

Long-term stability of mine tailings, Macraes Mine, Otago: Comparison to a geological analogue

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Abstract

Bulk ore tailings from the Macraes gold mine gold extraction process are stored in a large (ca 0.6 km², 80 m deep) mixed tailings impoundment whose pH is maintained near 8 by natural rock neutralizing capacity. The mixed tailings will be stored in this impoundment in perpetuity after mining ceases. Confidence in the long term environmental stability of these tailings can be gained from examination of mineralogically and chemically similar geological situations in the immediate vicinity. A sequence, typically about 5 m thick, of sands and gravels derived from the Macraes mineralized zone 12 000 to 28 000 years ago contains rounded detrital sulphide mineral grains which are unoxidized despite close proximity to the surface and occasional incursion of oxygenated waters. Saturating water pH is currently 7-8. Sands with 0.2 to 0.8 wt % organic carbon host sulphate-reducing bacteria (SRB), and localized cementation by authigenic framboidal pyrite has occurred. Comparison of the 28 000 year-old sediments with the modern tailings suggests that similar chemistry will prevail, possibly with deposition of authigenic pyrite in the tailings, in the long term. As long as the present slightly anoxic and circumneutral pH environmental conditions are maintained in the mixed tailings dam, sulphide decomposition and acidification are unlikely. These sediments provide a plausible geological analogue for long-term benign storage of the mixed tailings impoundment.

Introduction

A large sulphide-bearing tailings complex is being progressively developed at Macraes Flat, Otago, New Zealand, associated with a gold mining operation. The tailings complex will ultimately be capped with rock and soil, and the site will be revegetated and left in perpetuity for non-mining land uses. Confidence in long-term stability of the tailings is essential before such rehabilitation can be carried out and the mine site abandoned. This confidence can be gained by examining natural sulphide-bearing sediments which occur in the immediate area. These sulphide-bearing sediments (Craw and Chappell 1999) were exposed during overburden stripping for the gold mine. This study makes a direct comparison between the modern tailings and the natural sulphide-bearing sediments with respect to physical and chemical properties, and shows that the sediments constitute a useful natural analogue for long-term stability of the sulphide bearing mine tailings under the climatic conditions of the East Otago uplands.

Macraes tailings complex

The tailings from the Macraes processing plant are retained in two earth rockfill impoundments (Figure 1B), the upper

being the smaller dam containing material from the cyanidation plant. These impoundments, which have upstream and downstream slopes of 30°, are built across the topographic depression of Maori Tommy Gully, a tributary of Deepdell Creek (Figure 1A). During the first four years of operation (1990-1993), the sulphide-poor separate slurry was dumped into the larger tailings impoundment, while the sulphide-rich tailings (containing up to 10% sulphides in a mainly silicate sediment) were pumped as a slurry to the smaller concentrate tailings impoundment (Figure 1B). In late 1993, the regime for tailings management was altered and all tailings were mixed together and deposited into the larger impoundment. The concentrate tailings in the upper dam are currently being reprocessed through the pressure oxidation plant and are scheduled for full consumption by 2003.

The large mixed tailings impoundment (Figure 1B) is about 1 km wide, 600 m long, and up to 80 m deep in parts. Earliest tailings (Figure 2A) were from processing of the oxidized cap on the Round Hill pit (Figure 1B), and this contained few sulphides. Sulphides are also rare in the flotation tailings deposited up to mid 1993 (Figure 2A), as most sulphides were deposited in the concentrate impoundment (above). The flotation process is c. 90% efficient, so the sulphide content

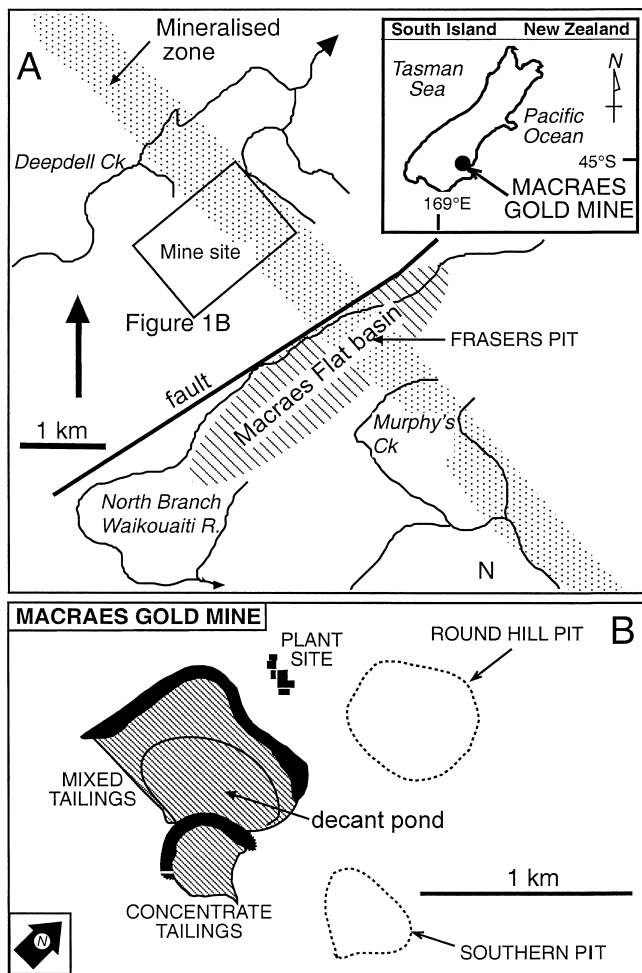


Figure 1. (a) Regional sketch map (inset) indicating the locality of the Macraes gold mine in the South Island of New Zealand. Geological map of the Macraes Flat area showing the location of the Macraes mine site and the currently mined Frasers Pit in the Hyde-Macraes Shear Zone. (b) Locality map of Macraes gold mine site showing the excavation pits and the mixed and concentrate tailings dams.

of the early flotation tailings is c. 0.05%. After the 1993 change in operating procedure, the proportion of sulphides in the tailings immediately rose to c. 0.4% (Figure 2A) for about 5 years. This resulted in a tailings layer 20–40 m thick in the impoundment. These tailings are overlain by a thin layer of oxidized mixed tailings and then a layer of sulphide-poor flotation tailings formed during a short period of concentrate separation leading up to introduction of pressure oxidation (Figure 2A). The mixed tailings are sandy (> 50 μm particles) throughout with a matrix of silt and clay sized particles, especially where the sulphide concentrate (<15 microns) was added. Typical hydraulic conductivities are on the order of 10^{-2} m/day for mixed tailings.

Chemistry

Sulphur content of ore samples is mainly 0.3–1 wt%, compared to typical schist which has <0.3 wt% S (Figure 3). Non-carbonate (graphitic) carbon content of typical schist is c. 0.1 wt% (McKeag et al. 1989), and ore samples have up to 2 wt%

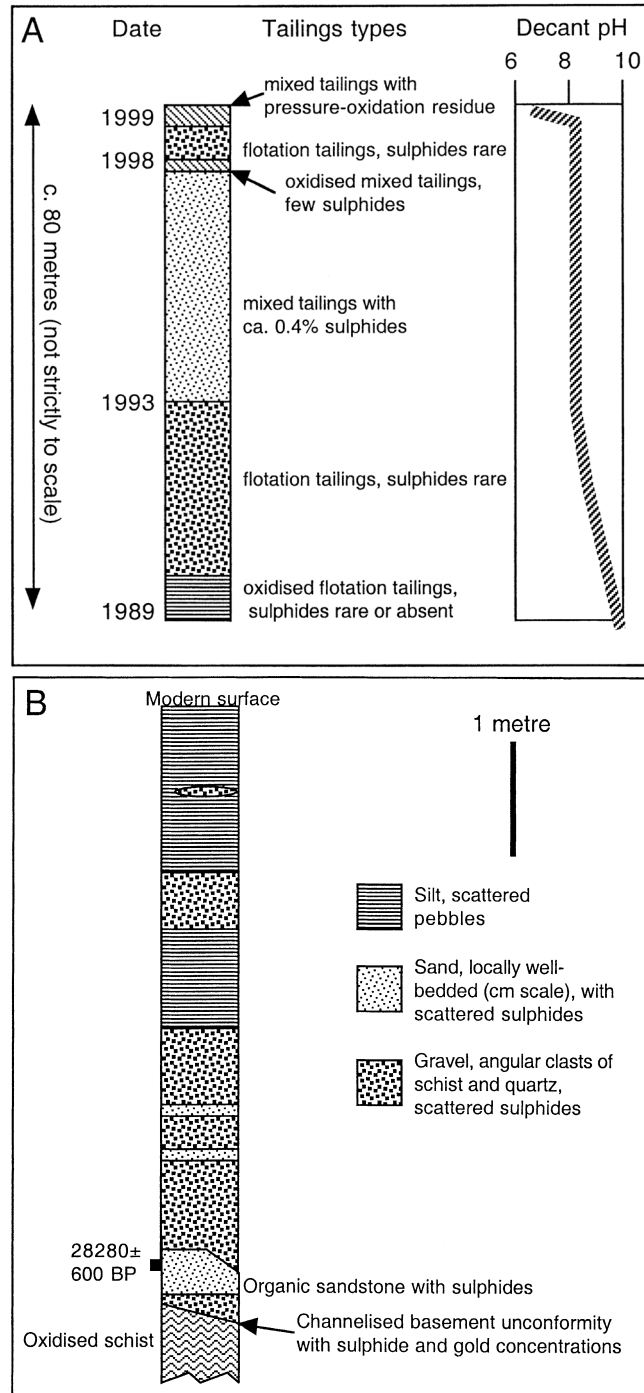


Figure 2. (a) Measured section through the mixed tailings dam showing the various layers of flotation tailings that have been deposited since 1989. The pH of tailings decant water has evolved with time from near 10 to about 8 for most of the tailings deposition period and with the commencement of pressure oxidation, minor acidification towards pH 6 has occurred. (b) Measured section of the Macraes Flat basin fill sediments in prospecting pit FR002, Frasers Pit area, from basement to the upper limit of exposure. Sample site for radiocarbon dating is indicated on the section.

C (Figure 3). Carbonate content of unmineralized schist, as indicated by acid neutralization capacity (Figure 4A), varies widely, from 1–15 wt%, but the higher values are for samples within the mineralized shear zone. Ore typically has 3–8 wt% CaCO_3 equivalent (Figure 4A). Carbonate has been leached

from oxidized rocks, and the carbonate content is typically <2 wt% (Figure 4A).

The pH of water in tailings buried in the impoundment is typically near 8 or higher (Figure 5A). Dissolved carbonate in the decant water has remained approximately constant at 100-200 ppm throughout the tailings deposition period (Figure 5A), but dissolved sulphate content has steadily increased to

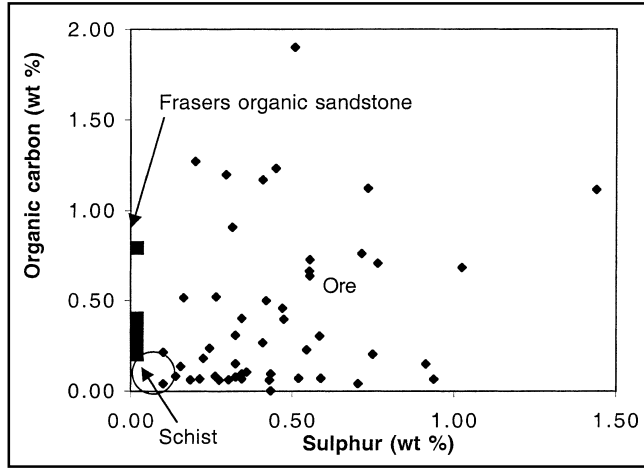


Figure 3. Variation of sulphur and carbon contents between the ore (solid diamonds), Frasers organic sandstone (solid squares) and typical schist (circle). The ore has higher levels of sulphur (to 2%) due to the presence of sulphides, and higher carbon levels (to 1%) due to enriched graphite and carbonate.

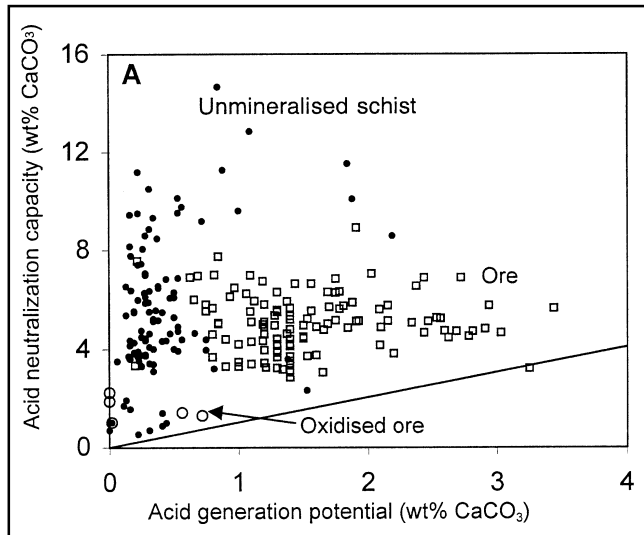


Figure 4. The carbonate content (solid diamonds) for unmineralised schist, as indicated by the acid neutralizing capacity, varies widely (1-15 wt%). The higher values are indicative of samples from within the mineralized shear zone. In the ore (solid squares) the carbonate levels are between 3% and 8% and in the oxidized rock (solid circles) the levels are below 2% due to the leaching of the carbonate. The line represents a 1:1 ratio between acid neutralizing capacity and acid generation potential. The area below the line could potentially yield acid mine drainage. The unmineralized schist, ore and oxidized ore at Macraes Mine lie above this line.

>1500 ppm from ca. 100 ppm initially (Figure 5B). Dissolved arsenic content of decant pond waters varied widely, from <1 to >25 ppm (Figure 5B). The highest values arose during the deposition of mixed tailings between 1993 and 1999.

Macraes Flat sediments

Macraes Flat (Figure 1A) is located in a topographic depression immediately southeast of the main Macraes mine area, and is host to one of the excavation pits of the mine, Frasers Pit (Figure 1A). The depression is an actively forming basin (Craw and Chappell 1999), which lies between low-lying faulted schist ridges to the southeast and northwest. Macraes Flat is the broad low-relief headwaters of the

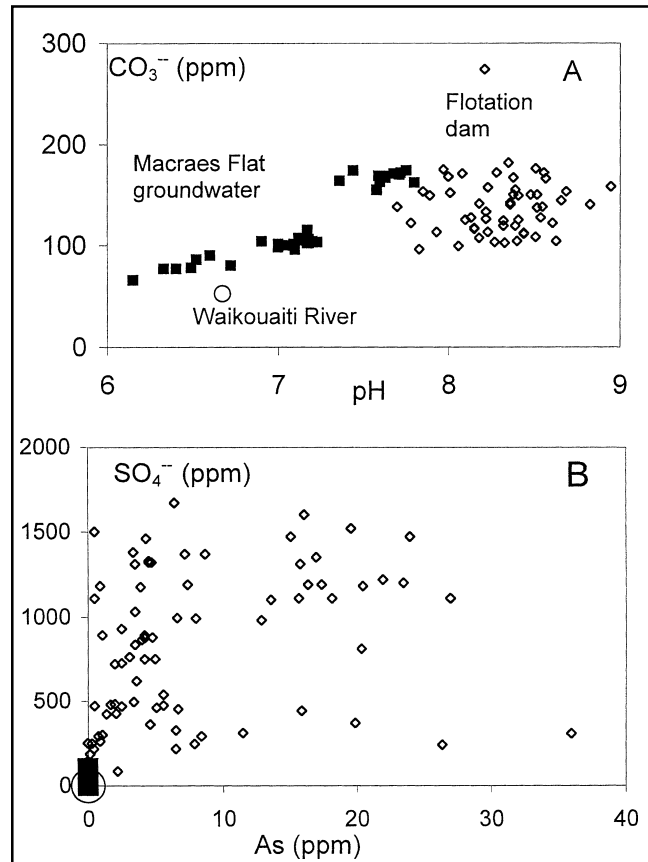


Figure 5. (a) Carbonate-pH diagram, showing water compositions in the Macraes area. Flotation dam decant water (diamonds) has a pH value between 8 and 9 with dissolved carbonate levels remaining fairly constant around 100-200 ppm. At Macraes Flat (solid squares), the dissolved carbonate concentration in the ground water is up to 180 ppm. These moderate levels reflect the generally high carbonate content of the unoxidized sediment provenance (see Figure 6A). The pH values of the Macraes groundwater are in the circumneutral range of 6 to 8. (b) Sulphate-arsenic diagram for water chemistry in the Macraes area (symbols as in A). The dissolved sulphate content of the flotation dam water was initially around 100 ppm but over time the levels have steadily increased to around 1700 ppm, whereas the dissolved arsenic levels vary widely from <1 to >25 ppm, with highest values arising during the deposition of mixed tailings between 1993 and 1999. By comparison, the Macraes Flat ground water has low dissolved sulphate levels of around 200 ppm while dissolved arsenic is below detection.

Waikouaiti River (Figure 1A), which is ephemeral in the area with a nearly imperceptible gradient. The river emerges from Macraes Flat into a steep-sided schist bedrock gorge.

The basin floor has a thin veneer of Pleistocene-Recent sediments covering it. Historic alluvial gold mining activities in these sediments extended to up to 3 m below the natural surface and have caused extensive disruption of the river bed and several ponds have been created. These ponds constitute the principal surface water bodies and are linked by the ephemeral river. Some of the coarser sediments, and immediately underlying oxidized schist (up to 1 m) were processed for alluvial gold in 1998 when they were stripped as overburden during development of the Frasers pit. A prospecting pit, FR002 (Figure 2B) had a complete intact section to basement, and was examined for this study 3 days after exposure. The sedimentary sequence in the Frasers pit west wall was examined 6 months after excavation.

Sediments include schist-derived gravels, sands and silts which are interlayered and bedded on a 0.3-1 m scale (Figure 2B). Some of the beds have a matrix kaolinitic clay component of up to 5%. Gravel bedding occurs throughout the sequence, exhibiting 1-10 cm planar or trough cross beds. The sequence in prospecting pit FR002 is capped by loess. Basal sediments, resting unconformably on the schist basement, are poorly sorted with clasts up to 10 cm in length, compared to the 1-2 cm long gravel clasts higher in the sequence. Individual grains of the main schist minerals (quartz, albite, muscovite and chlorite) make up the silts and are almost entirely fresh, with no evidence of oxidative decomposition or weathering. Iron oxyhydroxide coatings occur on some schist clasts in gravel layers, and stained zones cut across sandy and silty beds

Some poorly sorted sandy layers contain dispersed detrital organic material. Two samples of this organic material were dated by the radiocarbon method, yielding ages of 12670 ± 90 years in the Frasers pit wall, and 28280 ± 600 years near the base of prospecting pit FR002 (Figure 2B; Craw and Chappell 1999).

Detrital sulphides

Sulphide (pyrite and arsenopyrite) grains from the basal gravels and the underlying oxidized schist were extracted by the alluvial gold processing plant at the Macraes mine. The bulk recovered sulphide concentration is around 10 ppm, of which about 60% is coarser than 1 mm and the rest is 0.3-1 mm, and an unknown amount of finer sulphides was lost from the plant. Most grains have some degree of rounding and are clearly detrital, although a minor component of grains with sharp crystal outlines is probably derived from the underlying oxidized schist. Rounded edges of detrital grains show evidence for physical and/or chemical abrasion (Figure 6B, E), but fine details of crystal faces are largely preserved (Figure 6C). There is no evidence of oxidation and iron oxyhydroxide formation on any detrital grains.

Gray sands commonly contain organic material and are variably stained and impregnated with post-depositional iron

oxyhydroxide. Detrital sulphide grains found in the sands of the Frasers pit wall and downstream prospecting pits are much finer grained (ca. 50-100 μm) than those in the gravels and are sparsely distributed (<1%). The sulphides have rounded or irregular forms with sharp margins and no iron oxyhydroxide coatings.

Authigenic pyrite

Pyrite has been deposited authigenically in the matrix of the organic gray sandstone in the downstream FR002 prospecting pit. The pyrite occurs as framboids, with irregular crystals and spheres 1-5 μm in diameter cementing matrix material. Micron-scale pyritic framboid crystals also surround clastic grains in the sediment.

Chemistry

The cool semi-arid climate, with evaporation exceeding rainfall, means that most streams in the Macraes Flat area are ephemeral, with the majority of natural water being stored as groundwater in schist basement fractures and overlying sediments. Surface and ground water sampled from the Macraes Flat area have a circumneutral pH, often alkaline, with moderate carbonate levels reflecting the generally high carbonate content of the unoxidized sediment provenance (Figure 4A, 5A). Sulphate levels are low (<200 ppm; Figures 5A, B), and dissolved arsenic is below detection (Figure 5B).

Bacteria

Aerobic and anaerobic bacterial isolates were recovered from the organic material in the Fraser pit FR002 sandstone. Having been put through the initial screen testing, the isolates were inoculated into commercial identification strips. These systems helped to resolve some of the isolates. The aerobic bacteria were all Gram-negative various lengthed and shaped rods. Those isolates that were able to be identified using commercial systems include:

Pseudomonas aeruginosa, *Flavobacterium odoratum*, *Corynebacterium* spp, *Bacillus cereus*, *Enterobacter aerogenes*, *Serratia* spp, *Photobacterium* spp.

Thiobacillus spp. were isolated from thiosulphate plates (either pH 4 or 7). Around each colony a "hut" of sulphur (determined by X-ray diffraction) was deposited, giving the colonies a yellow crystalline appearance. The anaerobic bacteria isolated from the organic material were sulphate-reducing bacteria (SRB) grown on the selective Desulfovibrio medium.

It is interesting that both thiobacilli and SRBs were isolated from this site. It has been noted by other authors (Fortin et al. 1995, 1996) that a dynamic relationship exists between the thiobacilli and the SRB. They found that even in the oxic zone in abandoned and active tailings dumps in northern Ontario where thiobacilli fix inorganic carbon and oxidize Fe and sulphide from the waste rock, significant numbers of SRB were found. For SRB to grow they require an organic substrate, such as carbon, as an electron donor. The source

for this organic substrate at Macraes Flat may either be the organic matter present in the grey sandstone layer or it may come from the degradation of a dead microbial biomass (such as Fe-oxidizing bacteria e.g. thiobacilli). As Fe-oxidizing bacteria have also been isolated from the tailings dam one would expect a similar scenario there.

Discussion and conclusions

The physical and chemical conditions present in the mixed tailings impoundment and the Macraes Flat veneer sediments are similar, revealing a circumneutral pH, slightly anoxic and alkaline water, with low hydraulic conductivity and water saturation of the sediments. The levels of carbonate are sufficient to buffer any acid production due to the decomposition of sulphides. Organic carbon (to 1 wt%) and dissolved carbonate (to 200 ppm) are present in high enough concentrations to act as organic electron donors for the growth of sulphur-reducing bacteria (SRB). The death and degradation of Fe-oxidizing bacteria (e.g. thiobacilli) is another possible source for organic substrates. The presence of these Fe-oxidizing bacteria in the tailings dam as well as the Macraes Flat sediments therefore indicates that favourable growth conditions for SRB could be established in the tailings dam. The organic material in the sands in prospecting pit FR002 also has a reducing effect on the surrounding environment and this enables the sulphate-reducing bacteria to establish themselves in the groundwater zone above the basement schist, where they have facilitated deposition of authigenic framboidal pyrite.

Detrital sulphides were recovered from the active groundwater zone in the basin sediments about 5 m below surface. Sulphide

oxidation has been prevented at Macraes Flat because the sediments are water saturated, limiting the access of oxygen to the sulphides. The detrital arsenopyrite and pyrite grains have maintained their characteristic diamond and cubic shapes respectively, with slight rounding of edges and corners, for 28 000 years. Hence, the 28 000 year old Macraes Flat sediment provides a geological analogue that inspires confidence that on a long-term scale the Macraes tailings dam will remain environmentally benign.

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