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British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Groundwater conditions at Foss Mine, Aberfeldy

Groundwater Systems and Water Quality Programme

Internal Report IR/04/161

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BRITISH GEOLOGICAL SURVEY

GROUNDWATER SYSTEMS AND WATER QUALITY PROGRAMME

INTERNAL REPORT IR/04/161

Groundwater conditions at Foss Mine, Aberfeldy

Brighid É Ó Dochartaigh

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- The bedrock in the Foss area forms a low or very low productivity aquifer. The groundwater flow direction is likely to be northwards, and flow is likely to occur dominantly in the upper few tens of metres of the bedrock. Natural groundwater discharge is likely to be via springs or directly to streams on the hill slopes, or directly to Loch Tummel.
- Groundwater inflows to mine workings are very small. Surface water and/or rainwater also flow to mine workings via open abandoned borehole(s) and entrances to mine workings. However, water flow in the mine does not reportedly increase significantly during heavy rain.
- The bedrock is highly mineralised, in particular containing baryte, pyrite and dolomite.
- Groundwater may contain naturally high concentrations of certain elements present in high proportions in the bedrock, such as Fe and Zn, although there are no available data.
- The exposure of minerals in the bedrock to the air within the mine workings is likely to have created hydroxy-sulphate minerals through oxidation of sulphide compounds, such as pyrite. Water moving through the mine dissolves these minerals from rock surfaces, increasing its acidity and allowing metals in rock-forming minerals to be taken into solution.
- Virtually all water in the mine is currently pumped to ground surface and treated. Untreated mine water is reportedly of poor quality, with low pH and high concentrations of certain elements, such as Zn.
- Treated mine water is discharged to the Frenich Burn. Water quality in the burn immediately below the discharge point generally shows elevated pH and elevated (sometimes only slightly) concentrations of Cd, Cr, Cu, Fe, Pb and Zn, compared to water quality upstream from the mine. Chemical concentrations are generally within the allowable limits, although occasional exceedences occur, with the major element of concern being Zn. Water quality in the Frenich Burn at Frenich generally shows slightly elevated concentrations of Cd, Cu, Ni, Pb and Zn compared to water upstream from the mine, but generally lower concentrations than immediately below the mine.
- The main source for elevated Zn concentrations in stream water in the Frenich Burn is likely to be inadequately treated acid mine water discharged via the surface treatment lagoons. Inadequate treatment is thought to be associated with heavy rainfall causing increased surface water flow into the treatment lagoons, which overwhelms the treatment capacity at the site.
- During mining operations the risk of acid mine water discharging directly from groundwater to the Frenich Burn or other surface water body is likely to be very small. There may be a small risk of acid mine water re-infiltrating to the aquifer within the mine or recharging through the treatment lagoons, which would discharge to surface water down slope of the mine.
- Post mine closure, the main risk to groundwater and groundwater-dependent systems is likely to be caused by gradual flooding of the mine workings by groundwater, dissolution of hydroxy-sulphate minerals, and consequent increase in water acidity and mineralisation. The slow rate of groundwater flow means that this could take many years.

- Acid mine water will flow out of the mine either slowly, via fractures, or rapidly via artificial conduits such as tunnel entrances or abandoned boreholes. Acid water flowing from the mine through fractures will move to natural discharge points such as springs or streams down slope from the mine. Water quality may improve during groundwater flow, but the discharging groundwater is likely to be of poor quality.
- The slow rates of flow and small volumes of groundwater involved are likely to mean that the formation and outflow of acid mine water could continue for a considerable period of time.

1 Introduction

The Foss Mine operates under a consent to discharge under COPA (Controlled Pollution Act, 1974). As part of the Water Framework Directive groundwater risk assessment, the Scottish Environment Protection Agency (SEPA) has identified the mine as a potential issue with regard to surface water-groundwater interactions. This assessment was based primarily on surface water chemistry data for the Frenich Burn into which water from the Foss Mine is discharged.

Under secondment to SEPA, the British Geological Survey (BGS) carried out a short investigation of the hydrogeology of the Foss Mine to determine if either (a) resurgences of contaminated groundwater or (b) direct discharges from groundwater are occurring and could be impacting nearby streams.

The study is specific to the particular objectives of the Water Framework Directive and does not represent a comment on the current COPA consent.

The study addressed the geochemistry of the local bedrock, the chemistry of surface water and the available groundwater information, and involved:

- Examination of BGS records and data;
- Discussions with local area SEPA officers;
- A brief visit to the Foss Mine site.

The site visit took place on 30 September 2004, and involved a brief inspection of parts of the surface layout of the mine, and a brief underground tour along some of the mine tunnels.

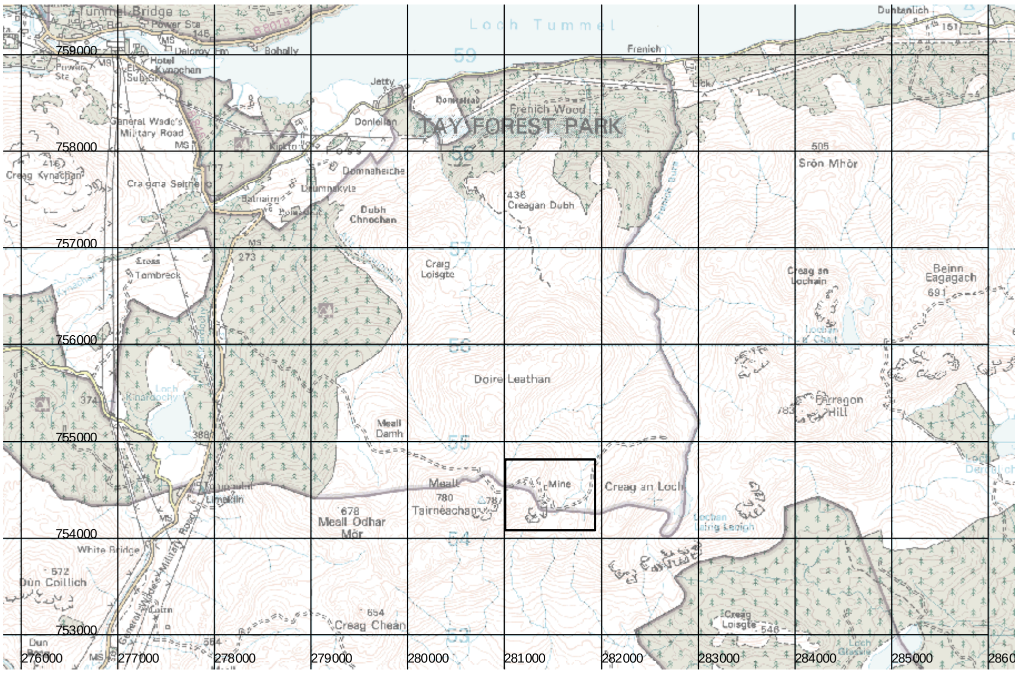

Figure 1 Location of Foss Mine

2 Foss Mine

2.1 LOCATION

The Foss Mine lies approximately 7 km northwest of Aberfeldy, on the south site of Loch Tummel (Figure 1). The mine is sited close to the summit of the Tay-Tummel watershed, on the upper slopes of Meall Tairneachan, which rises to 780 m OD. The main entrance to the mine lies at approximately 665 m OD.

2.2 MINE DEVELOPMENT

Barytes is extracted from the mine from world-class deposits within the metalliferous Dalradian Supergroup. Baryte is valued because of its great density as a component of the lubricating mud used in the oil production industry. The drilling mud is pumped down boreholes from the ground surface, and its weight counters the pressure of the upwelling oil. The baryte deposit at Foss was discovered in 1976 by the Mineral Reconnaissance Programme (MRP) of the BGS. Within this project, mineralisation was first identified by stream sediment geochemistry, with anomalous concentrations of zinc in stream sediments and baryte in panned concentrates. A detailed follow-up geochemical survey and reconnaissance geological mapping established that the source of the anomalies was stratabound baryte, spalerite and galena in Dalradian rocks. The surface extent and character of the deposit was subsequently detemined by detailed geological, geochemical and geophysical mapping, and a limited programme of shallow boreholes.

1n 1979, after publication of the MRP report describing the baryte discoveries, leases were acquired by Dresser Industries Minerals Division and for the following 3 years the mining potential of the 1.8 km of mineralised strike-length on the Foss property was evaluated by drilling and drifting. Since 1985 the Foss Mine has been operated by M-I, a joint venture between Smith Industries and Haliburton. M-I is the world’s largest oil well drilling fluid company and the world’s largest baryte user. Annual production from the Foss Mine is approximately 50 000 tonnes of direct-shipping-grade baryte.

2.3 CURRENT MINE CONDITIONS

Today the mine consists of a development on four levels, with some 120 m of vertical interval along a strike length of at least 500 m. The lowest current level is approximately 100 m below ground level at the mine entrance (Figure 2). Tunnel development has been controlled by the structural complexity of the ore body.

There is also a complex of small open pits extending 300 m east of the mine entrance. All current production is from underground mining, but economic deposit is present in the opencast pits that is likely to be worked before mine closure in the next 2 to 5 years.

Groundwater flows into the mine tunnels from the surrounding rock in addition to surface water ingress along tunnels. Surface water may also enter the mine by at least one abandoned, open borehole that now intersects a mine tunnel. The abandoned borehole(s) are also likely to form a rapid conduit for groundwater flowing from shallow depths in the rock. Water moving through the mine dissolves hydroxy-sulphate minerals (the products of oxidations of sulphide compounds such as pyrite) from the rock surfaces, which lowers the pH of the water and increases its ability to take metals, such as Fe and Zn, into solution.

The water flows to sumps at various levels in the mine, and from there is pumped up in stages to the ground surface. Some of the water collecting in the mine is recirculated and used for mining activities (e.g. dust suppression during drilling).

At the ground surface, the pumped acid mine water is discharged to the first of a series of three treatment lagoons. Calcium hydroxide is added to the lagoons at various points in the lagoons to raise the pH and encourage metals in solution to precipitate out. In the lowest lagoon, the water flows over an aeration system, which also encourages the precipitation of dissolved metal salts. From here, the water flows to the Frenich Burn, which flows north-westwards and northwards to Loch Tummel (Figure 1).

SEPA take regular surface water samples for chemical analysis from three points on the Frenich Burn: above the elevation of the Foss Mine treatment lagoons; just below the point at which treated water is discharged to the Frenich Burn; and at the base of the hill close to the point at which the burn enters Loch Tummel. The sampling schedule is normally five times per year, between April and October. No samples are normally taken during winter months. Water quality in the burn immediately below the discharge point generally shows elevated pH and elevated (sometimes only slightly) concentrations of Cd, Cr, Cu, Fe, Pb and Zn, compared to water quality upstream from the mine. Chemical concentrations are generally within the allowable limits, although occasional exceedances occur, with the major element of concern being Zn (the lower tier limit for Zn is 2 mg/l; the upper tier limit is 4 mg/l) (SEPA, *pers. com.*). Water quality in the Frenich Burn at Frenich generally shows slightly elevated concentrations of Cd, Cu, Ni, Pb and Zn compared to water upstream from the mine, but generally lower concentrations than immediately below the mine. Examples of Zn concentrations at the three monitoring points on the Frenich Burn during summer 2004 are given in Table 1.

Date	**Upstream of mine**	**At outflow from treatment lagoons**	**At base of hill near Loch Tummel**
7 / 8 July 2004	0.023	0.353	0.022
16 August 2004	0.004	6.990	0.035
19 August 2004	0.005	1.330	0.050

Table 1 Zinc (Zn) concentrations in the Frenich Burn (mg/l)

The elevated concentrations of pH and of Zn and other metals in the waters of the Frenich Burn are likely to be caused by the discharge of treated acid mine water from the treatment lagoons at the mine. The occasional exceedance of the allowable Zn limits is thought to be associated with heavy rainfall, which overwhelms the treatment capacity at the site.

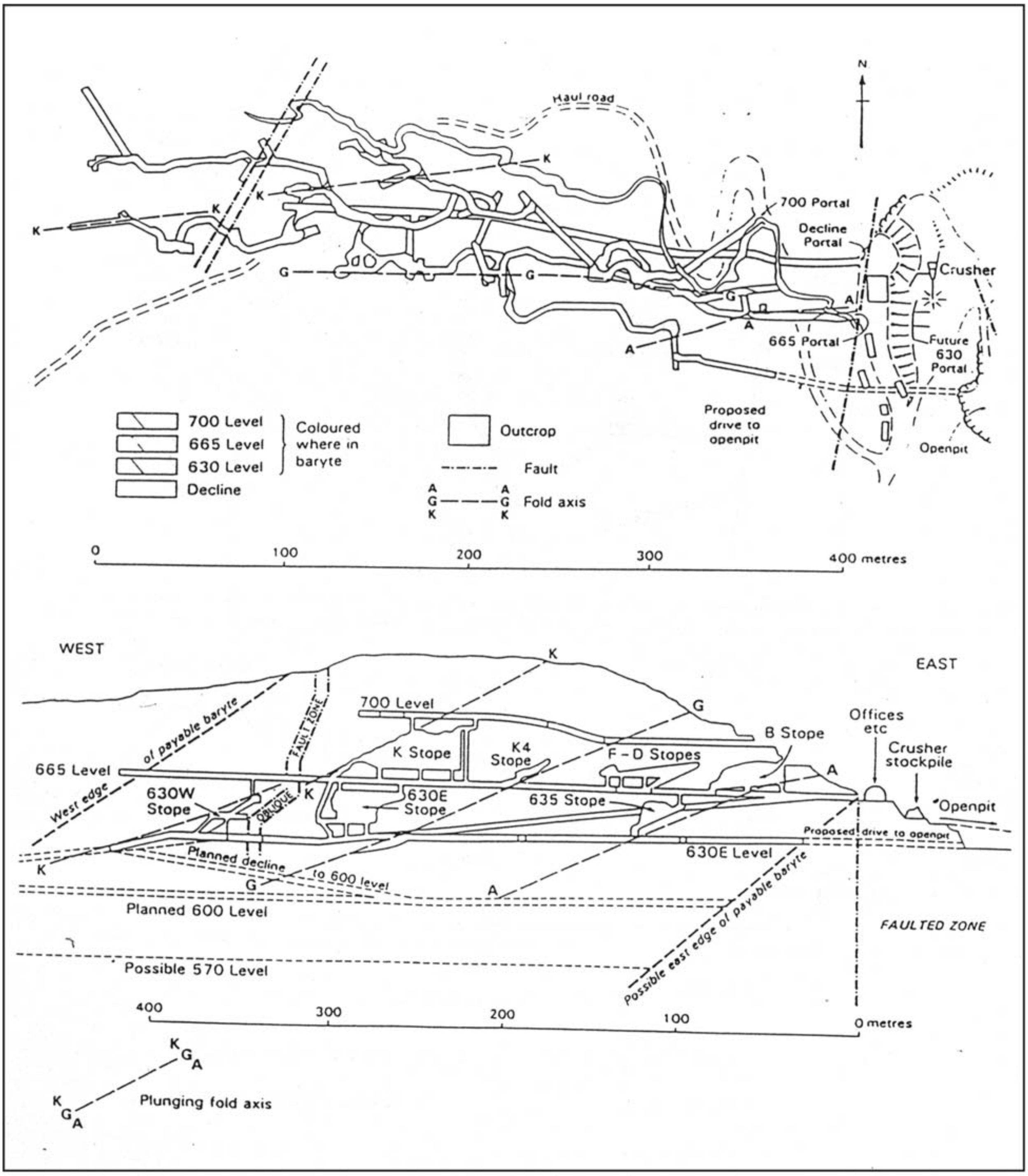

Figure 2 Foss Mine: (top) plan of underground workings at 1990 and (bottom) simplified long section of mine at 1990. Note that workings have been extended since 1990. (After Gallagher et al 1991).

3 Geology

The Foss baryte deposit is part of the Dalradian Supergroup, a 25 km thick sequence of Neoproterozoic marine sedimentary and basic volcanic rocks, which was folded and metamorphosed during the Early Palaeozoic Caledonian Orogeny.

The deposit occurs in the upper part of the Ben Eagach Schist Formation (Figure 3), which is part of the Middle Dalradian Argyll Group. The formation is dominated by graphitic mica schist with subordinate interbedded quartzite and carbonate rock. The succession locally includes units of chloritic, metabasite and calc-biotite rock representing metamorphosed intrusive and extrusive basic igneous rocks, respectively. In the Foss area, the Ben Eagach Schist is overlain by the Ben Lawers Schist, which consists largely of calcareous pelite.

The Foss deposit comprises two levels of baryte and/or quartz-celsian (barian feldspar) rock, separated by graphitic schist, some of which is also enriched in barium. The baryte bed shows considerable variation in thickness both along strike and down dip, ranging from less than 1 m to over 5 m, with an average of 3 m.

The baryte has distinctive centimetre-scale banding picked out by enrichment in pyrite and other sulphides, or in magnetite, often accompanied by enrichment in quartz. Other constituents include carbonate, micas and chlorite. The quartz-celsian rock commonly shows fine lithological banding, which results from sharp variations in the amount of quartz, dolomite, celsian, sphalerite and pyrite, and is often highly dolomitic and pyritic. The rock is very hard and competent.

The Dalradian of the Foss district has been affected by several deformation events, which caused regional metamorphism and folded the rocks so that the original structures, including the baryte seams, now have a complex spatial pattern. The overall dip of the rocks is moderately steep to the south-east, but there is considerable variation in orientation. The Foss deposit is affected by a number of north-south to north-northeast trending faults.

Because of the upland nature of the surrounding land, bedrock is exposed at the ground surface across most of the area. Superficial deposits are restricted to the stream valleys, and on the current 1:50 000 scale map are usually mapped as till or hummocky moraine (Figure 4).

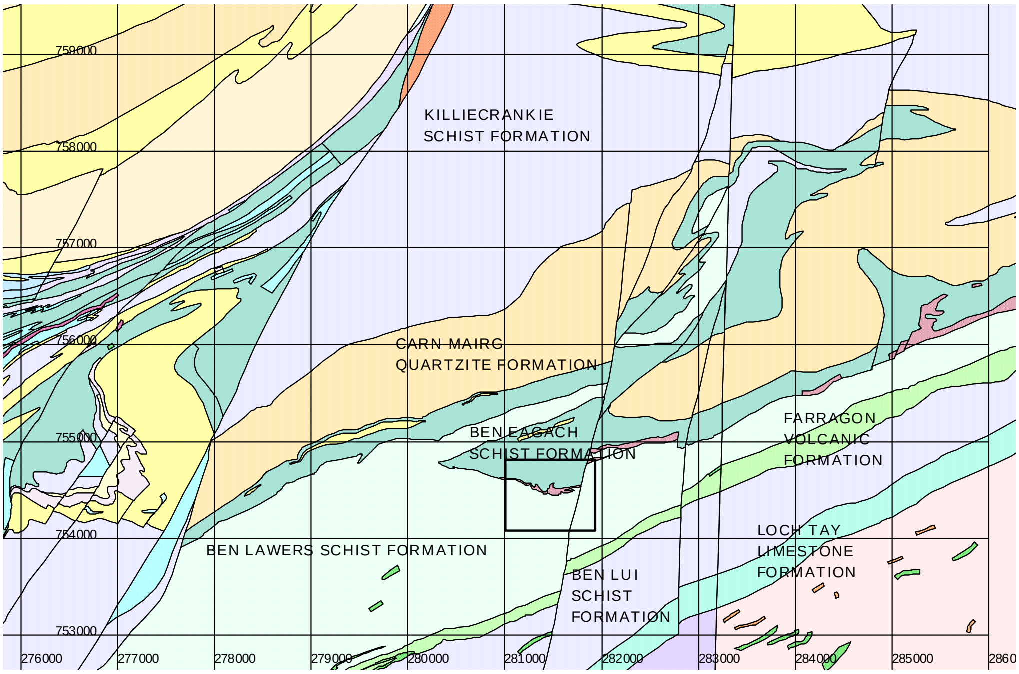

Figure 3 Bedrock geology of the Foss Mine area (1:50 000 scale, from DigMap)

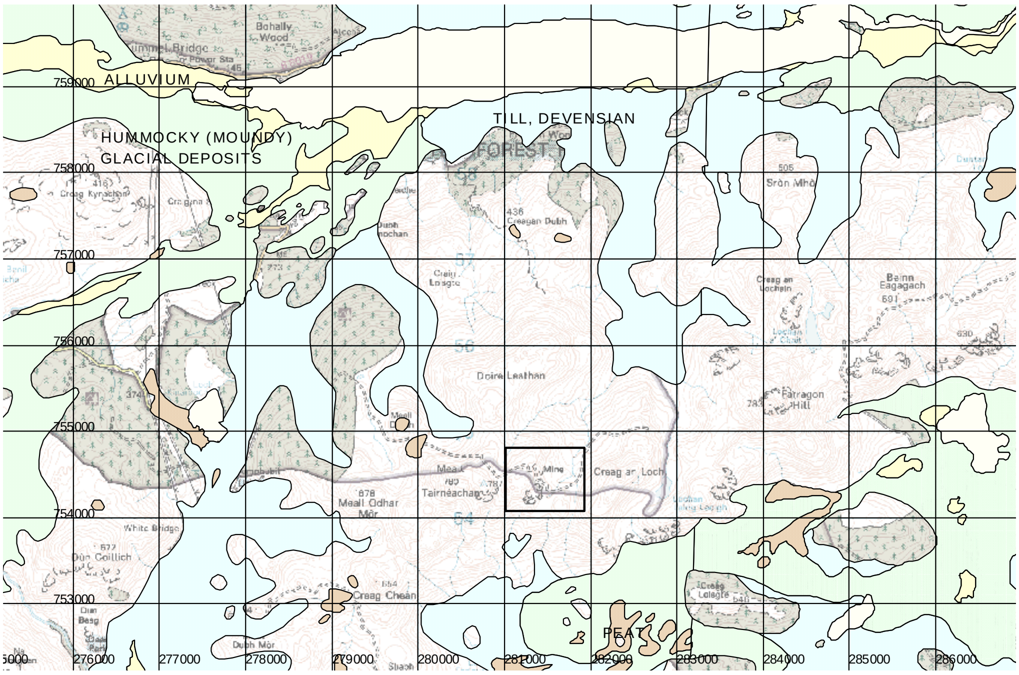

Figure 4 Superficial deposits of the Foss Mine area (1:50 000 scale, from DigMap). Where no superficial deposits are mapped, bedrock is present within 1 m of the ground surface.

4 Hydrogeology of Foss Mine and surrounding area

4.1 GROUNDWATER FLOW

4.1.1 Natural groundwater flow conditions

The Dalradian schists of the Foss district are generally classed as a low productivity aquifer (MacDonald et al 2004). Intergranular porosity, permeability and transmissivity in the schists are negligible, except in shallow weathered zones, which are typically restricted to the uppermost 1 to 2 m of the bedrock. Below this, groundwater storage and flow are entirely dependent on the presence of fractures in the bedrock. These fractures are infrequent and isolated, as observed during the site visit to the underground mine. The bulk of the rock mass making up the walls of the mine workings is dry, with no groundwater flow or seepage. Stained, but dry, fractures on rock faces are evidence of occasional groundwater movement (Figure 6). The staining results from precipitation of minerals such as iron hydroxides as groundwater moves along the fractures. Such groundwater movement may be seasonal, flowing the wetter winter months, or it may be periodic over longer time periods. Current natural groundwater movement is restricted to very infrequent seepages along fractures (Figure 7).

Evidence from other parts of Scotland suggests that the groundwater flow regime in low productivity fractured aquifers is typically shallow, with most groundwater flow occurring in the uppermost few tens of metres of the bedrock aquifer. Observations and anecdotal evidence from Foss Mine support this. Most of the groundwater inflow to the mine appears to occur in the upper levels, closest to the ground surface. In the deeper levels, which are over 100 m below ground level, there is very little observed groundwater inflow through the tunnel walls and roof.

The volume of groundwater moving through the rock is very small. The typical yield of a borehole (150 to 200 mm diameter) abstracting groundwater from low productivity metamorphic aquifers in Scotland is on the order of 0.2 litres/second (l/s). Groundwater flow to such boreholes typically occurs through a small number of discreet fractures, and in many cases through a single fracture. The available evidence, of infrequent and small groundwater inflows through the mine tunnel walls, indicates that the rock in the Foss area may have particularly low productivity even compared to these standards. The volume of water pumped from the mine as part of dewatering activities provides further evidence of the magnitude of groundwater flow through the aquifer. A maximum volume of approximately 100 m^3/day (1.1 l/s) is pumped to the surface. As well as groundwater inflow to the mine, this includes surface water entering through the tunnels and abandoned open boreholes. As the mine stretches over a lateral area of at least 500 x 100 m and a vertical distance of at least 100 m, this represents a very small inflow rate.

The natural direction of groundwater flow in the area is likely to be northwards, following the direction of the hill slope down towards Loch Tummel. The lowest current mine levels, at approximately 550 to 565 m OD, are at a much higher elevation than the loch, at approximately 155 m OD. Groundwater flow is likely to occur dominantly in the upper few tens of metres of the bedrock. Natural groundwater discharge is likely to be partly via small flows to springs or directly to streams (such as the Frenich Burn and its tributaries) on the hill slopes, and partly directly to Loch Tummel in the valley floor. Much of natural groundwater discharge is likely to occur on the hill slopes below the elevation of the current mine.

Figure 5 Stained but dry fractures are evidence of former groundwater movement

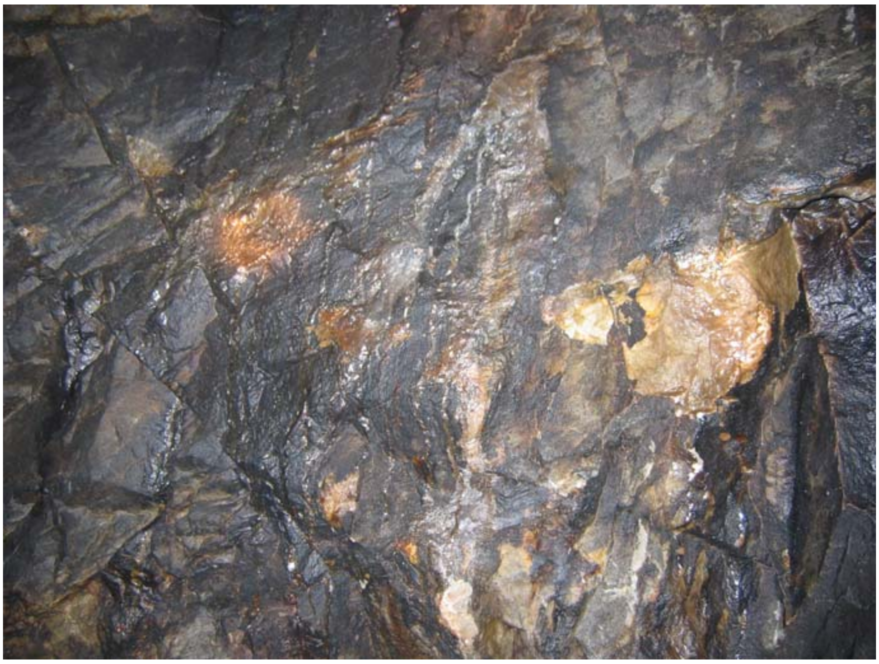

Figure 6 Groundwater seepages along fractures

4.1.2 Impacts of mining on groundwater flow

4.1.2.1 Inflow to the mine

Mining has altered the natural groundwater system in and immediately around the mine. The mine workings have artificially increased the natural permeability of the aquifer in this area, and the mine tunnels, and abandoned open boreholes, act as conduits for rapid water movement through the aquifer. The largest single flow of water observed into the mine during the site visit was not a natural groundwater flow, but derived from an abandoned, open trial borehole which now intersects a mine tunnel. The borehole appears to act as a conduit, channelling groundwater from shallower depths in the rock and/or rainwater from the surface into the mine.

An additional source of water inflow to the mine workings appears to be from rainwater entering the tunnels directly from the ground surface. However, the volume of water pumped from the mine is not reported to increase significantly during rainfall events, and so the volume of rainwater entering the mine directly may be relatively small.

4.1.2.2 Impacts of mine dewatering

During mining operations, the impact on local hydrogeological conditions is likely to be small. There is likely to be very little re-infiltration of water from the mine tunnels into the surrounding aquifer, due to the regular pumping of water from the mine, combined with the naturally low permeability of the surrounding rock. This may have caused dewatering of the surrounding aquifer, and consequent lowering of the natural water table. Consequently, there is likely to be very little natural discharge to the ground surface of groundwater directly from the mine, which means that natural discharge points for groundwater (springs or direct flows to streams) may have dried up. This may have caused a reduction in natural flows to streams, particularly the Frenich Burn, down slope from the mine. However, this is likely to be more than compensated for by the discharge of treated mine water to the Frenich Burn (see below).

4.1.2.3 Impacts of mine water treatment

The treatment lagoons are depicted in Figure 7. The integrity of these lagoons is not known. The main impact of mine water treatment is the discharge of treated mine water (comprising the bulk of groundwater flowing into the mine) to surface water in the Frenich Burn. The water quality impacts of this are discussed below. Because the discharge point is near the watershed, the discharged water dominates the flow in the Frenich Burn at this point.

During heavy rainfall events, relatively large volumes of rainfall reportedly flow overland or via shallow interflow to the lagoons. This can reportedly have the effect of overwhelming the treatment capacity of the lagoons (see below).

A proportion of the water stored in and flowing through the lagoons may infiltrate the ground. The amount of water infiltrating is likely to be small, because of the low permeability of the bedrock.

Figure 7 Treatment lagoons at Foss Mine

4.1.3 Impacts of post-mining changes

When the mine closes, and pumping of water from the mine tunnels stops, the situation will change. The tunnels will continue to act as conduits for any groundwater inflow through tunnel walls, and will provide large volumes of groundwater storage. Water entering the tunnels will flow downwards to the lowest mine level. There are no drainage adits from the mine to the ground surface at this level, and re-infiltration of this water to the surrounding aquifer is likely to be limited by the low permeability of the rock. Although groundwater inflows are slow, the volume of water in the mine will gradually build up, and the water level in the mine will begin to rise. If tunnel openings to the ground surface, and any abandoned boreholes, remain open, surface water may also enter the mine.

Once the water level rises to higher mine levels, where open, potentially water-bearing fractures are likely to be more common than in the deeper levels, the rate of re-infiltration of water to the surrounding aquifer may increase. If dewatering has lowered the water table in the surrounding aquifer, so that there is a large head difference between water in the mine and water in the aquifer, the initial rate of re-infiltration may be particularly rapid. This rate may decrease as the head difference between decreases. Re-infiltrating groundwater is likely to move down slope and discharge to surface water via existing natural discharge points.

If the water level reaches an artificial opening to the ground surface, such as a mine tunnel opening or abandoned open borehole, water will flow freely to the surface. Any water flowing out of the mine may be of poor quality.

4.2 GROUNDWATER CHEMISTRY

4.2.1 Natural groundwater chemistry

There are no recorded analyses of natural groundwater chemistry in this area, either pre- or since the onset of mining. In other similar groundwater environments in Scotland, groundwater tends to be young and relatively weakly mineralised, with pH values of between 6 and 7.5, an SEC value of less than 350 μS/cm, and low concentrations of metals in solution. However, the mineralisation of the bedrock aquifer in the Foss area, in particular the presence of pyrite, may lead to the dissolution of soluble pyrite oxidation products in groundwater and the consequent decrease in pH below 6. This can cause metals in the rock to be taken into solution, and may lead to naturally high concentrations of elements such as Fe, Mn and Zn in groundwater.

The nearest indicator of groundwater chemistry is the local stream water chemistry. SEPA regularly sample surface water from the Frenich Burn below the Foss Mine, and have also carried out surveys of stream water chemistry in other streams in the area. These surveys indicate that there are naturally high concentrations of some elements, such as Al, in local stream water (SEPA 2003). This is likely to be controlled by the pH of rainwater and by the limited buffering capacity (limited availability of base cations such as Ca and Mg) of the bedrock. It may be that natural groundwater chemistry in this area shows some of the same trends, but note that groundwater chemistry is also influenced by other factors, including flow rates and residence time.

4.2.2 Impacts of mining operations on groundwater chemistry

4.2.2.1 Impacts within the mine

Mining operations can expose potentially reactive minerals in the bedrock to the atmosphere. The exposure to atmospheric oxygen of areas that would otherwise be essentially oxygen-free can lead to oxidation of sulphide compounds (such as pyrite) to form hydroxy-sulphate minerals on the surface of exposed rock, such as tunnel walls or fractures in the surrounding rock (Younger 2000). These minerals can contain ferric (soluble) Fe and SO_4, among other constituents (Rees et al. 2002). Groundwater flowing through the mine will dissolve the minerals, causing significant increases in acidity and in the concentrations of constituents such as SO_4, Fe and other metals.

If this mineralised groundwater is subsequently oxygenated within the mine, minerals such as Fe can precipitate out and be deposited on rock walls. The most striking examples of this in the Foss Mine are in areas where large flows of water occur: where water is flowing down an abandoned borehole and where it is being pumped up from lower levels in the mine (Figure 8).

(i) Flow through abandoned borehole (ii) Water being pumped from lower mine levels

Figure 8 Mineral staining (probably dominantly Fe) on tunnel walls caused by the oxidation of mineralised groundwater

4.2.2.2 Impacts down slope of the mine

The major impact on water chemistry down slope of the mine is on stream water chemistry in the Frenich Burn, as a result of the discharge of treated mine water from the lagoons. The pumping of the bulk of groundwater from the mine, and the probable limited re-infiltration of water in the mine to the surrounding aquifer, mean that any discharge of acid groundwater down slope of the mine is likely to be minimal. There are consequently not likely to be significant direct impacts (via groundwater flow) on groundwater or surface water chemistry down slope of the mine.

4.2.3 Impacts of post-mining changes on groundwater chemistry

4.2.3.1 Impacts within the mine

In most mining operations, the main dissolution of hydroxy-sulphate minerals in groundwater occurs once mining and mine water pumping has stopped, and groundwater floods the mine workings. The initial flooding of mine workings by groundwater typically causes a ‘first flush’ of acidic, highly mineralised water, followed by a gradual removal of the products of hydroxy-sulphate mineral dissolution from the mine workings as fresh recharge flushes through the workings (Younger 2000).

If mine workings become saturated with groundwater, sulphide oxidation largely stops, due to the limited availability of oxygen. Beyond the ‘first flush’ the long-term chemistry of mine water discharge is controlled by recharge water chemistry, the relative abundance of acid-generating and buffering mineral assemblages in the mine, and their relative reactivity (Rees et al 2002). Alternatively, if abandoned mine workings are above the water table, they will remain free draining, and sulphide oxidation can potentially continue to produce soluble hydroxy-sulphate minerals and to generate acidity. These two alternative processes are illustrated in Figure 9.

The dominant process most likely present at Foss Mine is not clear, because the natural local water table is not known. However, it is highly likely that at least the lower mine levels (which are more than 100 m below ground level) will be flooded, and that this water may become acidic and highly mineralised.

4.2.3.2 Impacts down slope of the mine

The water building up will at some point begin to flow out of the mine. Although the outflow of water will be slow, a small volume at least of acid mine water is likely to flow out through the aquifer. This water will discharge to natural discharge points, such as springs and streams, at some point down-slope of the mine. Although some dilution may take place, the water quality is unlikely to improve significantly before it discharges. There is therefore a risk of acid mine water discharging to the surface down slope of the mine.

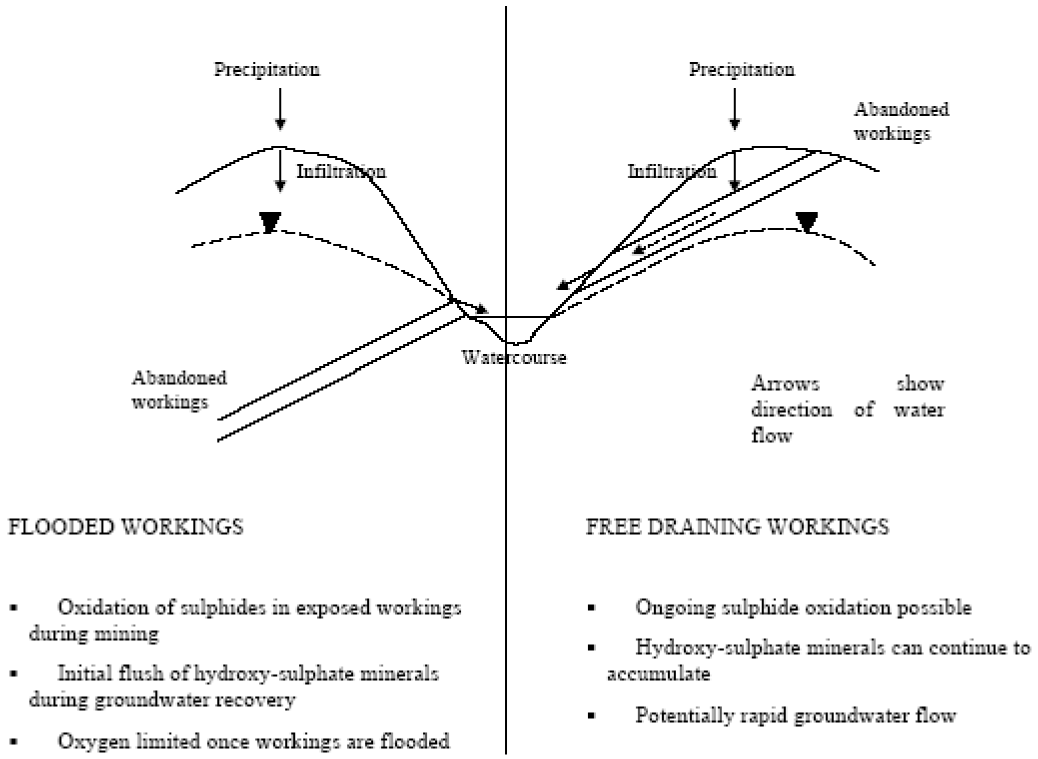

Figure 9 Summary of processes occurring in flooded and free draining abandoned mine workings that can affect groundwater discharge chemistry (after Rees et al. 2002).

5 Summary of risks to groundwater and groundwater-dependent surface water and terrestrial ecosystems

5.1 RISKS DURING MINE OPERATION

The main risk during mine operation is the elevation of concentration of certain metals, in particular Zn, in surface water in the Frenich Burn. The main source of elevated Zn concentrations is acid mine water (mostly groundwater, but also including a proportion of surface water that has entered the mine) pumped to surface treatment lagoons and thence discharged to the burn. Acid mine water is produced as a result of the dissolution of hydroxy-sulphate minerals from exposed rock surfaces as water flows through the mine. This process increases water acidity and consequently the capacity of water to dissolve metals and other constituents from the rock.

Under normal circumstances, treatment in the lagoons is effective and the discharged water is within acceptable quality limits. However, during high rainfall events the treatment capacity of the lagoons appears to be overwhelmed, and inadequately treated water is occasionally discharged to the burn.

Therefore, although the source of the main risk is largely groundwater, the major route by which Zn enters surface water during mine operations is via surface water flow.

There is a minor risk of acid mine water recharging to the aquifer via re-infiltration within the mine, or of inadequately treated acid mine water recharging either via the treatment lagoons or via streambeds after discharge to the Frenich Burn. This water could subsequently discharge to surface water at lower elevations on the hill slope. The risk is considered to be very minor due to the low aquifer permeability.

5.2 RISKS POST MINE CLOSURE

The main risk after mine closure is the increase in acidity and mineralisation of groundwater in and down slope of the mine and, via groundwater discharge, in surface water down slope of the mine.

If water is no longer pumped from the mine after mine closure, groundwater will gradually flood the mine workings. The dissolution of hydroxy-sulphate minerals by flooding groundwater will lead to an increase in water acidity and mineralisation. The slow rate of groundwater flow means that this process could take many years. If tunnel entrances and/or abandoned boreholes are not effectively sealed, surface water inflow will speed up this process.

At some point the water flooding the mine workings will flow out of the mine, either slowly via groundwater flow through fractures, or rapidly via artificial conduits such as tunnel entrances or abandoned boreholes. Acid mine water flowing through fractures will discharge down slope from the mine via springs or streams. Water quality may improve during groundwater flow, but the discharging groundwater is likely to be of poor quality.

The slow rate of groundwater flow, and the small volumes of groundwater involved, mean that flows of acid mine water are likely to be small. However, because of these low flows, the formation and outflow of acid mine water could continue for a considerable period of time.

5.3 EXTENT OF POTENTIAL IMPACTS

Any impacts to groundwater quality, and/or to surface water quality as a result of groundwater discharge, are likely to be restricted to the sub-catchments of the Frenich Burn, and possibly the neighbouring burns. Because the groundwater flow system is expected to be shallow, groundwater moving from the Foss Mine is likely to discharge to the surface within these surface water sub-catchments.

6 Conclusions

- Groundwater in the aquifer surrounding the Foss Mine may contain naturally high concentrations of certain elements present in high proportions in the bedrock, such as Fe and Zn, although there are no available data.
- Natural groundwater quality within the mine is likely to be degraded as a result of the exposure of minerals in the bedrock to the air within the mine workings, which creates hydroxy-sulphate minerals through oxidation of sulphide compounds, and the dissolution of these minerals from rock surfaces as water moves through the mine. The effect is likely to be an increase in the acidity of mine water, allowing metals in rock-forming minerals to be taken into solution.
- Virtually all water in the mine is currently pumped to ground surface and treated. Untreated mine water is reportedly of poor quality, with low pH and high concentrations of certain elements, such as Zn.
- Treated mine water is discharged to the Frenich Burn. Water quality in the burn immediately below the discharge point generally shows elevated pH and elevated (sometimes only slightly) concentrations of Cd, Cr, Cu, Fe, Pb and Zn, compared to water quality upstream from the mine. Chemical concentrations are generally within the allowable limits, although occasional exceedances occur, with the major element of concern being Zn. Water quality in the Frenich Burn at Frenich generally shows slightly elevated concentrations of Cd, Cu, Ni, Pb and Zn compared to water upstream from the mine, but generally lower concentrations than immediately below the mine.
- The main source for the exceedance of the allowable Zn limits in the Frenich Burn is likely to be inadequately treated acid mine water discharged via the surface treatment lagoons. Inadequate treatment is thought to be associated with heavy rainfall causing increased surface water flow into the treatment lagoons, which overwhelms the treatment capacity at the site.
- During mining operations the risk of acid mine water discharging directly from groundwater to the Frenich Burn or other surface water body is likely to be very small. There may be a small risk of acid mine water re-infiltrating to the aquifer within the mine or recharging through the treatment lagoons, which would discharge to surface water down slope of the mine.
- Post mine closure, the main risk to groundwater and groundwater-dependent systems is likely to be caused by gradual flooding of the mine workings by groundwater, dissolution of hydroxy-sulphate minerals, and consequent increase in water acidity and mineralisation. The slow rate of groundwater flow means that this could take many years. Acid mine water will flow out of the mine either slowly, via fractures, or rapidly via artificial conduits such as tunnel entrances or abandoned boreholes. Acid water flowing from the mine through fractures will move to natural discharge points such as springs or streams down slope from the mine. Water quality may improve during groundwater flow, but the discharging groundwater is likely to be of poor quality. The slow rates of flow and small volumes of groundwater involved are likely to mean that the formation and outflow of acid mine water could continue for a considerable period of time.

7 Options for minimising impacts on groundwater and groundwater-dependent surface water and terrestrial ecosystems

During mine operation:

- Prevent the inflow of large volumes of surface water to the treatment lagoons, so that the treatment capacity of the lagoons is not overwhelmed.

Post mine closure:

- Minimise the inflow of surface water and/or rain water to the mine tunnels, for example by sealing tunnel entrances and any abandoned open boreholes, and/or by diverting surface water flow away from these conduits. This will slow down the rate of water level rise in the mine tunnels.
- If pumping of mine water to the surface is stopped, monitor the water level in the mine tunnels. The rate of water level rise will provide information on the balance between water inflow and outflow. If the water level does not rise far, it may mean that groundwater is flowing out to the aquifer at low levels in the mine. If the water level rises to higher levels, it suggests that there is little outflow at lower levels, and that there is a risk of outflow through any unsealed conduits such as adits or abandoned boreholes.
- Depending on the results of monitoring of the water level in the mine, check for discharges of acid mine water via natural flows to springs and streams, or via conduits such as unsealed mine adits. If mine water levels remain low, discharges are likely to occur at lower elevations on the hill slopes below the mine. If water levels are high, discharges may be concentrated at higher elevations.

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Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

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