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Journal of Geochemical Exploration 52 (1995) 57–65

JOURNAL OF GEOCHEMICAL EXPLORATION

Geomorphology and pollution: the environmental impacts of lead mining, Leadhills, Scotland

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Received 10 May 1994; accepted after revision 26 August 1994

Abstract

The Glengonnar Water has experienced severe environmental degradation resulting from historic lead mining operations. Though now abandoned, the legacy of the mining era remains in the form of river and floodplain sediments grossly polluted with metals, particularly lead which exhibits surface concentrations in excess of 75 000 mg kg^{-1} total-Pb. Geomorphological investigations link the most recent mining period to a major phase of floodplain aggradation, which acted as an efficient sink for particulate-bound metals. The pattern of metal contamination within the floodplain has been complicated by subsequent fluvial entrenchment. However, preliminary evidence indicates that lateral and vertical variations of metals (both total and available) can be accounted for in terms of age of deposit, distance downstream and local hydraulic conditions. The effectiveness of floodplains to interrupt the delivery of sediment-bound contaminants was highlighted by a metals budget developed for the main channel length. This confirmed that channel-bank erosion of contaminated floodplains soils is now the major source of metals to the fluvial system.

1. Introduction

The Glengonnar Water, situated in the Lowther Hills of southwestern Scotland (Fig. 1), has an extended history of environmental degradation. Documentary sources indicate intermittent extraction spanning 700 years, with the most recent lead working period ca. 1850–1915, particularly intensive in terms of mining and processing output (Smout, 1967; Burt et al. 1981). At the peak of production, the Leadhills and adjacent Wanlockhead mining districts, contributed more than 90% of total Scottish production and as much as 10% of the national UK output of lead. However, little work has been undertaken to assess the impact of the mining upon the local environment. The need for such a study was recently highlighted by Moffat (1989) who reported elevated blood Pb levels in Leadhills villagers.

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SSDI 0375-6742(94)00053-0

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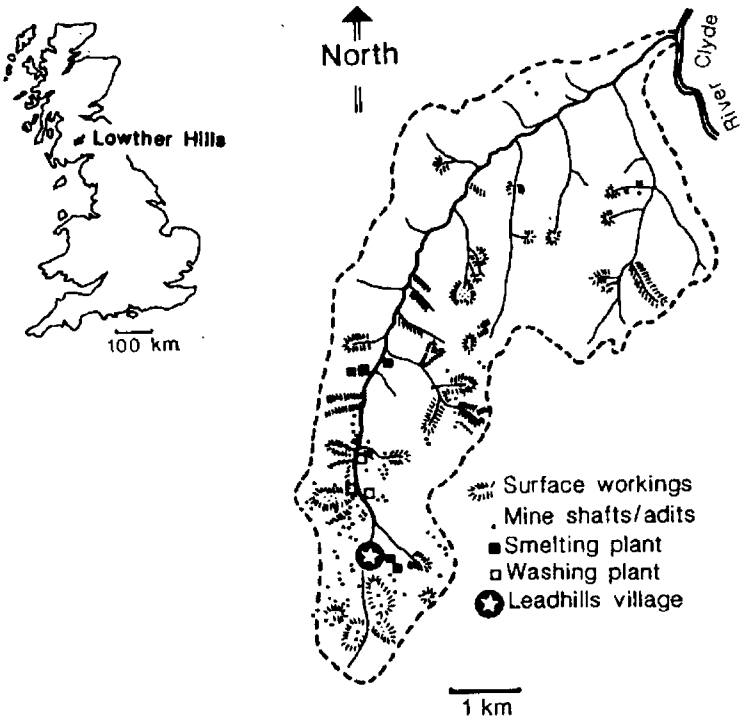

Fig. 1. Study area indicating former mining and processing sites.

Atmospheric dispersion of dust from spoil heaps and historical emissions from former smelting operations were identified as the main sources to the village population. The local water authority (the Clyde River Purification Board) monitor the amounts of dissolved metals from the main channel and selected adits (G. Best, CRPB, pers. commun., 1993). However, no systematic attention has previously been given to the cycling and distribution of metals associated with the contaminated sediments.

The aims of the present study were to assess the geomorphological consequences of mining activity in the Glengonnar Water and to provide base-line data on the extent of metal pollution. There is a growing body of literature examining geochemical gradients in floodplains and river channel sediments in regions affected by mining and mineral processing (e.g. Alloway and Davies, 1971; Graf, 1979; Passmore and Macklin, 1994). Two main areas of consensus emerge from this interface of geomorphology and geochemistry. Firstly, that metals acting as passive tracers offer considerable scope to elucidate the dynamics of fluvial sediment transport and deposition, and as a corollary, geomorphology offers a framework to explain metal dispersal in both space and time (Macklin, 1985; Bradley, 1988). Secondly, that pollution studies on abandoned mine sites provide lessons for the improved management of contemporary mining operations (Markham and Repp, 1992).

2. Survey area

The Glengonnar Water has a catchment area of ca. 24 km^2. Elevations range from 550 m a.s.l. in the southern headwaters, to 230 m at its confluence with the River Clyde. Mean

annual precipitation exceeds 1500 mm yr^{-1}, and the 12 km long main channel has an estimated bankfull water discharge of 24.8 $m^3 s^{-1}$. Below the village of Leadhills, the floodplain is well developed and 80–200 m wide. Land is presently managed as grouse moor, with rough grazing for sheep on the higher slopes and enclosed pasture on the floodplain. The regional geology consists mainly of Silurian and Ordovician greywackes, shales, mudstones and cherts. Mineralisation in the locality was primarily associated with the Caledonian Orogeny. The main primary ore minerals in the mineralised vein system are Galena [PbS] and Chalcopyrite [$CuFeS_2$], but a wide range of secondary minerals are also present in the upper oxidised weathering zone. These include many rare species such as Leadhillite [$Pb(SO_4)(CO_3)_2(OH)_2$] (Gillanders, 1981).

3. Field approach and laboratory methods

To evaluate spatial variations in floodplain metal contamination, a 6 cm (i.d.) coring device was used to sample surface sediments (top 15 cm) along a number of cross-valley transects. The transects were established throughout the length of the main valley and topographically surveyed (Fig. 2). Individual transects were selected to reflect the variability of the floodplain environment, and thus exhibited a range of morphological features such as terraces, abandoned channels and scroll bar sequences. The sample sites contained sufficient common units (i.e. synchronous terrace remnants) to enable consideration of attenuation effects in sediment-metal concentrations. A parallel investigation using historical maps and air photographs allowed the reconstruction of channel pattern changes (cf. Lewin et al., 1983), and the dating of specific deposits within a control chronology of 1858–1986. By this means, rates of bank erosion were estimated for individual study reaches.

Variations in metal concentration with depth were examined from selected bank sections where stratigraphic sequences were exposed and could be sampled directly. Profiles were also obtained from trenches dug to reveal local sediment architecture. The cylinder technique of Lambert and Walling (1988) was used to examine contemporary channel sediments. This technique is used to quantify the mass of fine-grained sediment stored as a matrix within the gravels which dominate the channel bed. Samples were collected at regular intervals down the main channel. Both mass specific concentrations and metal inventories (mass/unit area) were determined. Matrix sediments have short residence times (< 1 year). The survey was therefore used to locate the present sources of metals entering the channel system.

The degree of mining induced pollution can only be established relative to uncontaminated "background" sites (Macklin and Klimek, 1992). However, in mineralised regions the metal levels in soils and sediments may be naturally enhanced. A selection of soil and sediment samples were therefore collected from sites where the secondary influence of mining was negligible. Such sites included valley-side bluffs where the channel was undercutting Pleistocene glacial deposits, soils on undisturbed hillslopes, and channel sediments from tributary streams distant from the main mining sites.

Channel sediments were sieved to <63 μm, while floodplain and "background" soils were screened to <2 mm prior to metal assay. Determinations were made for Pb, Zn, Cu and Cd on standard and graphite furnace variants of the Perkin-Elmer 2280 atomic absorp-

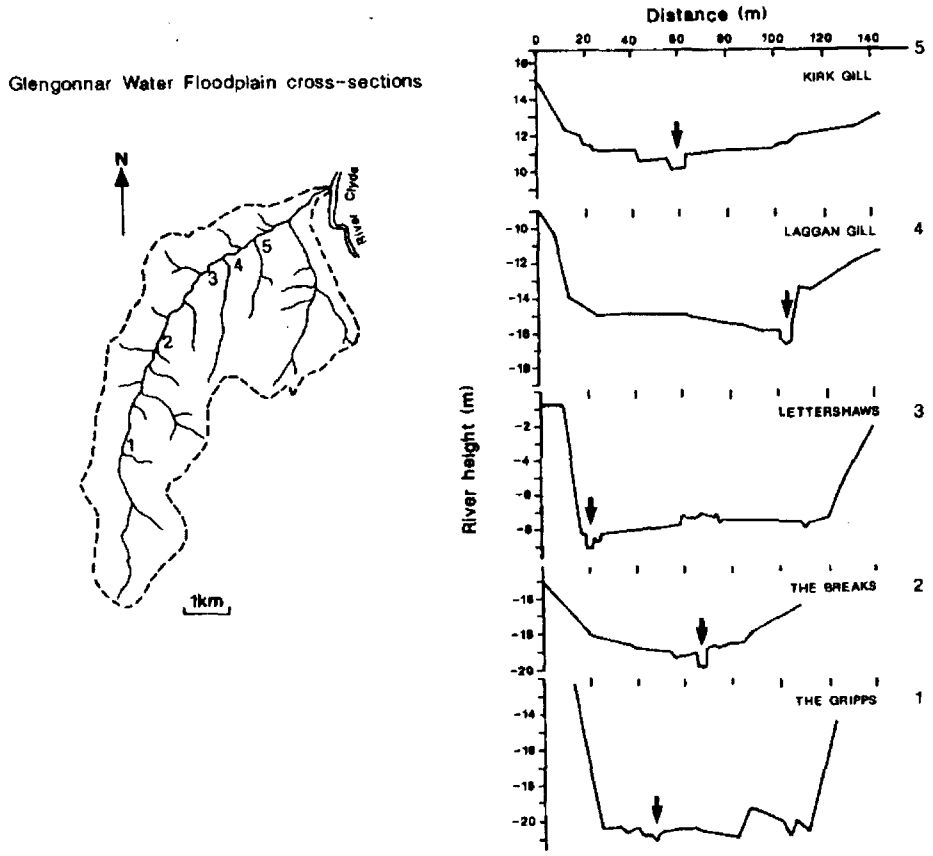

Fig. 2. Floodplain profiles surveyed at various distances down the main valley. Multiple terraces indicate entrenchment into metalliferous mining deposits. The arrow indicates the present channel location.

tion spectrophotometer. Appropriate calibration was made between instruments to ensure comparable results. Duplicate air dried sediments were placed in acid washed glassware and digested under reflux with analar grade concentrated NHO_3. The samples were then allowed to evaporate to near dyrness, and 0.5% HNO_3 added. The samples were then filtered through 542 Whatman filter papers and brought to volume with 0.5% HNO_3. In most cases dilutions were required to keep AAS readings within the linear range of the calibration curves (Förstner and Wittman, 1989). The precision of the analysis is expressed in terms of coefficients of variation — with values of 4.2, 5.4, 8.8 and 10.7% respectively for Pb, Zn, Cu and Cd. Total and available metal (extracted with 0.1 M $CaCl_2$) concentrations were determined, however only the former will be discussed below.

4. Results

Both floodplain and channel sub-environments evidenced elevated metal concentrations, with mean values exceeding background levels by 2–3 orders of magnitude (Table 1). In

Table 1
Summary statist
the Glengonnar

Sampling site

Floodplain soils
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Channel sedimen
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Table 1.
Summary statistics of metal concentrations determined from floodplain, channel and background samples within the Glengonnar Water

Sampling site	Metal concentration (mg kg^{-1})			
	Pb	Zn	Cu	Cd
Floodplain soils (n = 65)				
Mean	33 200	1200	210	4.8
St. dev.	23 200	560	180	6.0
Max.	75 600	2300	1000	25.8
Min.	3800	400	0.5	0.5
Channel sediment (n = 23)				
Mean	15 300	830	170	0.14
St. dev.	9750	340	100	0.04
Max.	35 900	2050	450	0.2
Min.	3300	510	80	0.04
Background samples (n = 10)				
Mean	80	50	15	0.47
St. dev.	13	8	7	0.44
Max.	95	60	30	0.9
Min.	60	40	9	0.03

the UK, the Inter-Departmental Committee on the Redevelopment of Contaminated Land (ICRCL) uses the concept of "*threshold trigger concentrations*", as guidance on possible environmental hazard. These threshold values vary by metal and with land use, as do the "*action trigger concentrations*" defined as the level above which there is strong likelihood of injury to grazing animals or crop yields (ICRCL, 1990). The mean lead concentration in surface soils of the Glengonnar floodplain is 30 times higher than current action trigger level of 1000 mg kg^{-1} for grazing livestock on reclaimed mining land. The extent of the mining induced pollution on the local environment is thus highlighted.

The results of the transect sampling programme revealed a complex distribution of metals within floodplain sediments. However, the variability can be resolved into three components (i.e. lateral, down-valley and vertical trends). Two floodplain profiles situated 2.5 and 6 km downstream of the catchment divide are illustrated in Fig. 3. Both reaches display distinctive terraces and abandoned channels, and reveal an obvious association between metal concentrations and relative elevation. The upper and by definition oldest surfaces, consistently yield the highest metals burden up to 75 000 mg Pb kg^{-1}. Such a pattern is consistent with a mining related phase of floodplain aggradation followed by channel incision and sediment scour. Accordingly, the higher terraces retain surface metal signatures corresponding to sediment deposited during the peak of the mining period, while the lower units exhibit more complicated metal distributions due to reworking. Bradley and Cox (1986) similarly concluded that floodplain metal inventories systematically reflect deposition patterns prevailing throughout the mining era. The transects in Fig. 3 also illustrate downstream attenuation effects. Terrace segments A and A″ represent remnants of a formerly

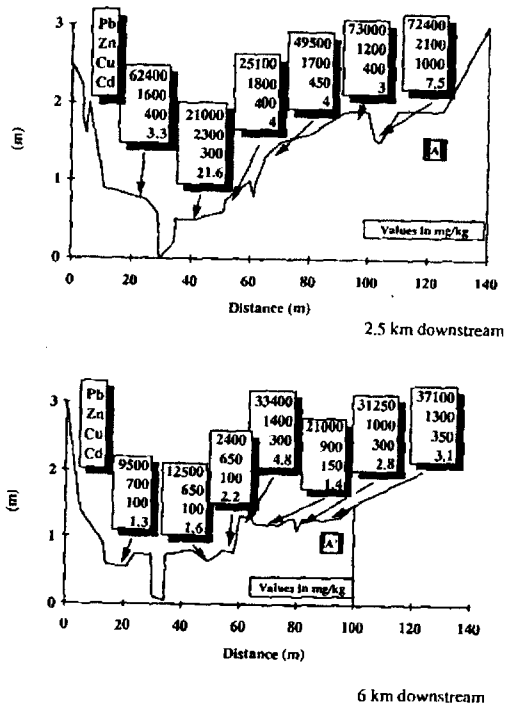

Fig. 3. Representative metal concentrations in the top 15 cm of floodplain soils. Transects were located 2.5 and 6 km downstream of the catchment divide. (Note: Synchronously deposited terrace remnants A and A′ display evidence of downstream attenuation in metal concentration.)

continuous floodplain surface (i.e. synchronously deposited). Statistically significant logarithmic decay models ($p > 0.05$) were established for Pb, Cu and Zn levels within these equivalent terrace surfaces. Lewin and Macklin (1987) reviewed such decay phenomena from a geomorphological perspective and suggested hydraulic sorting, loss to storage and dilution effects to be the dominant processes.

Particulate-bound metals become incorporated into floodplain sequences by two discrete mechanisms. Coarse grained deposits result from the lateral accretion of point bars and gravel splays, while fine-grained sediments are introduced to the floodplain surface by overbank flows during flood events. Both processes are represented in the Glengonnar floodplain, but the latter were more significant because overbank deposits physically dominate the stratigraphy and are rich in the geochemically active $< 63\ \mu m$ size fraction. Lewin and Macklin (1987) suggest that mining derived sediments and metals can be mobilised either as part of the "natural" sediment load and thus "passively transported", or, that if the sediment supply exceeds the capacity of the pre-existing channel system "active transformation" can occur likely involving extensive channel aggradation and floodplain building. On the spectrum of response, the Glengonnar experience lies closer to the latter and thus many parallels are recognised with similar sites where accelerated geomorphological activity has been well documented (e.g. Graf, 1979; Meade, 1982; Knighton, 1991).

The flat upper terraces characteristic of much of the Glengonnar floodplain are indicative of deposition phases involving sediment of relatively uniform calibre. In frequently inun-

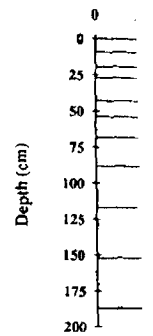

Fig. 4. (a) Total Pb concen
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Fig. 5. Lead concentratio
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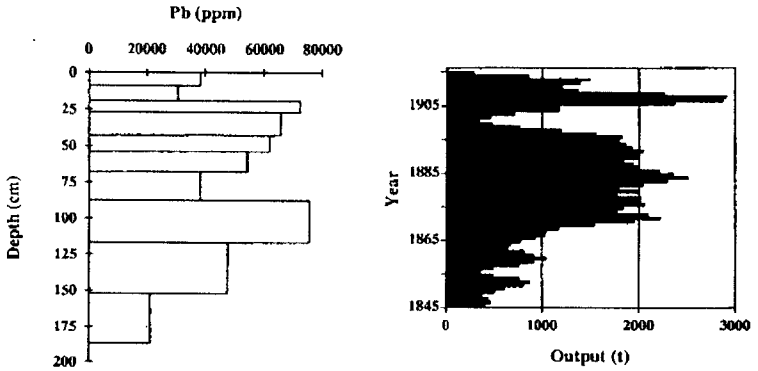

Fig. 4. (a) Total Pb concentrations in eroding channel bank. The sampling interval corresponds to main lithostratigraphic units within the sequence. (b) 3 year moving average of lead production from Leadhills (based on the mining returns detailed in Burt et al., 1981).

dated areas, free from the influence of a laterally unstable channel, continuous deposition of metalliferous-sediments can be used for infer accretion rates (e.g. Macklin, 1985; Knox, 1989). Fig. 4a illustrates the total-Pb distribution in an eroding 2 m bank section. The sampling interval corresponds to the major lithostratigraphic units present and reveals lead concentrations ranging from 21 200 to 75 500 mg kg^{-1}. Cu, Zn and Cd were similarly present in elevated levels, though profile shapes varied as a function of supply and differential mobility. Lead output generated from mining production statistics (Burt et al., 1981) is plotted in Fig. 4b, and displays very similar trends as recorded in the sediment profile. Further work using a range of geochemical indicators and metallic ratios e.g. Pb/Ag, has confirmed the value of this dating approach and will be discussed more fully in a subsequent paper.

More relevant to the present purpose is that floodplain erosion is an important mechanism in remobilising these metalliferous deposits. The depth-weighted Pb concentration of the profile illustrated in Fig. 3a was 43 330 mg kg^{-1}. Decadal derived bank erosion rates of 30–50 mm yr^{-1} estimated from historical maps and air photographs therefore suggest an average annual lead supply rate of ca. 9 kg Pb m^{-1} yr^{-1} (unit bank length). The importance of this source is revealed in Fig. 5 which displays Pb storage in contemporary channel sediments. The presence of elevated metal levels in sediments estimated to have a residence time of less than one year confirms that replenishment is on-going. Downstream of the peak

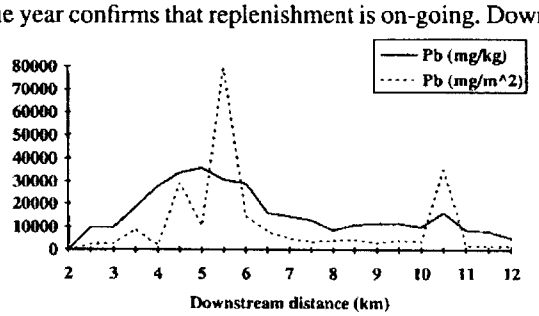

Fig. 5. Lead concentrations and total lead inventory stored in the fine-grained matrix sediments (< 63 μm) of the main channel bed.

value, metal concentrations declined logarithmically with decay rates following the trend of Pb > Cu > Zn > Cd. These results indicate that the main supply of metals into the present channel is from the upper reaches of the floodplain where original contamination levels were greatest and the channel system remains most active. A full assessment of alternative contributing sites such as eroding spoil heaps or adit drainage remains to be completed, however existing evidence strongly points to floodplain reworking as the dominant contemporary sources of metals.

5. Conclusions

Historical mining activities introduced significant quantities of wastes into the Glengonnar Water. Evidence to date indicates a catchment wide sediment response to the most recent mining period involving phases of accretion and floodplain building. Since the cessation of mining, the channel system has been reworking these sediments resulting in a complex pattern of surface and subsurface contamination and a sustained supply of metals to the channel system. Future studies will determine the predominant speciation and partition dynamics of metals at varying distances from the main sources integrating physical transport concepts with other environmental considerations such as pH, Eh and hydrogeology. However the present findings underscore the importance of geomorphological processes to the biogeochemical cycling of mining-derived heavy metals.

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