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Tracing surface-to-depth flow and mixing at the Con Mine, Yellowknife, Canada: An analogue for the hydrogeology of radioactive waste repositories

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One concept for nuclear waste disposal is burial at depths >500 m in crystalline bedrock to isolate radionuclides against transport to the biosphere. This study examines the impact by an underground mine in the Canadian Shield on deep groundwater flow, as a physical analogue for a radioactive waste repository. The objectives of this work were to trace groundwater flow pathways, determine the rate at which modern meteoric water is migrating to depth, and to assess the importance of hydraulic gradients in safety assessment models. The study examined workings in an area extending from surface to 1.6 km depth, with a 3-dimensional array of subsurface sampling locations on five drift levels between 700 m and 1600 m depth. Sampling sites were established on exploration boreholes that intersected any of three principal water-bearing faults within the mine.

Salinity follows a general log-linear increase with depth (Cl^- from 48 mg/L to 194 g/L), with local variations of over an order of magnitude within a single drift where water is associated with different faults. This is due to mixing between Ca-Cl brine (Frape *et al.*, 1984; Macdonald, 1986) and modern meteoric infiltration ($\delta^{18}O \sim -19.2‰$ and $\delta^2H \sim -150‰$). Waters from the 3900 to 5300 ft levels carry an excess of ^2H with respect to ^{18}O, and follow a mixing trend towards a rock-equilibrated Shield brine (Fritz and Reardon, 1979).

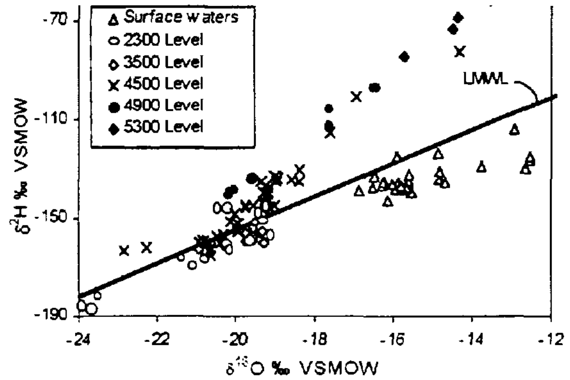

Fig. 1 Relationship of $\delta^{18}O$ and δ^2H in surface waters and groundwaters.

The isotopic depletion observed in groundwaters from the 2300 to 4900 levels indicates a third mixing component in mine groundwaters. Winter recharge can be discounted as the source of the observed isotopic depletions in the third component, as the sampling depth is far too great to permit preservation of seasonal $\delta^{18}O$ signals. Further, tritium modeling indicates recharge to be a multi-year mixture. The origin of these depleted waters is attributed to infiltration of glacial meltwaters at about 10 ka, when the Laurentide ice sheet margin was retreating eastward across the Yellowknife area. Significant meltwater recharge would have taken place below the margin of the ice sheet, fed by an extensive network of subglacial meltwater channels (Björnsson, 1998) and under high glacial hydrostatic head.

Tritium was measured at all underground sites sampled. The lowest ^3H contents are observed for the deepest sites at 1,615 m below surface (5300 level) where only a very minor component of modern meteoric water has mixed with the brine and glacial water. Repeated sampling of inflows on the 4500 level since 1980 has allowed calculation of surface-to-depth transit time of the modern meteoric component (Fig. 2). The tritium content, corrected for mixing with brine and glacial meltwater, has been used to model mean transit times (MTT) for recent meteoric water using the combined exponential flow and piston flow model - FLOW (Maloszewski and Zuber, 1996). Optimum matches with the assembled input data were obtained where the modeled effect of piston flow was four times greater than that of exponential flow, consistent with fault plane flow paths.

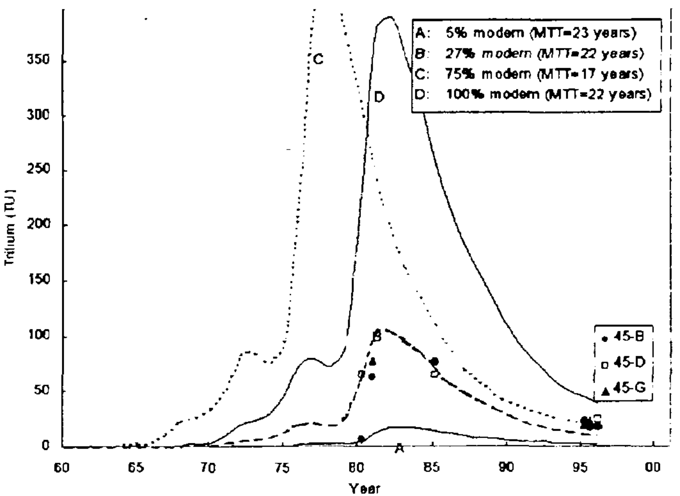

Fig. 2 Results for modeling mean transit times for recently recharged meteoric water sampled at 45-B, using FLOW (Maloszewski and Zuber, 1996). Measured tritium concentrations, corrected for dilution by tritium-free brine and glacial meltwater, are compared with optimized models for mean transit times (MTT). Model allows mixing of modern (tritiated) and submodern (tritium-free) meteoric waters.

The model shows that the modern meteoric water includes a submodern, tritium-free component. Curves A, B and C represent the best matches to the data, using a range of modern and submodern mixtures. Results indicate a 23-year MTT for 1980-1985 discharge, decreasing to 17 years for 1995-1996 discharge. Higher dilution with ^{3}H-free water is required to match the early data (curve A).

In summary, groundwater inflows sampled from drifts excavated in the unmined area of the Con Mine, are mixtures of three waters: Shield brine, early Holocene glacial meltwater and recent meteoric recharge. The brines were flushed from higher elevations in the mine site during the early Holocene by glacial meltwaters, which circulated to depths as great as the 4500 level. High topography along the ablating glacier margin would have provided the steep gradients required for meltwater to infiltrate glacio-tectonically activated faults of the bedrock. Christienson et al. (1982) give geological evidence for such flow, which differs from subglacial meltwater injection as proposed by Boulton et al. (1993). These early Holocene glacial meltwaters have been preserved in the subsurface up to present time under conditions of low hydraulic gradient. Mining activities, beginning in 1937, then induced deeper circulation of recent meteoric waters, now identified as submodern (pre-thermonuclear era) and modern (tritiated) groundwater.

As an analogue for a radioactive waste repository, this study demonstrates the significant modification that such an underground opening can have on groundwater flow rates in a faulted crystalline terrain by generating vertical hydrodynamic gradients. Further, under conditions of low hydraulic gradients, deep groundwater circulation in highly permeable faults is minimal. At this site, groundwaters recharged at *ca* 10 ka were essentially immobile in the subsurface up to the onset of mining activities. Thus, once the steep hydraulic gradients imposed by mining decay to natural pre-mining conditions following closure, the potential for advective transport from depth to surface would be diminished. However, this conclusion is valid only for the deep subsurface, as this study was restricted to a 700 to 1600 m depth interval.

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