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Using environmental tracers to characterize groundwater flow in an alpine watershed underlain by sedimentary rock

Andrew H. Manning[1], Lyndsay B. Ball[1], Richard B. Wanty[1], Philip L. Verplanck[1], and Kenneth H. Williams[2]

[1]U.S. Geological Survey, Denver, Colorado, USA

[2]Lawrence Berkeley National Laboratory, Berkeley, California, USA

A growing number of studies indicate that bedrock groundwater is an important component of streamflow in mountain watersheds, yet mountain fractured-rock aquifers remain poorly characterized largely due to a lack of wells. Environmental tracer data from springs and tunnels can provide useful information, but are limited by the fact that spring occurrence is sporadic, and tunnels often disturb the natural groundwater system by acting as deep drains. We present dissolved noble gas, age tracer (^3H, $^3He/^4He$, and SF_6), chemistry, and temperature data from two relatively deep (46 and 81 m) boreholes and multiple shallow hand-drilled stream-side piezometers in Redwell Basin, Colorado, USA. The snowmelt-dominated watershed is underlain by sub-horizontally bedded, hydrothermally altered (sulfide-rich) sandstones and shales, and is being studied to better understand hydrogeochemical processes controlling sulfide weathering and metal exports from mineralized mountain headwater catchments. The boreholes were completed with multi-level monitoring wells allowing discrete-depth sampling, and the stream-side piezometers provided integrated samples of groundwater discharge at various points along the stream course. The chemistry of deeper groundwater at depths >10-20 m is markedly different from that of shallow groundwater: pH is 7-8 versus 4-6; specific conductance is 400-600 versus 100-300 µS/cm; and concentrations of multiple metals (e.g., Fe, Zn) are lower by a factor >5. Apparent $^3H/^3He$ and SF_6 ages for the shallow groundwater are mainly 5-15 yr, whereas the deeper groundwater is dominantly premodern (>60 yr old) with high terrigenic He concentrations of 4-8 times solubility. Preliminary results from a 2D coupled heat and fluid flow model calibrated with the tracer-based ages and temperature data from the two deep boreholes suggest that active groundwater circulation (Darcy velocities >1 cm/yr) below a depth of 10-20 m is unlikely. This circulation depth is considerably shallower than previously reported depths of generally 100-200 m for mountain watersheds (these being underlain dominantly by crystalline rock), and is probably due to low vertical hydraulic conductivity (K) of the altered sedimentary rocks. Noble gas, age, and chemistry data from the piezometers suggest little to no deep, stream-parallel flow from upper to lower parts of the basin, further supporting relatively shallow active groundwater circulation. The age and chemistry of the piezometer samples also display spatial variations likely attributable to K anisotropy in the bedrock aquifer. The tracer, chemistry, and temperature data thus provide information critical for the development of reliable conceptual and numerical hydrogeochemical models of the watershed.