The hydrogeochemical evolution of groundwater inflow to ventilated underground voids

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ABSTRACT

The nature and magnitude of changes induced in low-permeability rocks that enclose operating underground excavations (e.g. tunnels, galleries, caverns, mines and storage facilities) is being evaluated by analysing hydrogeochemical data from voids that have been in existence and use for up to fifty years. Initial field investigations indicate that atmospheric conditions within the voids play an important role in the hydrogeochemical evolution of the disturbed zone and associated rock/atmosphere interface. In particular, the elevated temperature and reduced humidity of a ventilated underground atmosphere affects the formation of efflorescent (surface) and subflorescent (below surface) minerals on and within the wall rocks. The formation of these minerals (particularly sodium sulfate) on tunnel and void walls is of concern for the long-term maintenance of underground infrastructure. Investigations are underway on the relationships between groundwater inflow chemistry, atmospheric conditions, mineral crystallisation phases and changes in redox conditions in the near-field environment of the void.

INTRODUCTION

Understanding the processes and quantifying the hydrogeochemical changes that occur in the rock mass immediately surrounding deep ventilated underground voids is important to a broad spectrum of problems in the engineering and geoscience fields including underground disposal of radioactive waste, long-term engineering and environmental effects on tunnels, underground power stations, underground storage facilities and mines. Knowledge gained through this research will be an aid when assessing:

- potential long-term operation and maintenance liabilities due to groundwater inflow;
- rock mass weathering and stability;
- design constraints on underground waste storage facilities (chemical and radioactive); and
- environmental implication (hydrogeochemical) of eventual abandonment and flooding of underground voids.

HYDROGEOCHEMICAL CHANGES INDUCED BY VOID EXCAVATION

EXCAVATION-INDUCED CHANGES

Hydrogeochemical changes induced by void excavation, drainage and ventilation result from the disruption of the enclosing rock mass. Changes in permeability in the near-field of the void (the disturbed zone surrounding the excavation) govern the rates of groundwater flow and therefore the potential for changes in hydraulic saturation. This excavation-induced change in permeability controls the scope for development of unsaturated conditions around an underground void. If unsaturated pores (fractures) develop around a ventilated void, the rock mass can receive oxygen (and other oxidising gases). Ingress of these gases to the rock mass determines the extent of alteration in rock mass mineralogy and geochemistry. Where the rock mass around the void remains saturated, mineralogical changes are restricted to formation of speleothems and evaporative minerals inside the void. Where the void is in contact with unsaturated rock, mineralogical changes (principally precipitation of redox-sensitive species and formation of evaporite salts) may possibly extend some distance into the rock mass.

THE EFFECTS OF TIME ON THE CHEMISTRY OF GROUNDWATER ENTERING VOIDS

Research conducted on the behavior of existing excavations over time has generally been linked to engineering operational requirements, such as the geotechnical stability and testing of tunnels (Hansen, 1996; Haack et al., 1995), groundwater inflow (Russell and Iske, 2000; Cesano et al., 2000), seepage pressures on tunnel and excavation walls (Fazio, 1984), effects of groundwater chemistry on engineering infrastructure (Robins, 1997), weathering rate of tunnel walls (Oyama and Chigira, 2000) and deterioration and maintenance of tunnels (Inokuma and Inano, 1996; Richards, 1998).

Geochemical and hydrochemical aspects of some studies have generally been limited to mine water rebound chemistry (Younger, 2000), quantifying alkali-silica reactive processes (Wakizaka, 2000; West el al., 1998; BRE, 2000) and assessing diffusion coefficients, porosity and mineralogical changes to evaluate the relationship between depth of oxidation and time of exposure (Oyama and Chigira, 2000). Recent studies related to the underground disposal of radioactive waste have involved detailed characterisation of recently excavated rock mass, near-field and far-field groundwater, and used these geochemical and hydrogeological data as input to predictive modeling (Gascoyne et al., 1995; Johnsson et al., 1998; Laaksoharju, 1999; Thury and Bossart; 1999). Most of these studies reveal changes in salinity (mixing, evaporation) and redox status (oxidation) to be the key modification in groundwater inflow chemistry over time (Younger, 2001). Although rates of kinetics for dissolution/precipitation reactions have been determined for these systems, much of this research has been conducted on rocks unaffected by long-term atmospheric exposure.

GROUNDWATER CHEMISTRY AND REDOX REACTIONS IN THE NEAR-FIELD

Studies on temporal changes in groundwater chemistry due to void excavation are rare. Relevant studies have detailed: redox changes that occurred after a void intersected major fractures in granites (Banwart et al, 1994; 1996; 1999); hydrogeochemistry of seepage water in a tunnel (Chae et al, 2001); and degassing of deep groundwater around boreholes and drifts (Jarsjo and Destouni, 2000). The nature of water-rock-air interaction is fundamentally different between voids that remain permanently below the water table, those where the void intersects or fluctuates above/below the water table, and those located within the vadose zone. This project only covers voids that are located deep enough to remain permanently below the water table, where groundwater within the rock mass remains in an anoxic state except where the void is located.

The problem of measuring redox potential in the field and defining redox reactions has been highlighted by Grammosipov and Grammosipova (1999), Grenthe et al. (1992) and Pitsch et al. (1995). The mineral assemblages sampled from fracture skins and present day groundwater chemistry can be compared with saturation indices obtained from laboratory redox experiments.

POST-VOID MINERAL PRECIPITATION PROCESSES IN THE NEAR-FIELD ENVIRONMENT

Principal processes of post-void precipitation include at least three categories of minerals;

- Common evaporite minerals (halite, epsomite, etc.) formed through the mechanisms illustrated in Figure 1;
- Acidic evaporite minerals (ferric/ferrous hydroxysulphates) formed by evaporative concentration of pyrite oxidation waters;
- (Hydr)oxides of redox-sensitive metals (Fe and Mn); and
- Other minerals (authogenic illite, carbonates, etc.).

RESEARCH SITES

DESIRABLE SITE FEATURES

A review of sites within the United Kingdom suitable for in situ characterisation of the enclosing rock mass and groundwater inflow sampling has been undertaken. Selection criteria used in the consideration of these sites were:

1. An environment similar to that of an underground repository site, such as: deep crystalline or other rock mass of low permeability;

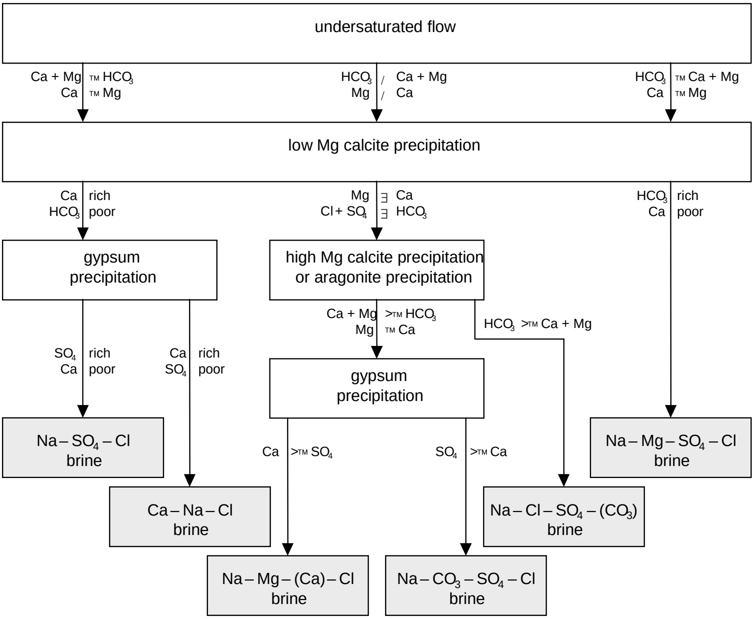

Figure 1. Geochemical pathways for brine and evaporate mineral formation from waters of varying chemistry (modified from Shaw et. al., 1989)

  - a low degree of mineralisation in order to minimise metal complexation;
  - circa-neutral pH groundwater environments;
  - rock mass has remained saturated throughout the void existence;
  - activities within the void have not artificially enhanced wall-rock degradation (e.g. aggressive environment of road vehicle tunnels and active mines with diesel powered equipment and poor ventilation);
  - evaporation and drying of seepage water from tunnel wall into underground space; and
  - the presence of man-made support structures (e.g. concrete lining, grouting, bolting, etc.).
2. Documented site history, including:
   - past and present use of voids;
   - sources of geological/geotechnical/groundwater data in the form of reports, borehole logs, construction plans; and
   - age and condition of voids.
3. Site access and health and safety considerations, including:
   - permission from owner/operator to sample and conduct invasive testing in voids; and
   - cost effective location, using Newcastle as a base.

CRUACHAN PUMPED STORAGE SCHEME

The Cruachan underground power station was completed in 1965 and was one of the first major pumped storage voids constructed in the United Kingdom. The site is located beneath Ben Cruachan and alongside Loch awe in Western Scotland. The system was constructed within granite and phyllite rocks of low permeability to a maximum depth of approximately 500 m below the ground surface, equivalent to 10 m below sea level (Figure 2). Along with the main excavations associated with the power generating infrastructure, there are 15 km of aqueduct tunnels connecting surrounding catchments to the power station reservoir. These tunnels are located up to 700 m below the surface and operate under open channel flow conditions.

DINORWIG PUMPED STORAGE SCHEME

Construction of the Dinorwig Power Station in the North Wales region of Snowdonia was completed in 1979. It is one of the largest pumped storage plants in Europe. Excavation was carried out by drill and blast technique in slates of low permeability, forming nine caverns and interconnecting tunnels to a maximum depth of 400 m below the ground surface. Void walls are concrete lined in the generating hall, transformer hall and where tunnels intersected jointed slate. There are also areas of unlined tunnel sited in more competent slate and diorite.

The site is located in a region that is well documented with regard to engineering investigations due to historic open-cast and underground slate quarrying dating back to the 1700’s. As a result, exposed slate surfaces (both above and below ground) can be correlated with substantial lengths of exposure.

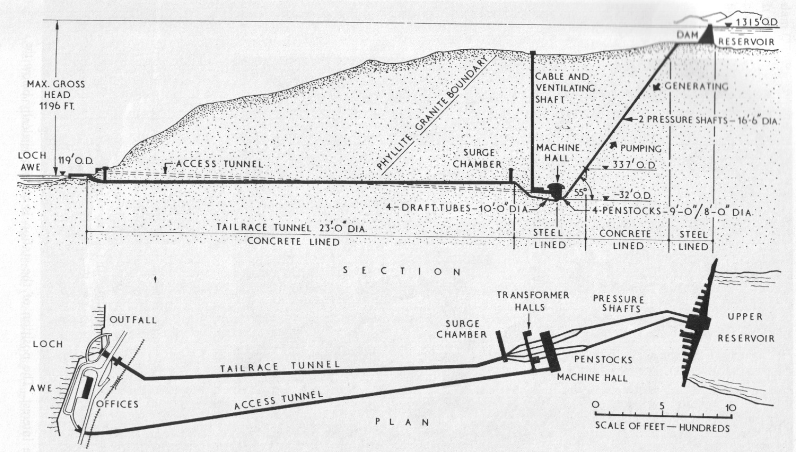

Fig.6. Cruachan Pumped-Storage Scheme.

Figure 2. Layout of Cruachan pumped storage scheme (Young, 1966)

RESEARCH METHODS

We are assessing the long-term changes to host rock, fracture mineralogy and groundwater inflow chemistry associated with the void's presence in order to identify and quantify anticipated near-field (within the excavation disturbed zone) hydrogeochemical changes.

To develop an understanding of the dominant hydrogeochemical processes associated with groundwater inflow to the Cruachan voids, we are collecting data by undertaking a range of activities, including:

- geological and structural mapping of surface outcrops and underground features intersected by the tunnels and chambers;
- sampling and analyses of surface water sources and groundwater inflow;
- quantifying groundwater inflow rates from specific fractures;
- sampling and analyses of mineral precipitation on void walls, fracture/void intersection planes and bacterial activity at groundwater inflow points; and
- monitoring of atmospheric conditions in the power station chamber and access tunnels.

PRELIMINARY RESULTS – CRUACHAN

GEOLOGICAL AND STRUCTURAL CONTROLS ON GROUNDWATER INFLOW

The Loch awe region is located in granite and phyllite host rocks, which are dominated by two sub-vertical joint sets, striking north-south and east-west. Structural features that control groundwater flow include geological boundaries, zones of shearing and faulting, and intrusions and associated contact margins.

HYDROCHEMICAL EVOLUTION ALONG FLOW PATHS

Chemical analyses of groundwater inflow to tunnels along individual joint planes and structural features show both chemical and temperature variations between joints of close proximity (Figure 3a). Preliminary analyses of these results indicate a low degree of mixing of groundwater flowing along individual fractures from surface recharge to tunnel / fracture plane intersection.

Figure 3b presents chemical data for surface waters that act as recharge sources to the fractured aquifer. Hydrochemical evolution along the fractured aquifer flow path results in surface waters dominated by Na–Ca–HCO_3–Cl evolving to Ca –Na –HCO_3–SO_4 dominated groundwater.

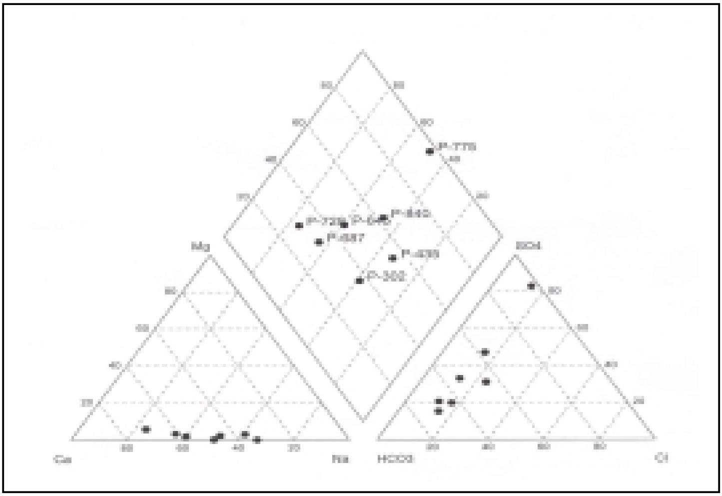

Figure 3a. Cruachan power station access tunnel groundwater inflow quality

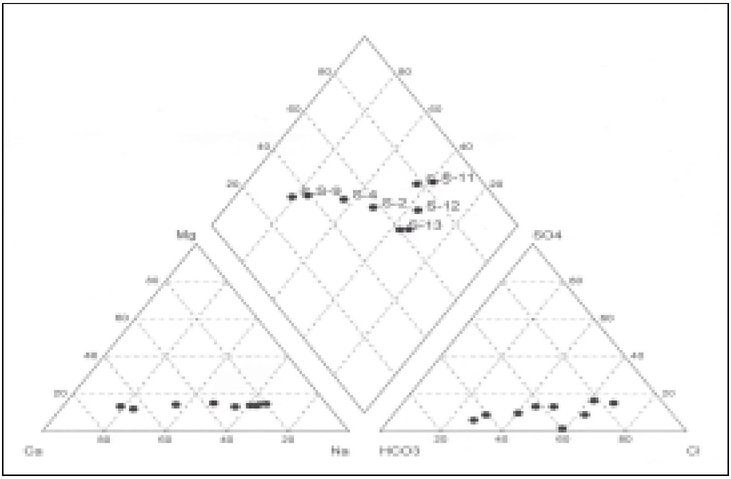

Figure 3b. Cruachan surface water quality

ATMOSPHERIC CONDITIONS

The operation of high voltage transformers in the underground chamber in the Cruachan facility produces elevated temperatures. To maintain acceptable underground atmospheric conditions for both machinery operation and workplace environment, the chambers and access tunnel are cooled by an air conditioning and ventilation system. The resulting atmosphere has a temperature range of 15 to 25°C; with relative humidity varying from 70% in the generating chamber to 100% in the access tunnel 300 m from the generating chamber (Figure 4).

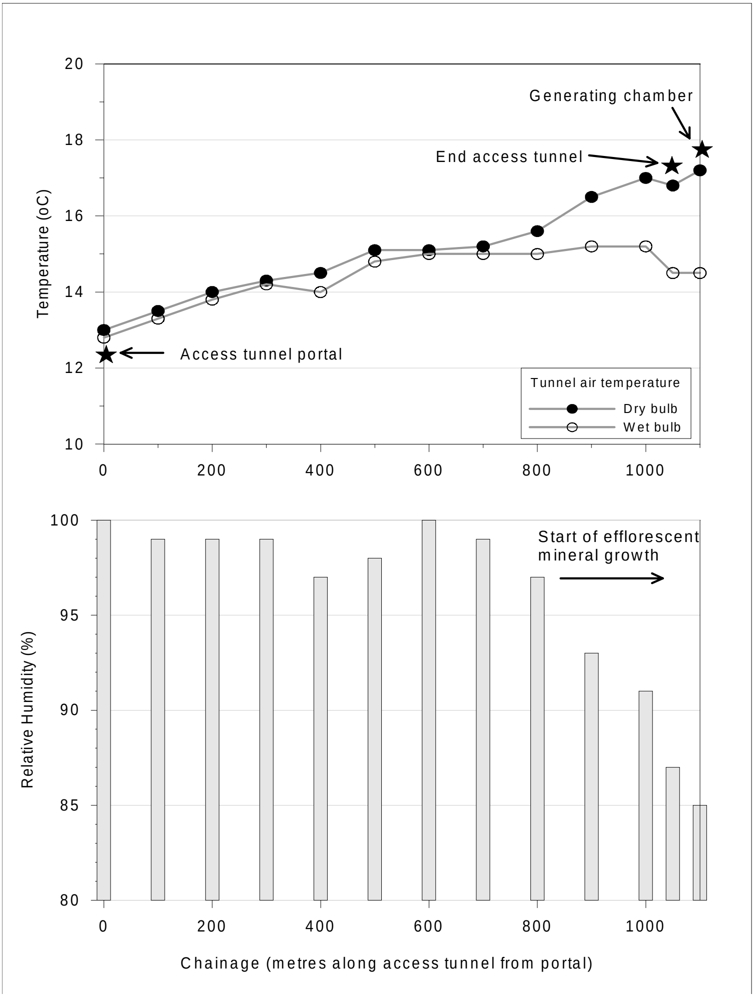

Figure 4. Atmospheric conditions in Cruachan power station access tunnel

The aqueduct tunnels have no artificial ventilation, with their atmosphere controlled by seasonal climatic conditions. Air temperature in the tunnels are controlled by groundwater inflow temperatures (6–9°C), the temperature of surface water flow through the tunnels (1–10°C), and outside air temperatures (-10–20°C). Relative humidity is close to the dew point (95–100%).

EVAPORITE MINERAL FORMATION

Atmospheric conditions within the generating chamber and proximal section of the access tunnel have resulted in the formation of evaporite minerals on the wall-rock surface and along fracture intersections (Figure 5). These minerals form when the evaporation rate of the void atmosphere exceeds the groundwater inflow rate. The precipitants have been characterized by X-ray diffraction and include calcium sulfate, sodium sulfate, sodium calcium sulfate, and carbonate minerals. These minerals have formed from groundwaters with a low level of mineralization (i.e. total dissolved solids less than 200 mg/L). Studies to investigate the relationship between groundwater chemistry and the resulting mineralogy and phases (efflorescent vs. subflorescent) of evaporate minerals are underway.

PRECIPITATION OF HYDROXIDES AND OXIDES

Hydroxides of redox-sensitive metals such as $Fe(OH)_2$ and $Mn(OH)_2$ form on tunnel walls where groundwater with a degree of mineralization flows in through fractures. At some points, the buildup of these hydroxides can seal the entry point, rerouting flow to another section of the fracture. Studies to investigate the relationship between groundwater chemistry and the resulting mineralogy of these hydroxide and oxide minerals are underway.

Figure 5. Efflorescent mineral buildup along fracture plane intersection with tunnel wall

BACTERIAL ACTIVITY

The presence of sulfur oxidizing bacteria may be linked to elevated temperatures in the power station tunnel. These bacteria exist as jelly-like colonies at points of groundwater inflow (Figure 6). Studies to investigate the relationship between bacterial activity, groundwater chemistry and atmospheric conditions within the tunnel are underway.

Figure 6. Sulphur oxidizing bacterial slime at groundwater inflow points

PROJECT DIRECTION

We hope to develop an understanding of the relationship between groundwater inflow chemistry, atmospheric conditions, mineral crystallisation phases, the level of bacterial activity and changes in redox conditions within the near-field environment of the void.

FUNDING

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