

Conceptual Isotope Hydrostratigraphic Models for North American Sedimentary Basins: Understanding Water Sources in Deep Subsurface Mines

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Abstract

Literature review indicates multiple North American sedimentary basins hosting deep subsurface mines contain three component fluids based on age (Modern, Pleistocene, pre-Pleistocene or “ancient”). Pleistocene cool climate recharge apparently occurs regardless of basin position relative to limits of Laurentide glaciation. Three component mixing models are proposed to monitor for potentially troublesome vertical migration of shallow subsurface fluids to leaks in deep mine shafts and workings. Component fluids in mixtures can be differentiated using stable isotopes of hydrogen and oxygen, in combination with tritium, major metals (Ca, Na, Mg, K), select anions (Cl, SO₄, Alkalinity, Br), and total dissolved solids.

Keywords: sedimentary basins, isotopes, mixing models, mine leaks

Introduction

Many wet, deep underground mines have operated successfully in North America relying upon life of mine pumping and/or grouting programs to manage inflows. Costs of protracted pumping and associated effects on the physical and geochemical hydrogeological environment are weighed against costs and potential efficacy of grouting. Decision-making on water control approaches also factors in the life span of shafts and other components of mine infrastructure that require continuous use and, hence, durability.

Pumping to depress the water table around shafts and mine workings is one preferred method of water ingress control for gold, zinc and copper mines (Straskraba and Effner, 1998). In multiple cases, base metal and precious metals mines appear to have relatively short operational lives (perhaps a decade). Pumped water is relatively low in dissolved solids and can be discharged safely, and wetness in the mine workings does not adversely affect the integrity of the ore and country rock. Consequently, mine water is merely a geotechnical nuisance with an associated cost to manage. After shaft sinking, grouting is often done to supplement

other water control measures, but grouting is not critical to the survival of these “hard rock” mines.

In contrast to “hard rock” mines that have relatively short lives, mines extracting stratabound and diapiric ores, such as evaporites, can operate for decades. For example, multiple salt mines in North America have remained active for more than a century without substantial disruption (e.g. Avery Island, Cayuga and Detroit). Potash has been mined from deep shafts in the Williston Basin of Saskatchewan starting 61 years ago (Patience Lake – 1958). Eight of the ten still-active operations have produced for nearly 50 years or longer (Saskatchewan Mining Association 2014). For mines with such long operational lives that are surrounded by saline or otherwise poor quality groundwater, grouting has an environmental and mine sustainability advantage over pumping for water control.

Risk of Substantial Water Influx

Differences in the way “hard rock” and “soft rock” mines approach water control also leads to a practical understanding that the risk of substantial water influx varies according to the transmissivity of the

rock type(s) hosting and overlying the ore bodies. In the absence of direct connection to surface water bodies, mines in crystalline rock may be less vulnerable to catastrophic flooding events because of the typically low transmissivity and storativity of most igneous and metamorphic rocks (Fetter 2001; Freeze and Cherry 1979), as well as their resistance to natural erosion, dissolution and to mine damage (blasting and subsidence). Water control for mines in crystalline rock may, therefore, be hydrogeologically more accommodative to life of mine pumping than grouting because water is more of a nuisance than a geotechnical hazard.

Conversely, underground mines in sedimentary basins are more vulnerable to catastrophic inflows because of potential connections to multiple regional aquifers in the stratigraphic sequence, the vulnerability of some sedimentary rocks to slake/weaken when wetted, evaporite dissolution and greater potential for damage from mining. Mines in sedimentary basins that operate over many decades may be at higher risk, particularly if they expand beyond the limits of adequately dense characterization data collection. Strata-bound ore bodies may maintain regularity over vast distances, but an unexpected geological anomaly that cross-cuts stratigraphy and transmits water can terminate mine life.

Grouting serves an important role in water management for many mines situated at depth in North American sedimentary basins. In fact, grouting is essential to the survivability of wet evaporite mines, because the ores are highly water-soluble. Mine stability can be lost quickly if inflows are not controlled to minimize pillar dissolution and loss of support. The Retsof Mine in western New York, the first Belle Isle Mine in Louisiana, and the Patience Lake Mine in Saskatchewan were all lost because of uncontrolled flooding (Van Sambeek et al. 2000; Goodman and Hocking 2016; Genzwill and Martin 1996).

Potential for Mixing of Waters from Multiple Hydrostratigraphic Units

Many underground mines in North American sedimentary basins operate at depths between 250 and 1000 meters. Consequently,

there is a large hydrostratigraphic section penetrated by shafts. The stratigraphy above the mines often includes more than one regional-scale aquifer. Each aquifer in the local, vertical sequence often has its own unique water quality and stable isotopic signature in an undisturbed state. So, there is commonly a layered geochemistry within the layered physical hydrostratigraphy. The subsurface formation waters can range from very modern to millions of years old. The geochemical facies and isotopic signatures in the hydrostratigraphic section can vary with depth. Typically, but not always, there is normal superposition of waters of different ages, with youngest near surface and oldest at depth. A notable exception where waters of different ages are stratified in unpredictable sequences is the Williston Basin in Saskatchewan (Rostron and Holmden 2003).

When water seepage into mine workings begins, an immediate question arises as to which water-bearing formation is serving as the source aquifer. Often, the lowest aquifer (i.e. the one closest to the mine ceiling) is initially the culprit, but if the water influx is not stopped in a short period of time, or if the inflow rate increases over time, a second question arises as to whether or not more than one aquifer has connected to the mine inflow. The purpose of this paper is to advocate use of major ion and stable isotope geochemistry, in combination with other tools (e.g., pressure/flow monitoring, microseismic and subsidence surveys), to detect undesired subsurface changes that promote vertical mixing of deep and shallow formation waters around mines.

Monitoring Programs and Analyses Useful for Detecting Vertical Fluid Migration in Advance of Mine Inflow

Because the field laboratories for mine hydrogeological studies are so large (often more than 25 km²), well and piezometer networks to monitor potential source water aquifers can be quite expensive. Furthermore, installing and testing wells *after* a mine inflow starts, in some cases, is too slow a process to provide timely answers to hydrogeological questions on which to base water control decisions, particularly when answers are needed under duress. Hence, installation and

sampling of wells/piezometers *before* and *during* both mine development and operation can provide critical baseline information for evaluation in the event of a substantial mine leak breakout, particularly when integrated with shaft water databases, mine subsidence and closure surveys, and microseismic monitoring.

Exploratory holes drilled during the early mine planning and characterization phase of development can be instrumented with wells and piezometers to monitor for changes over the operational life that may span decades. Routine, vertical profiling of water seepage in mine shafts is recommended to catalogue isotopic and major ion water signatures in each major and minor water-bearing zone penetrated, starting at the time of pilot hole drilling, continuing through sinking and then periodically over the life of the mine.

Stable isotopes of hydrogen (δD) and oxygen ($\delta^{18}O$), in combination with tritium ($3H$ with enrichment), major metals (Ca, Na, Mg, K), select anions (Cl, SO_4 , Alkalinity, Br), total dissolved solids (TDS) and specific gravity are useful for hydrostratigraphic characterization in most basins. Alkalinity can be broken down into specific carbon dioxide species by the analytical laboratory or by reference to Figure 19 in Hem (1985) if pH and temperature are documented (often measured in the field at the top of sampling). Sulfur isotopes may also be useful when formation waters are high in sulfate (Matheson et al. 2018), and strontium isotopes may also be useful in carbonate-dominated systems. Chloride-bromide ratios are a powerful tool in evaporite basins to differentiate between saline connate formation waters with a complex evolutionary history and simpler salt-contact brines (Richter and Kreitler 1993).

Baseline Information from the Literature

Existing, published geochemical and isotopic data for several North American sedimentary basins can be analyzed to determine representative signatures for key hydrostratigraphic units. For purposes of this paper, we focus not on the particular geologic formations comprising basin-specific aquifers, but stratification of water types and

their interpreted ages in each basin sequence. Our literature review included isotopic and geochemical studies of formation waters in the U.S. Gulf Coast, the Permian Basins of New Mexico, Texas and Kansas, the New York State and Ohio portions of the Appalachian Basin, the Michigan Basin and the Findlay-Algonquin Arch region of Ontario, Canada that separates the Michigan and Appalachian Basins.

Published data provide baseline information for mines to compare against their own databases. In many North American basins, there are at least three end-member fluids to consider. In the northern basins these are: modern meteoric recharge, Pleistocene glacially-enhanced recharge, and highly evolved ancient basinal fluids (often brines). To the south, a similar tripartite hydrostratigraphy is apparent. Even beyond the limits of Laurentide glaciation, Neogene or Pleistocene-aged water is commonly reported that appears to record enhanced recharge under wetter, cooler climate conditions.

To take practical advantage of these patterns, mixing models are proposed to monitor for potentially troublesome vertical migration of shallow subsurface fluids to leaks in deep mine shafts and workings. Mixing models are important, because water control engineers/scientists must be able to interpret subtle changes in water geochemistry and isotopic signatures as they relate to potential source aquifers for mine leaks and assess those connections for their associated flooding risk to the mine.

Mixing models for two basins, the Appalachian Basin (New York State portion) and the U.S. Gulf Coast are presented in Figure 1. Both basins appear to contain the three aforementioned component fluids within the hydrostratigraphic interval of relevance to active mining (Yeager et al. 2001, Siegel et al. 1990 and Noll 1989 for the Appalachian Basin; Knauf and Kumar 1983, Kumar 1983 and Knauth et al. 1980 for the Gulf Coast data). The three components plot well apart on a stable isotope plot. A global meteoric water line (GMWL) is added for reference.

Mixing models in Figure 1 assume sampling and analysis of a single control

point related to an unabated mine leak. These simple models also assume a normal superposition of water types with ancient brine on the bottom, Pleistocene recharge in the middle and Modern water at the top. Each model starts at inflow inception with a water signature reflective of the deep ancient fluids found closest to the deep mine. Over time, the drawdown cone from the mine leak pulls in an increasing percentage of Pleistocene water up to 50% (arbitrary) resulting in a shift of the isotopic signature toward the lighter Pleistocene component. In as much as mining involves evaporites in both of these basins, the introduction of undersaturated Pleistocene

fluids results in halite dissolution, thereby causing a substantial increase in Cl/Br ratio.

At the point in time of a 50:50 ancient brine and Pleistocene mixture, the base of the Modern water horizon is reached by the cone of depression, and the isotopic signatures change projection from the mid-point between the ancient and Pleistocene components towards the position along the GMWL for the local modern waters. Assuming a modern atmospheric ^3H concentration of 10 tritium units (TU), detectable concentrations of ^3H (approximately 1 TU) appear when the percentage of modern meteoric water in the mixture rises to 10%.

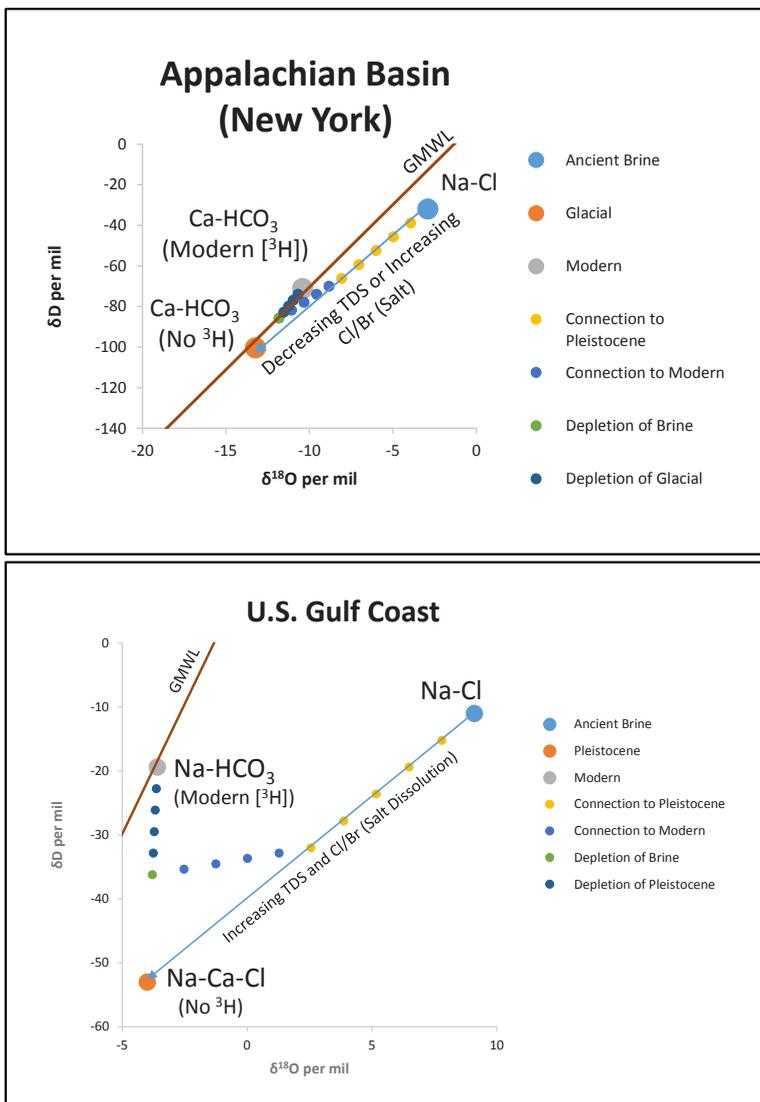


Figure 1 Mixing Models for the New York State Portion of the Appalachian Basin and U.S. Gulf Coast.

Conclusions and Recommendations

Routine sampling and analysis of mine shaft fluids and any waters discharging from roof and rib strata are recommended over the operational life of the mine, because doing so offers the potential to detect changes in fluid migration that could portend broadened hydrogeologic connections and greater risk of more substantial water ingress. Stable isotopes of oxygen and hydrogen, in combination with tritium and major ion chemistry, are helpful geochemical tools for monitoring such effects.

In some cases, the detected connection of mine leaks to shallow groundwater can be linked to a man-made conduit. Improperly abandoned boreholes, mining carried out too close to an overlying aquifer, or inadequate ground support of workings in the mine design are examples of potential man-made causes of hydrogeologic communication between mines and aquifers.

Conversely, some transmissive features connected to mine leaks are naturally-occurring. These include faults, fractures, dissolution features and formations with relict primary porosity. Many natural features can be detected during the characterization phase of mine development and during drilling of pilot hole testing for shafts. Geophysical surveys can be used to identify larger features that can be targeted for drilling.

We offer the following recommendations on how to respond to findings from routine sampling and analysis of mine water that suggest a growing connection of a mine or shaft leak to a major aquifer/source of fresh water. A technical plan for characterization and mitigation of a mine leak is optimized when several different types of data can be integrated into a comprehensive source water investigation. In addition to the isotopic and major ion analyses described in this paper, review of microseismic data would assist in determining where anomalies suggestive of rock damage are originating. Of course, availability of microseismic data necessitates that a monitoring network is installed and operating prior to a substantial leak breakout.

Evaluation of ground subsidence and mine closure data could reveal if there is a

locus of unusual behavior. If there are specific suspicious areas identified, a drilling plan can be developed to target those areas. Drilled holes can be used as pressure-relief wells to take water off of the mine roof (if closure data are suggesting build-up of fluid pressure and seismic data are suggesting hydraulic fracturing) and/or for grout injection into damage zones to seal water.

Proactive grouting programs are recommended for all mines in sedimentary basins, but particularly for evaporite mines, to minimize potential for sudden increases in water inflow. A variety of grouts are useful for leak mitigation (Goodman et al. 2018). Rapid initial response and periodic maintenance grouting to manage inflows at low rates into evaporite mines are required to avoid mine-threatening ground damage. As an interim measure, some evaporite mines inject brine to minimize the amount of salt dissolution taking place while grouting programs are developed and implemented.

In non-evaporite mines, sufficient time will likely exist to carry out testing and grouting. However in evaporite mines, that luxury is not usually available as events can escalate out of control very rapidly. Some extenuating circumstances might include the possibility that the ability of the aquifer to produce water is limited and/or the overlying aquifer is sufficiently unconsolidated that sediment flows into and plugs the solution cavity. This process often creates sink holes.

Critical to the success of a leak mitigation grouting program is achieving a connection between the injection well and the mine leak. The connection can be demonstrated by correlating pressure/flow testing data with mine inflow data or directly by using dye or other tracers.

Mapping of a cone of depression around a mine leak is often a recommended endeavor. It should be appreciated, however, that during an emergency response, initially there will be too few wells to fully map the drawdown cone. Action plans must, therefore, be based on the multiple, independent lines of evidence that individually may be incomplete, but when integrated offer the best chance for a successful water mitigation program.

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