Sear and Carver, 1996), leading to the formation of a suite of terraces in the wider floodplain reaches. Channel planform has also altered as a response to the post-mining reduction in sediment supply, with many of the braided reaches described in Section 4.5.2 reverting to single-thread channels.

However, evidence suggests that Gunnerside Beck has not fully ‘recovered’ from mining-related geomorphological alterations. Sediment supply is unlikely to have returned to pre-mining levels, due to the continuing input of material from unvegetated spoil tips and the persistence of mining-era sediment in the river system. This is demonstrated by the divided channel that persists in several reaches. In most cases, this takes the form of a single bifurcation around a partially vegetated medial bar (*e.g.* upstream of the hushes, as shown in Plate 4.7, and at the downstream end of the Sir Francis Level floodplain). The channel retains more pronounced features of braiding in the alluvial reach downstream of Birkbeck Wood, however. In this reach, the channel bifurcates around a series of large medial bars composed of very coarse material. It is likely that these deposits are partially reworked during large flood events, as is suggested by the coarse nature of the alluvial fan at the confluence between Gunnerside Beck and the River Swale.

This braided reach does not appear on the First Edition Ordnance Survey maps of the region (dated 1857), and so may have formed after the likely cessation of hushing in the catchment (braiding is not explicitly marked on these maps in the other reaches; however, a very wide channel which may be indicative of braiding is depicted). The construction of two large dressing floors on Sir Francis Level, approximately 2 km upstream of the islands, in the 1870s may be partially responsible for the formation of these channel patterns. It is likely, however, that the braid bars are primarily composed of material from the dressing floors and hushes of the Old Gang and Lownathwaite mines. Individual clasts are generally more rounded than those found further upstream, suggesting that they have been subjected to more extensive fluvial transport. The apparently long delay between the abandonment of the hushes and the formation of the coarse-grained features in the lower reach of the river may be due to the two narrow gorges located between the sites. These gorges obstruct coarse sediment transport, since many large clasts can only be transported through them during periods of very high flow (Pounder, 1989). Similarly slow rates of bed-sediment wave movement have been noted in other river systems (*e.g.* Roberts and Church, 1986; Jaeggi, 1987; Macklin and Lewin, 1989). The divided reach and alluvial fan are therefore symptomatic of the gradual downstream movement and eventual removal of coarse mining-related sediment from the Gunnerside Beck catchment.

Conversely, the presence of high concentrations of metals in floodplain surface sediments and channel sediments (Sections 4.4.4 and 4.4.5) suggests that fine-grained mining-related sediment is now transported under conditions of ‘passive dispersal’ (Lewin and Macklin, 1987; Rowan and Franks, 2002). This implies that the river system is able to transport fine sediments with minimal geomorphic impact, whereas coarser material instigates morphological changes.

4.5.4. Summary: The geomorphological legacy of mining in Gunnerside Beck

Field evidence suggests that lead mining has had a significant impact on the fluvial geomorphology of Gunnerside Beck. Sediment supply increased dramatically as a result of hushing and the processing of lead ore during the eighteenth century, leading to the formation of coarse flood deposits on the floodplain surface and the onset of channel braiding in several reaches. Fine sediment released from the dressing floors accumulated by vertical accretion processes in wider reaches of the valley floor, leading to the development of severely contaminated floodplain units. The cessation of mining in the early twentieth century considerably reduced sediment supply, causing the channel to incise into the floodplain and revert, in the most part, to a single thread channel. The spoil tips and hushes continue to act as a source of sediment to the river system, however, as reflected in the coarse nature of channel bed load and adjacent gravel bars. The divided channel and coarse alluvial fan in the lower reaches of Gunnerside Beck indicate that large volumes of mining-related sediment remain in the fluvial system, and are gradually being flushed into the River Swale. The river has therefore not completed its ‘recovery’ from the influx of coarse mining-related sediment, and is likely to continue to adjust for a significant period of time (*cf*. Gilbert, 1917; James, 1989). Although coarser mining-related sediment continues to impact the geomorphology of the catchment, finer mine waste is now transported by processes of ‘passive dispersal’, under which it continues to have a significant environmental impact.

4.7. CONCLUSION

This investigation has demonstrated that the Gunnerside Beck catchment is severely contaminated with sediment-associated metals such as Pb, Zn, and Cd. Extremely high concentrations of metals have been observed in floodplain and channel sediments, and in mine waste tips. Metal concentrations within active fluvial sediments are strongly influenced by fluvial geomorphology, particularly by factors such as gradient and channel width, which influence the ability of the river to transport sediment. In addition to severely contaminating the catchment, metal mining had a major influence on its fluvial geomorphology. The influx of mining–related sediment led to increased floodplain development and the initiation of braiding in the river channel. The subsequent decline in sediment supply as mining ended caused the channel to revert to a single-thread pattern and incise into the floodplain. However, the persistence of a divided reach in the lower reaches of the river, coupled with the coarse and highly contaminated nature of channel sediments, suggests that the catchment has not totally recovered from the impacts of historic lead mining one hundred years after such activities ceased.

Gunnerside Beck and other intensively mined tributaries are therefore likely to continue to be a major source of contaminated sediment to the River Swale system. This raises two key questions:

- How much contaminated sediment is stored within Gunnerside Beck and other formerly mined tributaries?
- How important are tributaries as sources of contaminated sediment to the Swale system?
- What is the likely environmental significance of metal storage and supply from formerly mined tributaries?

These issues will be explored in subsequent chapters. Contaminant budgeting techniques will be applied to Gunnerside Beck and other mined tributaries in the Swale catchment in order to provide an estimate of the amount of contaminated sediment that is stored in tributary sources. Floodplain sediment traps will be employed to examine the importance of formerly mined tributaries as sources of metal-rich sediment to the contemporary river system. Finally, the likely environmental impact of metal enrichment in tributary sediments will be assessed using U.K. environmental quality guidelines and estimated background metal concentrations.