

# Abandonment of Frazer's Grove Fluorspar Mine, North Pennines, UK: Prediction and observation of water level and chemistry changes after closure

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**Abstract:** Frazer's Grove was the last working deep mine within a carbonate-hosted Pb-Zn orefield in the North Pennines, UK. Closure of the deep workings for economic reasons led to speculation about the possible consequences for surface water courses in the area. The pumped mine water was heavily contaminated with up to 40 mg/l zinc and badly damaged the ecology of the receiving watercourse, the Rookhope Burn. Careful, repeated underground surveys allowed the identification of the nature and sources of the major components of the mine water make. Prediction of the rate of rebound took into account the likely reduction in head-dependent inflows as the mine flooded. It was also predicted that acidification of the water would occur when it reached the level of some pyrite-rich shales within the workings, but that further rise of the water table would be accompanied by neutralisation by limestone dissolution higher in the workings. Both the changes in water level and the changes in chemistry have been largely borne out by subsequent monitoring, demonstrating the increasing reliability of predictive methods for abandoned mines.

## 1 INTRODUCTION

Frazer's Grove mine is situated in the North Pennines in County Durham, UK; it consists of four mines: Frazer's Hush, Rake Level/Firestone Incline workings, Grove Rake and Greencleugh, as shown in Figure 1. They have been formerly worked for lead, but during this century only fluorspar has been worked. However, due to very low fluorspar prices, mining in the deep sections of Frazer's Hush was stopped at the end of 1998. The dewatering pumps were switched off and removed from the No2 Shaft, on March 5th 1999, at which point the groundwater started to rise. Mining of the shallower workings in the Rake Level/Firestone Incline workings continued until July of 1999 when the mining operations ceased and this, the last mine in the North Pennines was closed.

The pumped discharge from the mine was 1895 m<sup>3</sup>/d. The majority of this water came from the Great Limestone (an extensive aquifer throughout the North Pennines) and was strongly net-alkaline, with circum-neutral pH. The only contaminant present at problematic concentrations in the pumped discharge was zinc (Zn) which averaged 12.3 mg/l (Younger, 2000). Since discharges from abandoned mines are usually of worse quality than pumped discharges from working mines, a sampling routine was devised in conjunction with the

Environment Agency (EA) to monitor any environmental implications of the closure of Frazer's Grove Fluorspar Mine.

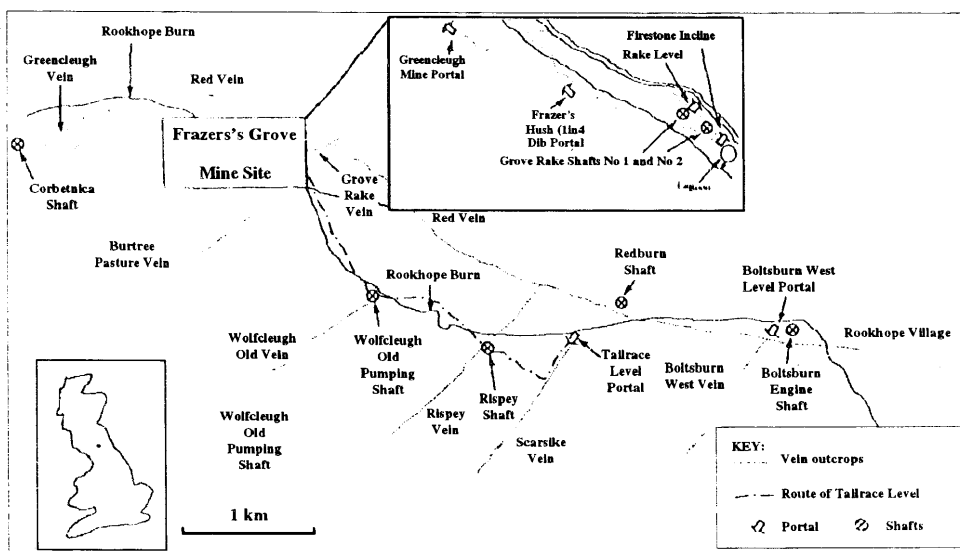


Figure 1 Sketch location map of the Rookhope Valley, County Durham, showing Frazer's Grove Mine and other mines mentioned in text.

## 2 GEOLOGICAL BACKGROUND

The Carboniferous rocks of the North Pennines are cut by numerous mineral veins. The veins are associated with the Caledonian Weardale granite but it is thought that the granite was not the principal source of heat for the mineralisation but instead may have directed hot mineralising fluids through the Carboniferous sediments (Dunham et al, 1965). Many veins are little over 1m wide but in places widths of over 10m have been recorded; veins of up to 3 m wide can be seen in the Firestone Incline at Frazer's Grove mine today. There is a marked zonation of the constituent minerals within the orefield, especially between the non-metalliferous or gangue minerals. Deposits in the central zone carry abundant fluorite ( $\text{CaF}_2$ ), with quartz, chalcopyrite ( $\text{CuFeS}_2$ ), galena ( $\text{PbS}$ ) and sphalerite ( $\text{ZnS}$ ) also present. Surrounding the fluorite zone is a wider zone of deposits in which barium minerals including baryte ( $\text{BaSO}_4$ ) and witherite ( $\text{BaCO}_3$ ) are the characteristic gangue. The presence of galena and other sulphide minerals is less common in this zone. The mineral zonation is interpreted as reflecting progressively lower temperatures of crystallisation from mineralising fluids as they flowed outwards from central 'emanative centres' above high spots (cupolas) on the underlying Weardale Granite (Dunham, 1991). Frazer's Grove Mine is located above this emanative centre within the fluorite zone.

### 3 PREVIOUS WORK

Previous work included an extensive sampling routine both above ground in the Rookhope Burn and underground within the mine (Younger, 2000). Underground inspections of the mine geology were carried out during 1998. The most significant features noted were the 20 m thickness of Great Limestone and the presence of acid generating minerals just below the limestone. The Great Limestone is a prolific aquifer throughout the North Pennines and plays an important part in the hydrogeology of the mine.

The underground surveys also suggested that around two thirds of the Frazer's Grove water make comes from the Great Limestone aquifer. After abandonment it was predicted that the water table would rise above the aquifer and this source of head-dependent water would stop. A final post-rebound water make of only 680 m<sup>3</sup>/d was anticipated. The underground survey located some pyritic shale beds below the Great Limestone and it was anticipated that the rebounding mine water would acidify before rising through the Great Limestone where it would subsequently be neutralised. It was anticipated that the rising groundwater would dissipate into the Great Limestone and that mixing between mine and limestone water would result in satisfactory discharge water quality (according to EA regulations). However, it was also pointed out that if the Limestone could not take up this water there would be a discharge at the Tailrace

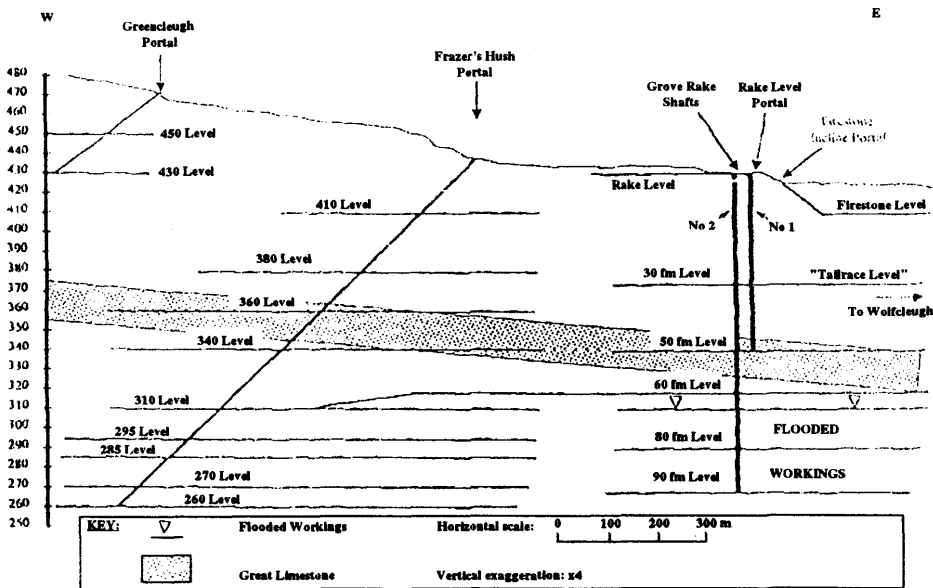


Figure 2 Cross-section of Frazier's Grove Mine, showing locations mentioned in Figure 1 and in text.

Level which is the lowest surface discharge point (364 maOD) for the water.

Hydrochemically, the highest zinc concentrations encountered in these surveys were 40 mg/l in water draining through a disused hopper deep within the Frazer's Hush workings at 285 maOD (Younger, 2000). However, the highest zinc concentrations seen in the pumped discharge was in the spring of 1996 when the No2 Shaft pumps failed. The water rose to 328 maOD flooding the pyritic shales just below the Great Limestone. The water quality deteriorated rapidly as acid generating salts in the shales dissolved resulting in a pH of 3.6 and zinc concentrations of 27 mg/l (Younger, 2000). The acid generating nature of these strata was reproduced in the laboratory by dissolving 1mg of the dried and ground sample in 20 ml of de-ionised water and agitating it for 30 minutes. This resulted in a drop in pH to as low as 2.7.

## **4 SAMPLING METHODOLOGY**

Samples are taken on a monthly basis from the Boltsburn Level, Tailrace Level, three points on the Rookhope Burn and from the uncased No2 Shaft at the mine (using a SEBA 1L depth sampler). It is assumed that the shaft water at depth is at equilibrium with the corresponding strata. Samples are taken every 10 m between the water surface (currently stable at ~373 maOD) and a depth of 315 maOD: it is not possible to sample below 315 maOD due to a platform across the shaft. Parameters such as pH, temperature, Eh, conductivity are measured on site using a calibrated Camlab MY/6P meter and alkalinity is measured using a Hach digital titrator. Two 200 ml sample bottles (one being acidified with 2 drops of concentrated nitric acid) are filled and returned to the Environmental Engineering Laboratory at Newcastle University for anion and cation analysis.

## **5 RESULTS**

The hydrochemical results are represented graphically as Figures 3 and 4.

### **5.1 Groundwater Rebound**

Groundwater rose within the mine at varying rates depending on the available void space within the mine; the average rate of rise was between 25 and 30 cm/day. There was no sign that this rate would decrease, therefore a treatment scheme was designed and built on the flat land near the portal of the Tailrace Level. The groundwater stopped rising (at 373 maOD) on 25th August 1999 and an increased discharge was noted at Tailrace Level on the same day. Unfortunately, flow measurement was not possible due to construction works for a mine water treatment system. The discharge was noticeably cloudy, as had been previously predicted.

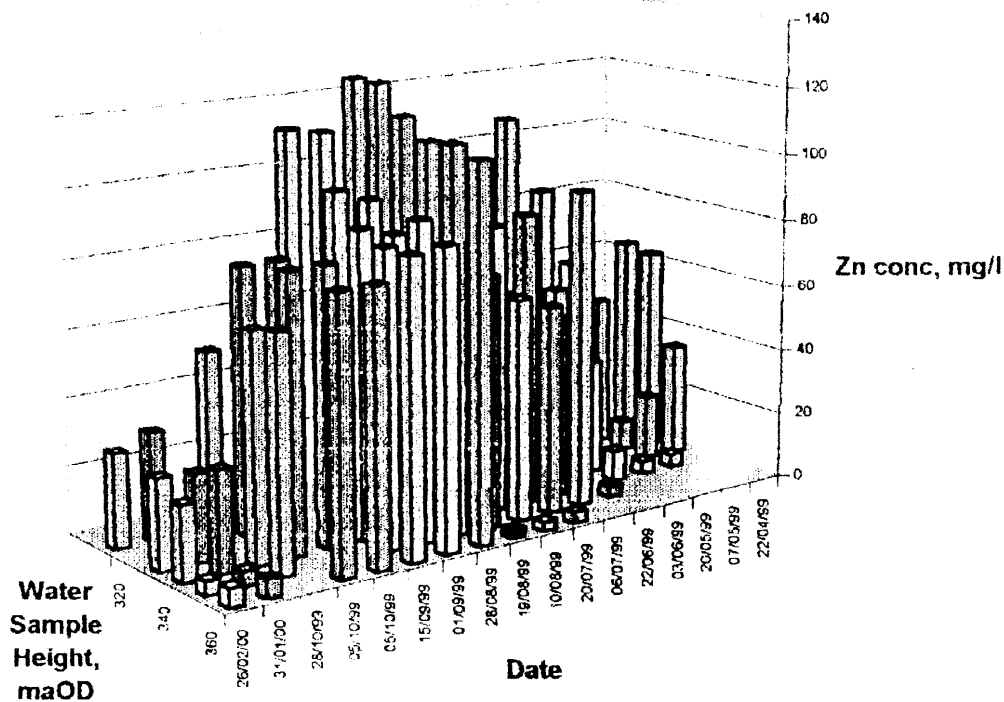


Figure 3 Zn concentrations in No2 Shaft at Frazer's Grove.

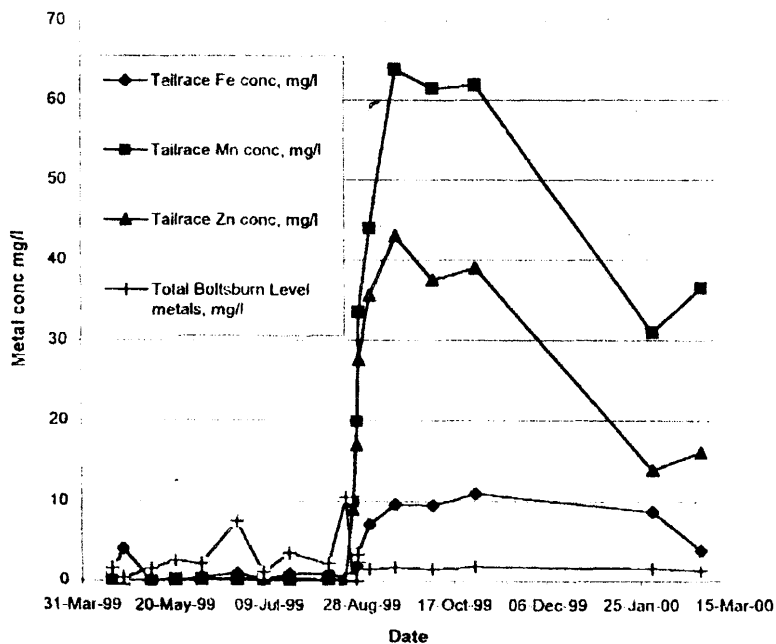


Figure 4 Metals concentrations at Tailrace Level and Boltsburn Level

## 5.2 Background Hydrochemistry

Boltsburn Level (Figure 1) was sampled at the same time as the depth sampling in the No2 shaft. The Boltsburn Level is situated on the outcrop of the Great Limestone and its discharge is typical of Great Limestone groundwaters (Ca~100 mg/l,  $\text{HCO}_3^-$ ~180 mg/l, conductivity~ 500  $\mu\text{S/cm}$ ). However, it does drain some old mineworkings and can have variable iron concentrations (1-10 mg/l). The Level is not directly connected to Frazer's Grove mine and is monitored in order to assess any changes in flow or chemistry in the Great Limestone aquifer (Figure 4).

The Rookhope Burn was sampled in three places: up and downstream of the Tailrace discharge, and further downstream at the Boltsburn Level. The Tailrace discharge has had no obvious damaging effects on the ecology of the Rookhope Burn. Zinc concentrations were raised to 30 mg/l in the Burn during September 1999 when flows were very low but are only 2 mg/l at present in March 2000.

## 5.3 Shaft Hydrochemistry

Figure 3 represents the zinc concentrations in the shaft throughout the water column and throughout time. Zinc is the most ecologically important of the parameters measured because of its toxicity to fish and invertebrates, and is also indicative of overall water quality. The graphs show that water quality decreases as the water rises through the acidic shales and then improves following contact with the Great Limestone. The quality deteriorates again between 22<sup>nd</sup> of June and the 7<sup>th</sup> July for reasons which are discussed in Section 6. Peak toxic metal concentrations seen within the shaft occurred when the overflow into Tailrace took place around 25<sup>th</sup> August 1999 with iron, manganese and zinc concentrations as high as 50 mg/l, 130 mg/l and 120 mg/l respectively. A standard geochemical modelling program, WATEQ4F (Ball & Nordstrom, 1991) has been used to model the water chemistry in the shaft. Results showed that goethite was supersaturated and that gypsum was close to saturation. This explains the orange ochreous precipitates in the samples taken and why, of the three metals measured, iron concentrations are by far the lowest.

The water column within the shaft was stratified until the 25<sup>th</sup> August when the shaft water overflowed into the Tailrace adit. It remained mixed until the end of 1999 when it once again became stratified. This led to the anomalous situation of the Tailrace water (Zn~16 mg/l on 22/2/00) being more contaminated than the water at the top of the shaft (Zn~5 mg/l on 22/2/00).

## 5.4 Tailrace Hydrochemistry

The Tailrace Level drains some old mineworkings but also carries a significant component of surface run-off which enters the level via crownholes. The water quality was fairly constant (conductivity ~400  $\mu\text{S/cm}$ ) until the shaft water

overflowed into it (Figure 4). The graph shows that water quality in the adit gradually worsened as the ratio of mine water to adit water increased with time. A peak value in metal concentrations (~40 mg/l Zn, 62 mg/l Mn, 10 mg/l Fe, conductivity ~1700  $\mu$ S/cm) was seen on the 15th of September and water quality has slowly improved since.

## 6 DISCUSSION

Two interesting points are clear from Figure 3. Firstly, the data show that when the water level in Shaft No2 reached 360 maOD there was an unexpected increase in metal concentration and corresponding decrease in bicarbonate concentration throughout the water column. Figure 2 shows that the strata present around this depth are 'Plate beds' and Pattinson's Sill beneath the Little Limestone. It was not possible to take samples from these beds during underground surveys as they were inaccessible. A literature survey has also revealed little information on their petrological nature. Dunham et al (1965) described shales above the Great Limestone as micaceous, ferruginous, dark blue-grey beds with scattered ironstone nodules. From this description, it is presumed that these beds contain acid generating minerals and that they were responsible for the dramatic decrease in shaft water quality between 22nd June and the 7th July 1999.

The high zinc concentrations in the shaft water seem initially surprising when we consider that the highest zinc concentration recorded during the underground surveys was ~40 mg/l (from 285E Hopper, Younger, 2000). The highest zinc concentration seen in the pumped discharge, when the pumps failed in 1996, was only 27 mg/l. When the water column was initially stratified, concentrations of up to 90 mg/l are seen in the No2 Shaft; with the break-up of stratification at the end of August 1999, zinc concentrations peaked at 120 mg/l. Such high concentrations within a mine have never been seen before in the North Pennines. Taking into account the diluting effect of the original Tailrace discharge on these very high zinc concentrations, the No2 Shaft water accounts completely for the 40 mg/l of zinc seen at the Tailrace Level discharge. It is presumed that the high zinc concentrations have been caused by dissolution of acid generating minerals in the shales and mudstones both above and below the Great Limestone. Acid generating salts which contain significant zinc (and indeed manganese) have not previously been mentioned in the literature but there is mounting evidence to suggest that they exist.

Secondly, Tailrace water is currently more contaminated than the water at the top of the shaft. Several theories have been considered for this scenario. However, the most likely is that the Tailrace adit is blocked at the No2 Shaft. Historically, water was pumped from lower levels into the adit and allowed to drain through it; however the Tailrace adit was never a successful gravity drainage feature as it tended to silt up. If this is the case the shaft water would find an alternative route. The next route is along the 40 fathom level and up the

No1 shaft to the Tailrace Level. Hydrochemical evidence supports this theory as metal ratios of 'shaft water (top of water column) to Tailrace water' have remained constant at approximately '1.5'. When re-stratification occurred and Tailrace water was seemingly more contaminated than the shaft water (top of water column) this relationship broke down. However, if since re-stratification, the source of water within the shaft is now 340 maOD and not the top of the water column (~370 maOD) then the relationship still holds.

However, the quality is expected to improve as flushing of flooded workings occurs. Younger (in press) found that it was possible to empirically relate the total length of this initial period of flushing (initial worst water quality) to the rebound time:

$$t_r = 4t_f$$

where:

$t_f$  is the total length of the first flush period

$t_r$  is the 'rebound period' (ie the time taken for the mine to fill to overflowing)

In this case, the 'rebound period' was approximately 5 months and therefore we can estimate the total length of first flush period to be 20 months. During this time, zinc concentrations are expected to decrease exponentially until they reach a relatively stable value of ~1/10th of the first-flush value (Younger, in press). In this case, the stable value should be approximately 4 mg/l zinc.

## 7 CONCLUSIONS

- Cessation of pumping at Frazer's Grove mine, has resulted in the rebounding groundwater discharging at the Tailrace Level;
- As a result of this discharge the previously stratified water column within the No2 Shaft became mixed;
- Re-stratification occurred after ~3months possibly due to silting up of part of the Tailrace Level;
- The discharge has lead to a dramatic decrease in water quality at the Tailrace Level with zinc concentrations peaking at 40mg/l;
- The source of this zinc is in the shales and mudstones present both above and below the Great Limestone within the mine;
- Water quality is improving exponentially with time and should be stable at ~4 mg/l zinc in Spring 2001.

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### **Zamknięcie kopalni fluorytu we Frazer's Grove, Penniny Północne, Wielka Brytania: prognoza i obserwacja zmian poziomu wody i składu chemicznego po zakończeniu eksploatacji**

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**Streszczenie:** Frazer's Grove była ostatnią czynną kopalnią głębinową w obrębie węglanowych złóż rud Pb-Zn w Penninach Północnych, Wielka Brytania. Wypompowywana z kopalni silnie skażona woda, zawierająca do 40 mg/l cynku, znacznie zniszczyła środowisko naturalne strumienia. Zamknięcie z przyczyn ekonomicznych głębokiej kopalni doprowadziło do spekulacji na temat dalszych możliwości degradacji jakości wód cieku ze strony odprowadzanych wód kopalnianych. Staranne kilkakrotne badania pozwoliły zidentyfikować pochodzenie składu chemicznego wody kopalnianej. Prognozy szybkości odbudowy ciśnień w trakcie zatapiania wykazały postępujące zmniejszanie się dopływów wód w czasie. Wykonana prognoza wykazała, iż procesowi zakwaszenia wód w trakcie zatapiania wyrobisk górniczych prowadzonych w serii łupków pirytowych będzie towarzyszyła neutralizacja tych wód w serii węglanowej. Zmiany tempa zatapiania wyrobisk jak i zmiany składu chemicznego wód są rejestrowane przez monitoring. Jego wyniki wskazują na coraz większą wiarygodność stosowania metod prognozowania.