Hydrogeology of the Colony Mine Site

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Abstract

Experimentation of various elements of the Electrofrac™ technology at the Colony Mine requires a comprehensive understanding of the hydrology and hydrogeology of the site. This evaluation has included review of prior hydrologic work at the site, a new hydrologic study, increased sampling for water chemistry and water levels, addition of water monitoring wells, and evaluation of fracture permeability within the Mahogany Zone (Mahogany).

Water entering the ground surface on the mesa tops surrounding the mine percolates through fractures in the uppermost Uinta Formation and the upper portions of the Parachute Creek member of the Green River Formation (Parachute Creek) to reach the saturated water table. This water table is at about 7400 ft elevation north and west of the mine bench but drops substantially to about 7100-7000 ft upon approach to the mine bench and the valley of the Middle Fork of Parachute Creek. At the mine bench, the Mahogany, where experimentation is being conducted, is within this unsaturated zone. However, there is active water flow within the A-Groove, immediately above the Mahogany. Within the mine, this zone contributes water into the mine workings near and above the Mahogany Marker to supply a flow rate of about 20 gpm to a stream flowing out of the mine. All water in both the saturated and unsaturated zones is stored within and travels through fractures, and vugs once occupied by the sodium carbonate mineral nahcolite. The kerogen-rich Mahogany acts as a leaky aquitard with water transmission by fractures through the unit. Many fractures exhibit little flow while others exhibit very good flow of water. The groundwater passing through the Mahogany enters the fractures and vugs of the B-Groove and the top of the R6 interval of the Parachute Creek. There is additional flow by seeps and springs from this interval into the canyon and canyon-fill alluvial aquifer. The alluvial aquifer has good permeability but reduced storage capacity due to limited thickness. Water travel times from the mine to the property boundary are estimated to be approximately 10 years.

Introduction

ExxonMobil is progressing with experiments of elements of the Electrofrac *in situ* oil shale conversion technology at the Colony Mine site (Colony). This site is located approximately 12 miles north of the town of Parachute, Colorado in the southeast corner of the Piceance Creek Basin of northwest Colorado, as indicated in **Figure 1**. The mine site is actually a small tunnel complex shown on the right panel of **Figure 1** adjacent to the Middle Fork of Parachute Creek (Middle Fork). This tunnel complex extends approximately 250 feet into the north-south trending ridge between the Middle Fork and Davis Gulch, the next stream valley to the west. The tunnel complex includes the two entry drifts, a cross-cut connecting these two entries and a longer tunnel running at an angle of about 12 degrees from near the base of the fill within the Middle Fork valley, westward toward Davis Gulch. This inclined tunnel was to house the coarse ore conveyor belt planned for the mine as of the time of its construction in 1982.

Figure 1 illustrates that drainage on the western half of the Colony property flows into the surface water and groundwater systems associated with Middle Fork and Davis Gulch. In general, available surface water infiltrates into the alluvial fill along the bottom of the Middle Fork valley. Any remaining surface flow is captured in one of four surface sedimentation ponds near the south end of the property such that no surface water actually leaves the site. As a result, the only water leaving the site is groundwater within the alluvial aquifer of the Middle Fork valley.

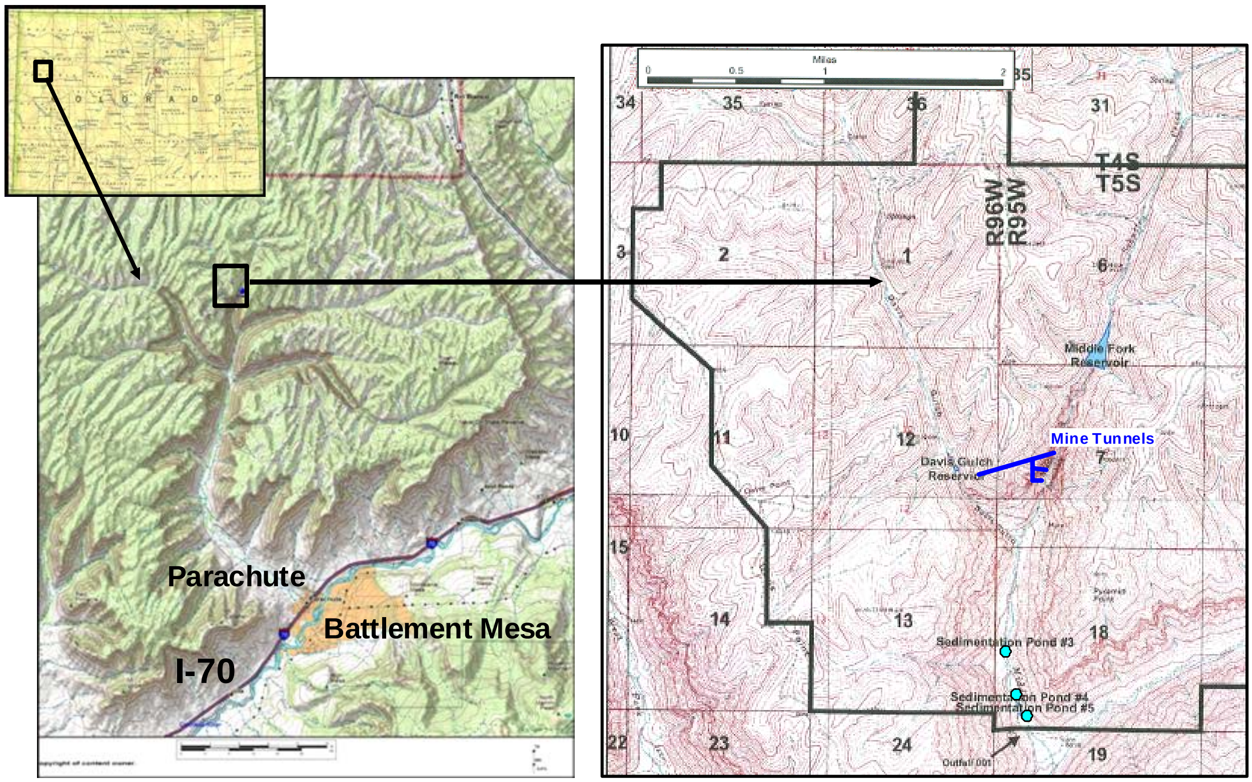


Figure 1. Location and physiographic map of the Colony site, and location of Electrofrac experiments.

Geology at Colony

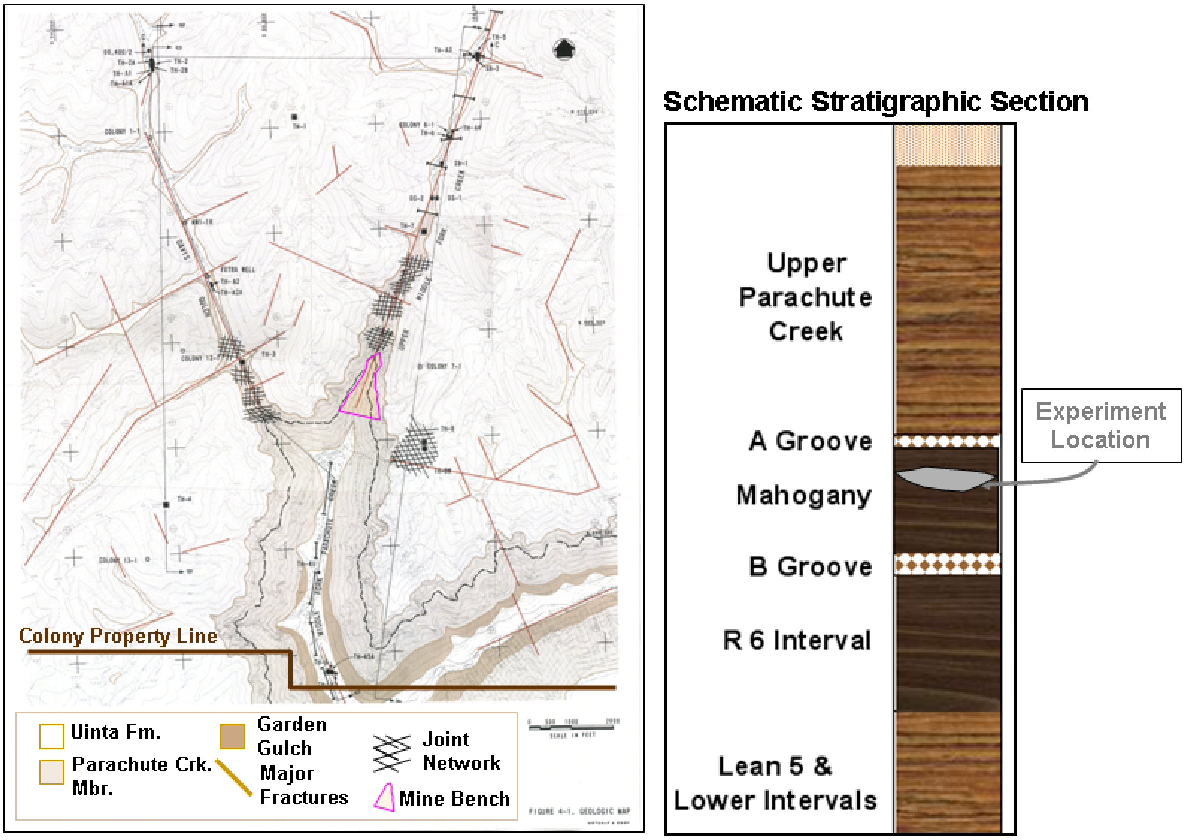
At Colony, the Parachute Creek member of the Green River Formation is exposed. This member is the oil-shale-bearing member in this portion of the basin. The interval for testing is the Mahogany Zone (Mahogany) pictured at right in **Figure 2**. This zone is an organic-rich oil shale interval within the Parachute Creek It is bounded above and below by the A-Groove and B-Grooves respectively. Both of these units are known aquifers within the Piceance Basin and here at Colony. The Electrofrac fractures are actually emplaced within the upper third of the Mahogany.

Figure 2 also shows the location of major fracture networks within the Parachute Creek. Many of these networks run parallel to existing drainage valleys. Also shown are mapped joint systems for various areas at Colony. Finally, the outcrop limits of the Parachute Creek and the Garden Gulch members (Garden Gulch) are illustrated. The Garden Gulch is a clay-rich unit below the Parachute Creek. It forms the bedrock in the floor of the Middle Fork valley. The Garden Gulch is covered within the valley floor with poorly sorted Quaternary and recent alluvium of varying thickness.

Planning for our experiments with the Electrofrac fractures, it is necessary to understand the hydrogeology of the groundwater system at Colony. Working with Wright Water Engineers, Inc. (WWE), we have developed several conclusions regarding the groundwater system at Colony.

1. Water flow within the Mahogany is dominated by fractures and connected vug systems

2. The A-Groove, B-Groove and lean oil shale adjacent to them, are the primary water flow units in the mine area, and
3. Travel time analysis of ground water flow at Colony indicates that minimal flow times of 10 years are required for groundwater to travel from an Electrofrac fracture within the Mahogany to the Colony boundary. Flow times assuming water can make it to surface drainage would be a minimum of 3 years, primarily because all flow from the Electrofrac fracture requires significant groundwater flow to reach surface water drainage.



Modified from Metcalf & Eddy, 1975

Figure 2. Electrofrac fractures are located within the upper third of the Mahogany, between the A- and B-Grooves.

Figure 3 depicts the location of the Electrofrac experiments within the context of the geology at Colony. The two Electrofrac fractures are actually coke-filled fractures created artificially with conventional fracturing methods within the Mahogany. This illustration shows the location of one of these fractures (EF-3) within the Mahogany and relative to the mine tunnels. The fractures are basically centered at an elevation equal to that of the mine tunnels and extend about 30-35 feet above and below the midline of the tunnel system. This puts each Electrofrac fracture within the richest zone of the Mahogany. Each Electrofrac fracture is above the lean zone at the base of the Mahogany, just above the B-Groove and just below the less rich (lean) upper portion of the Mahogany between the Mahogany Marker and the A-Groove. Both Electrofrac fractures occupy roughly the same stratigraphic thickness but are within different pillars separated by about 125 feet.

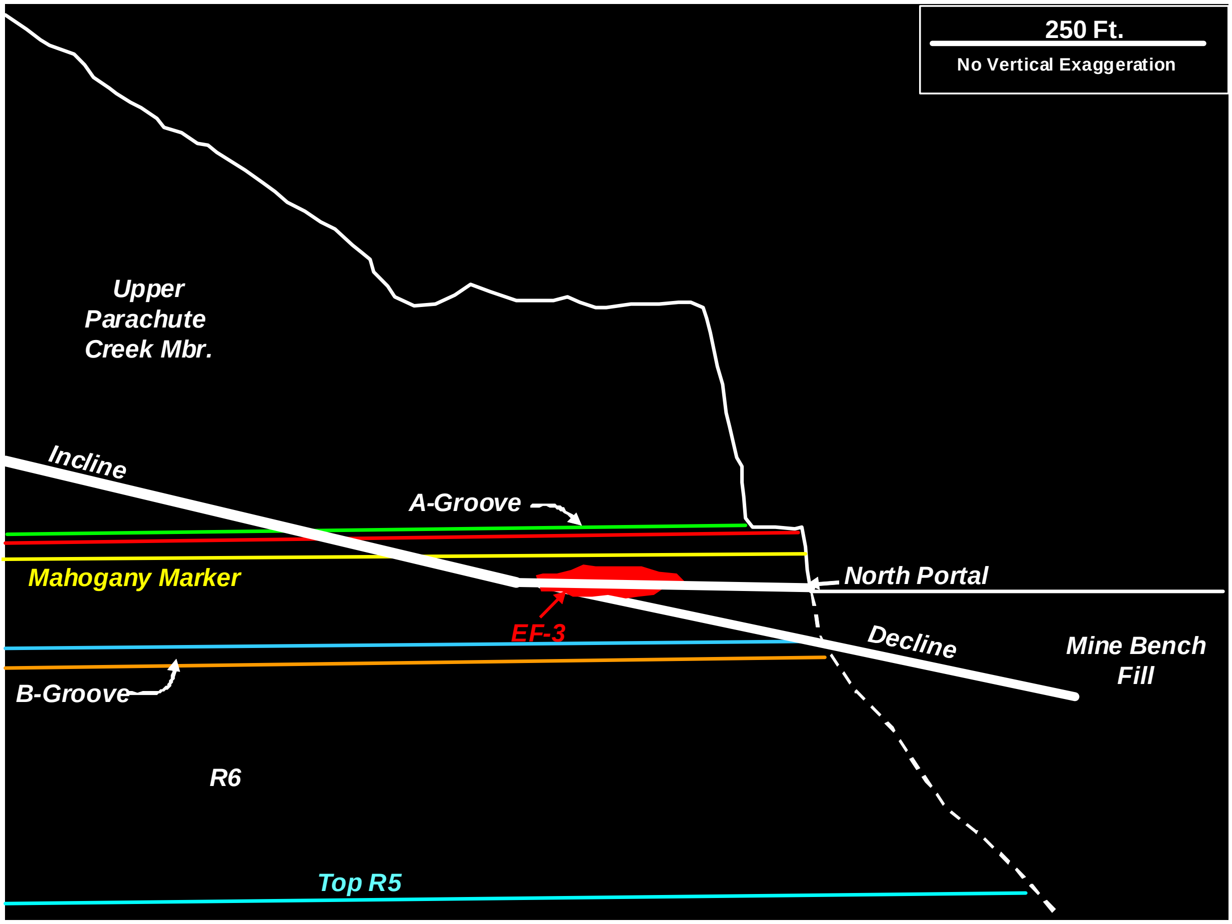


Figure 3. Electrofrac fracture location within the Colony tunnel system and the Parachute Creek unit.

The R6 zone is immediately beneath the B-Groove and consists of an upper lean zone, which in turn, overlies a thin relatively rich oil shale zone. Stratigraphic intervals below the R6 are generally not rich in organic material but do form massive carbonate cliffs in the outcrop.

Hydrogeology of the Colony Mine Area

The cross section in **Figure 4** shows the Mahogany, A-Groove and B-Groove in cross section from the midpoint of Davis Gulch to the Colony property boundary. The active experimental area is just to the east of the cross section line, but the cross section represents the potentiometric surface within the groundwater aquifers in the vicinity of the mine.

Snow melt and rainfall in this area total about 16 inches, of which approximately 10% ends up as surface runoff and 1% enters the groundwater system. Flow into the groundwater system is via fractures within the Uinta formation and the Parachute Creek. Water flow is primarily downward and to the south, southeast within these units. In the upper stretches of the valley, the potentiometric surface is near ground surface within the Uinta and upper portions of the

Parachute Creek. Springs are common in the upper reaches of these areas. These springs provide base flow for Davis Gulch and Middle Fork.

As one approaches the outcrop the potentiometric surface drops substantially to a point within or below the Mahogany due to springs and seeps that discharge from the outcrop along the cliff face. This is the situation in the mine workings that are within this vadose zone above the groundwater potentiometric surface. This is an area where some fractures consistently flow water, others flow water only at certain times of the year, and some appear to be permanently air filled.

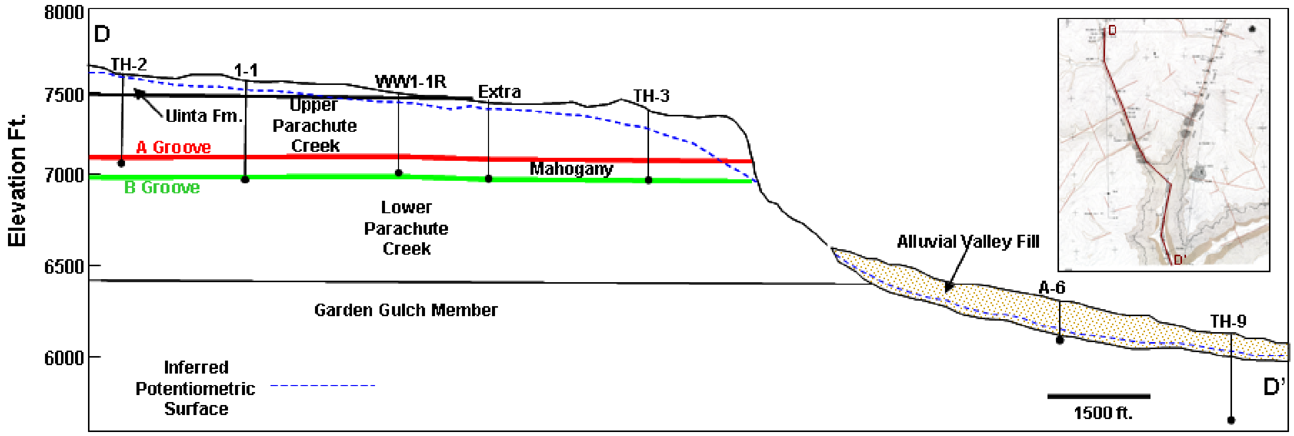


Figure 4. Potentiometric surface and geology along Davis Gulch.

The potentiometric surface resumes in the lower portion of the alluvial valley fill in the Middle Fork valley. Nearly all surface water infiltrates into the alluvium within this valley. Subsurface flow within the alluvial aquifer is the major means by which water exits the Colony property.

Observations of water flow within the mine and along the outcrop allow for a better understanding of the regional water flow in the mine area shown in **Figure 5**. Water flows downward and east through the Upper Parachute Creek as deep as a very rich oil shale zone within the Mahogany just below the Mahogany Marker. Downward water flow is partially impeded at this interval and forced east and south in the leaner portions of the Mahogany and the A-Groove until it discharges as perennial seeps and springs at the outcrop. This is evidenced by the icicles that appear at or just below the Mahogany Marker during the winter as shown in **Figure 6**. Some water flows downward through the organic rich portion of the Mahogany via fractures and enters the B-Groove and upper lean portions of the R6 unit. This water continues to flow south and east and exits the R6 just above a very organic rich layer within the R6.

A-Groove Characteristics

The A-Groove is a 12 foot thick lean carbonate marl just above the top of the Mahogany. The A-Groove is similar in composition to the Mahogany from a mineralogic standpoint.

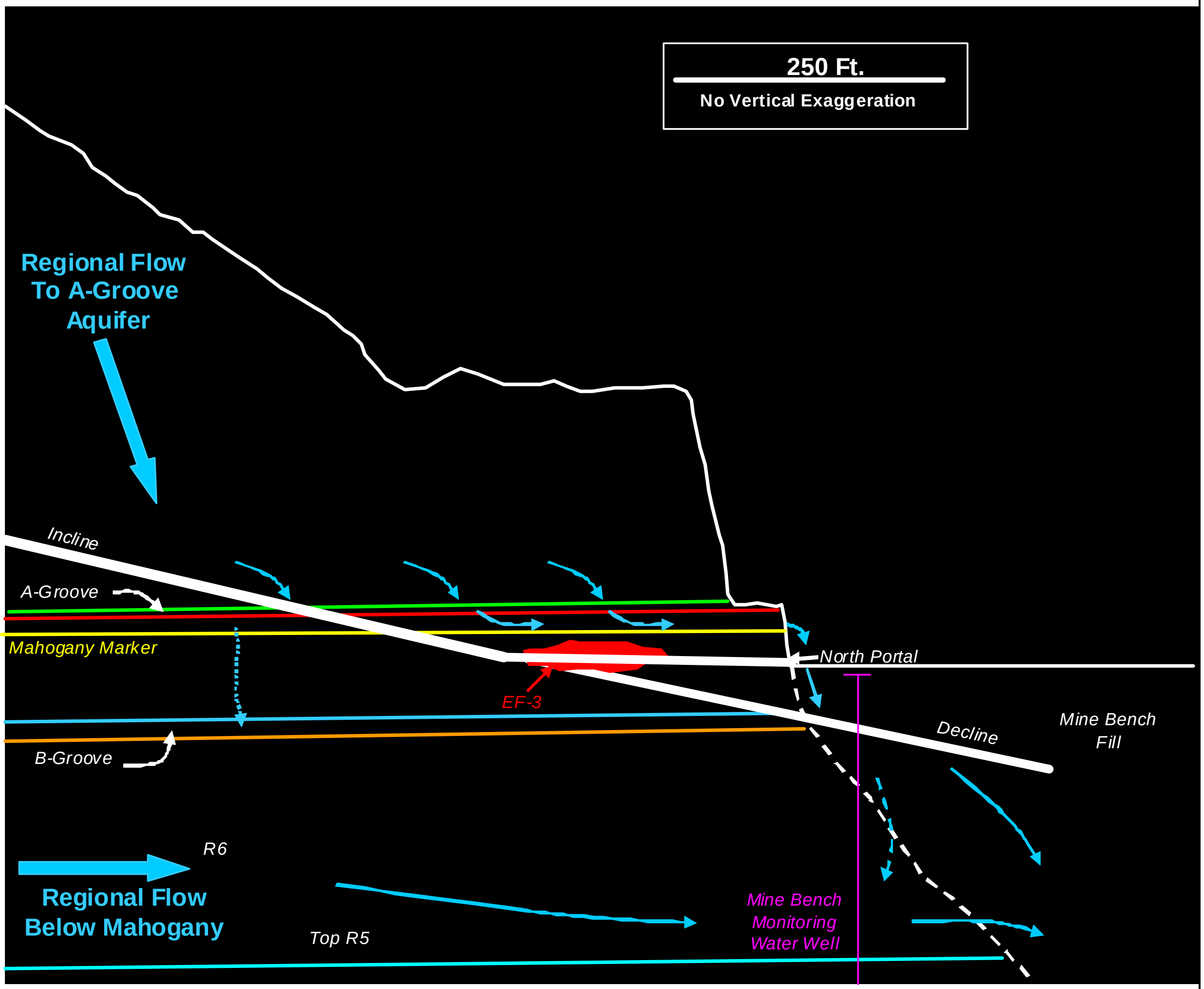


Figure 5. Hydrogeology of the Colony tunnel location.

Both are rich in carbonate and feldspar. Also, the A-Groove has very low matrix porosity and permeability. The thin section photograph in **Figure 7** illustrates the "tight" matrix of this unit.

The A-Groove is much leaner in terms of total organic carbon (TOC) content than the Mahogany or the overlying upper portion of the Parachute Creek. The A-Groove has an average TOC of 2.9% with a hydrogen index (HI) of 602; whereas the Mahogany has an average TOC of 13% and an HI of 890.

The A-Groove is more highly fractured than either the Mahogany or upper portions of the Parachute Creek. It appears that decreased quantities of organic matter in the A-Groove are at least partly reflected in increased fracture density. **Figure 7** shows the regressive A-Groove with a resistant Upper Parachute Creek above and Mahogany below it that is populated with vugs. The Parachute Creek has 1-3 fractures per five foot lateral interval. The A-Groove has fracture densities in excess of 10 per five foot interval. The A-Groove also exhibits numerous fractures that are parallel to bedding.

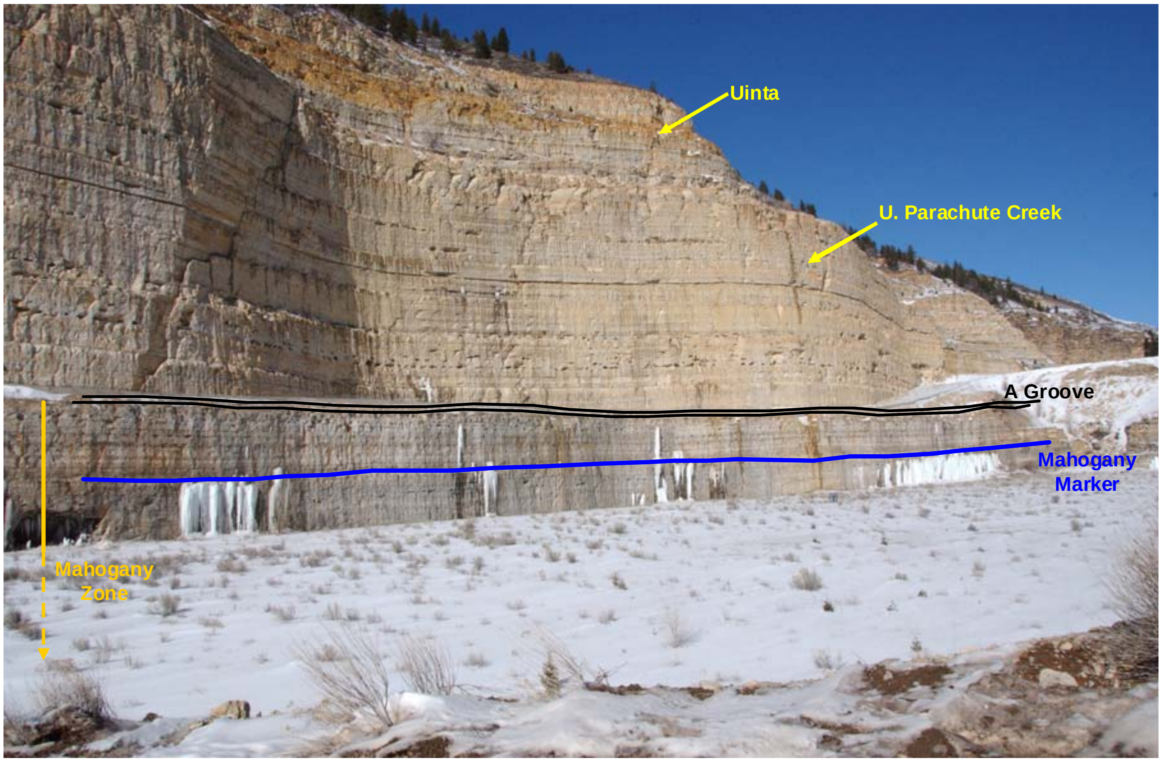


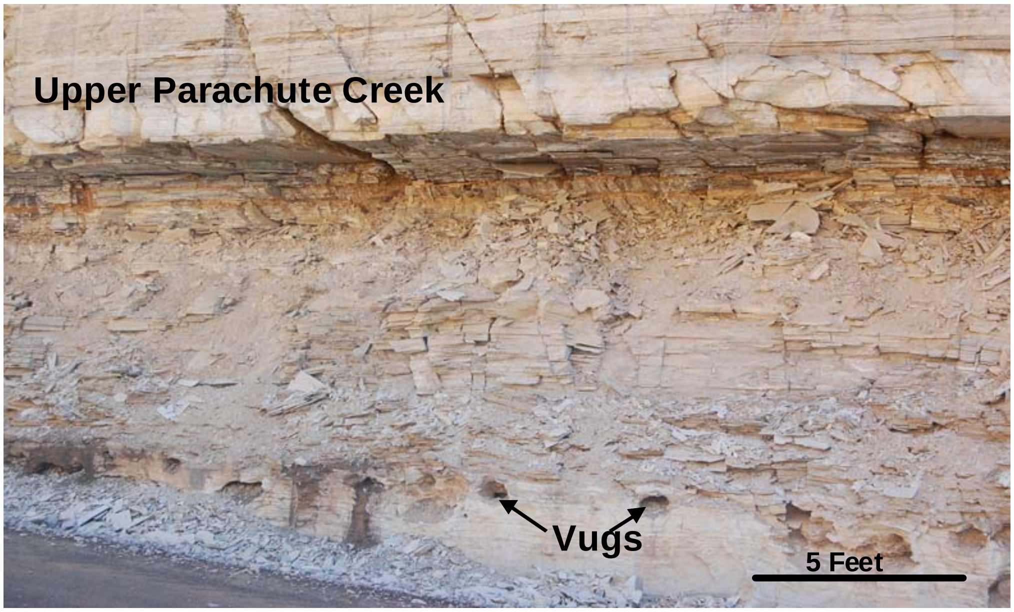
Figure 6. The Parachute Creek displays fractures for vertical flow of water. Seeps and springs (icicle areas) show exit points for water above the rich layers of the Mahogany.

Hydraulic conductivity of the A-Groove in this area is approximately 1-10 ft/d. This is equivalent to a permeability of about 1 Darcy. This unit in the mine tunnels contributes significant flow into a stream that originates in the inclined tunnel and runs out the north entry into the mine bench fill. This perennial stream flows at a rate of about 18-21 gallons per minute. All of this water enters the mine from areas within the interval from the top of the A-Groove to a very rich zone in the upper Mahogany. Above the A-Groove water flow into the inclined tunnel is minimal. This ponding of water above the very rich zone within the Mahogany is also confirmed by the presence of seeps and springs along this interval at or just below the Mahogany Marker at the cliff face as shown in **Figure 6**.

B-Groove Characteristics

The B-Groove is the unit immediately below the Mahogany. It consists of about 15 feet of carbonate rich siltstone that is organized locally into graded beds (**Figure 8**). It is also enriched in feldspar relative to the Mahogany. This unit is coarser grained and is organically, much leaner than the Mahogany. The TOC content of the B-Groove is < 2-3%.

The inset picture within **Figure 8** illustrates the high degree of B-Groove fracturing at the outcrop. Fracture frequencies in excess of 20 fractures per five foot lateral interval are common.



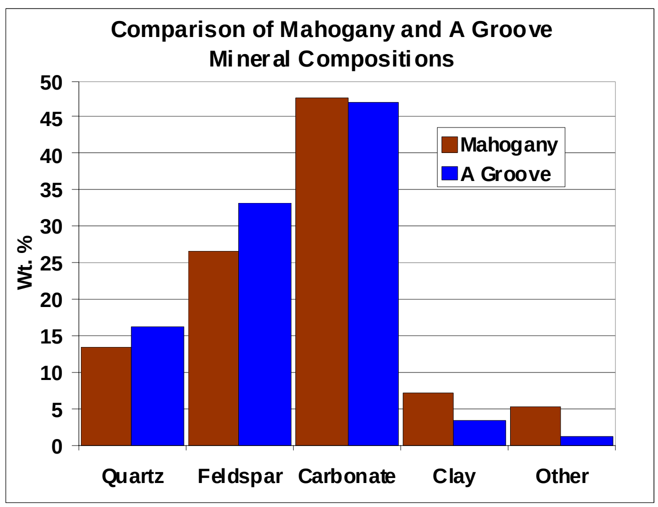


Figure 7. The A-Groove is a significant aquifer unit with a bulk mineralogical composition similar to the Mahogany and a non-porous, "tight" matrix. Flow is through numerous fractures.

Hydraulic conductivity is high with measured values of 2-4 ft/day or an equivalent permeability of about 1 Darcy. However, at the mine site, the B-Groove contributes little water where it is intercepted by the inclined tunnel. South of the mine workings, water from the B-Groove is observed to be flowing from springs and seeps along canyon walls. This flow is from just above a rich oil shale zone within the R6 interval.

The three monitoring wells are planned for completion in this interval to evaluate changes in water level and water chemistry at locations slightly down-gradient of each Electrofrac fracture.

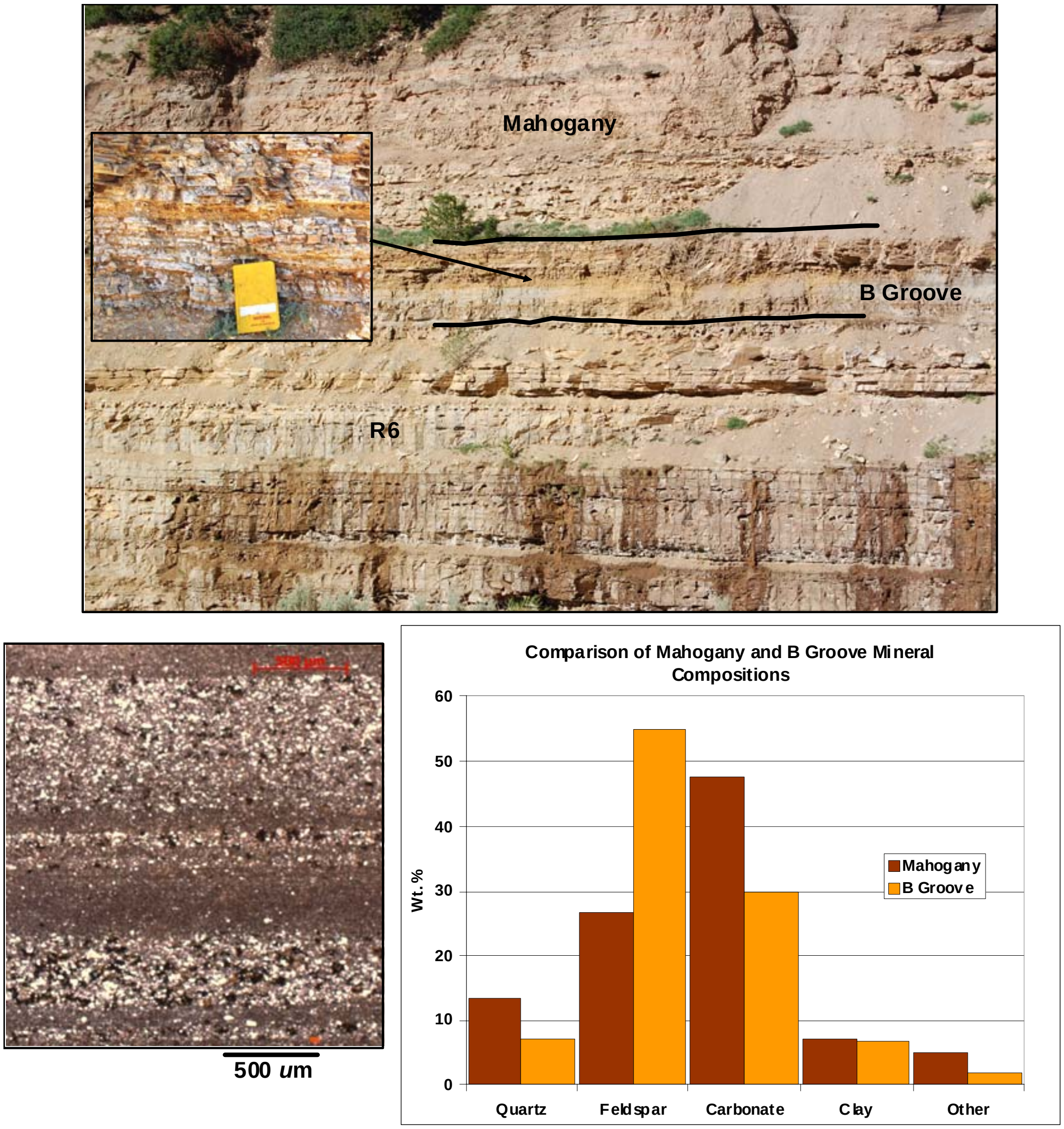


Figure 8. The B-Groove is also a significant aquifer. Note high degree of fracturing in upper picture and persistent water flow within the R6. Composition is more feldspathic than the Mahogany. Bedding is frequently graded as in the thin section photo at left.

Mahogany Characteristics

The Mahogany itself is generally a low porosity and permeability unit that generally acts as an aquitard with only a few discrete flowing fractures. The Mahogany has a very low matrix permeability < 1 mD; and porosity <0.1%. Measured hydraulic conductivities from USGS and Shell published data indicate a range of 10^{-4} to 10^{-2} foot/day for the bulk Mahogany. This equates to a permeability value from < 0.1 to 10 mD.

Near the outcrop conductivity may be higher due to a larger number of fractures and reduced stresses. Flow through the Mahogany is through select open fractures. **Figure 9** shows tracings of fractures and their vertical extent in the face at the mine. Note the discontinuous nature of these fractures vertically. However, there are well connected fractures with the upper water-bearing portion that do flow water continuously in rather significant amounts. In fact there are two such fractures within the mine area that flow large amounts of water, one being illustrated in the upper left of **Figure 9**. However, most fractures do not transport water, or only transport water during the wettest parts of the year.

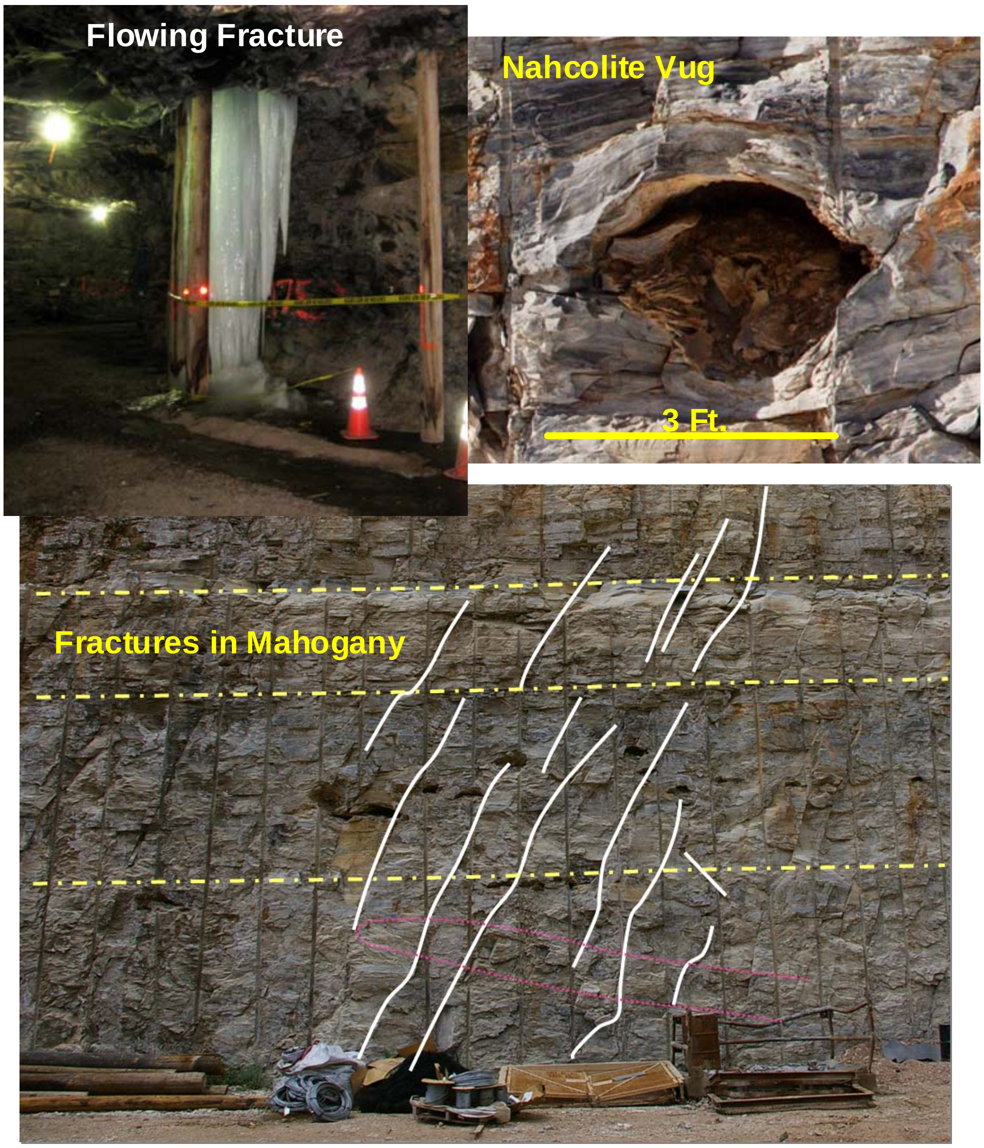


Figure 9. The Mahogany acts like an aquitard but has discrete flow paths in the forms of natural fractures and bedding-related nahcolite vug systems.

Vug networks may also represent major lateral transport zones. Vugs can be large and may be interconnected along the bedding planes in which they reside. Vugs are formed by the dissolution of a solid sodium bicarbonate mineral, nahcolite. An example is provided in **Figure 9**.

Fracture density increases upon approach to the outcrop as shown in **Figure 10**. There is a dominant fracture direction at the mine that is North 60-80^o East. These fractures are the dominant fractures in the crosscut area. They appear to be spaced such that "corridors" of fractures are marked as the grey ribbons in **Figure 10**. Close to the outcrop at the bottom of **Figure 10**, it is observed that the density of fractures increase and fracture orientation changes to a more east-west direction. These changes may be related to the relaxation of stresses near the outcrop.

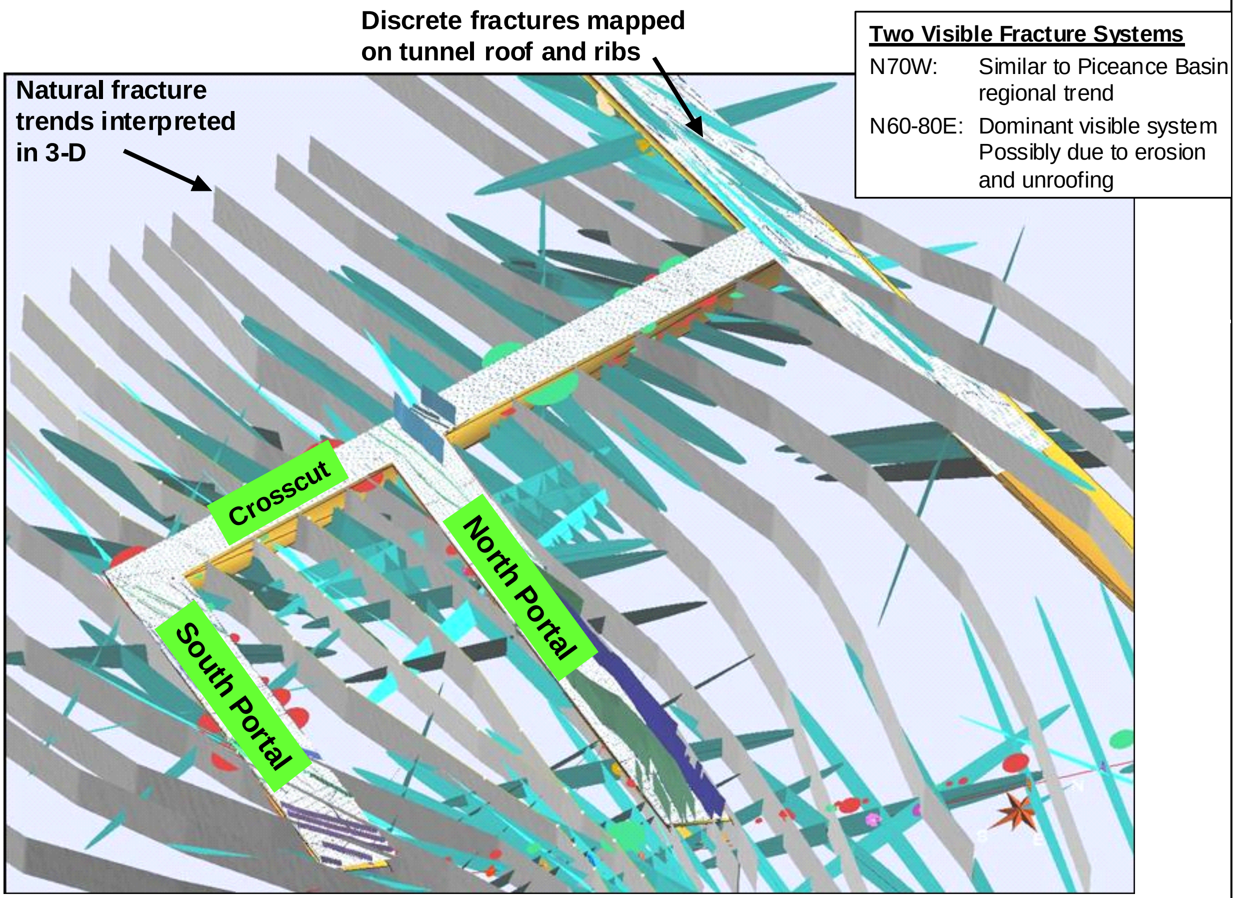


Figure 10. Fractures are abundant within the rock volume encompassed by the mine tunnels. Fracture frequency increases closer to the outcrop.

Relationship Between Fracturing and Organic Richness

Fracturing appears to be strongly related to organic richness in the Parachute Creek. The plot in **Figure 11** shows the correlation of fracture frequency to TOC within a set of three vertical cores located within about 20 feet of the mine highwall, between the portal openings. These cores span the entire Mahogany except for the very top five feet and the basal five feet. The fracture count includes fractures that are both parallel to and perpendicular to bedding.

Note that the lowest fracture frequencies are within the rich portions (as measured with TOC) of the Mahogany between 40 to 105 feet. Fracture frequency is highest in the leaner portions of the Mahogany near its top and base and where the core is within the A-Groove or the B-Groove.

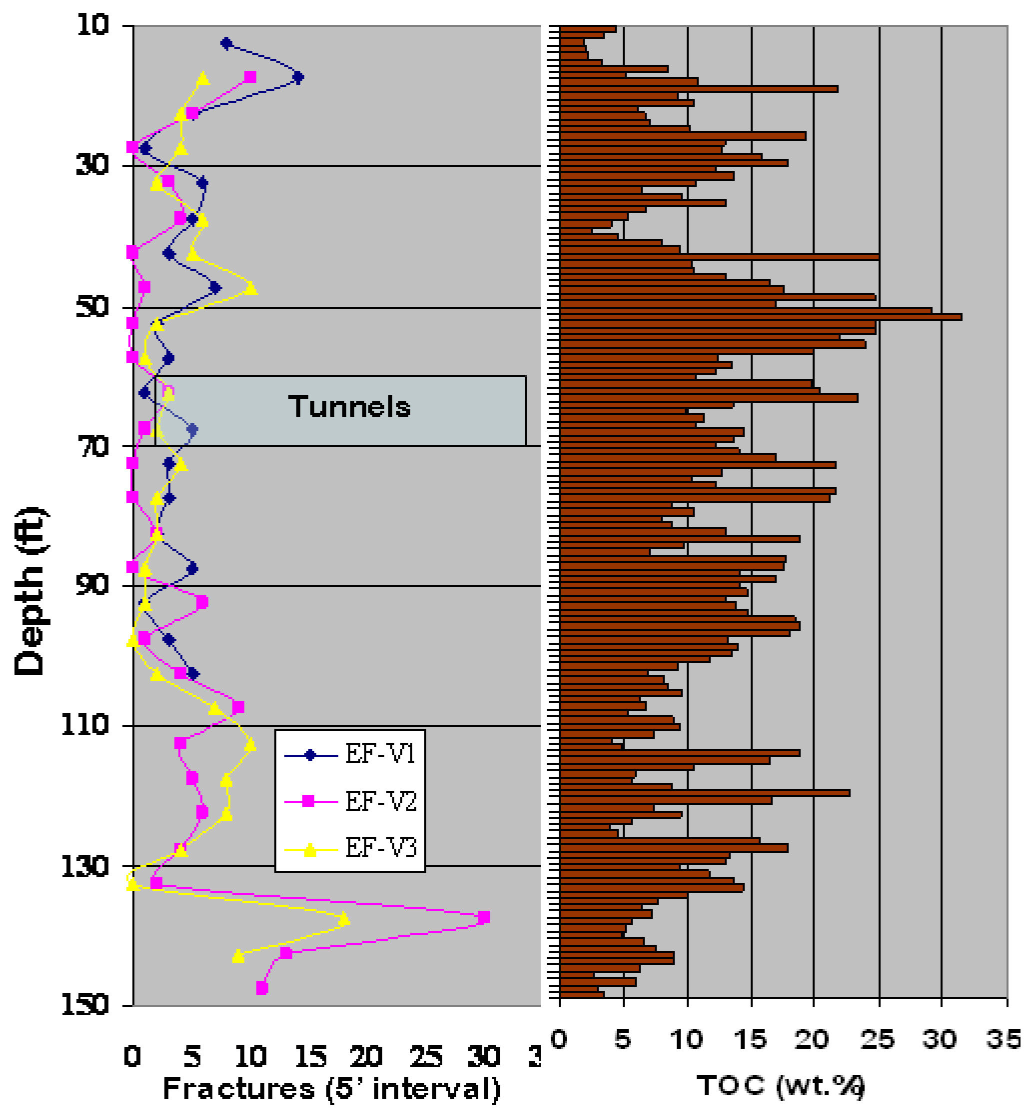


Figure 11. Plots comparing TOC with fracture frequency for the Mahogany.

Measurement of Flow within the Mahogany

To define the flow rates within the Mahogany, fracture permeability testing equipment was developed as shown in **Figure 12**. With this device, we can isolate portions of drill holes within the rock volume so as to measure flow through them. The results are shown in **Figure 13**.

The device illustrated in **Figure 12** uses a compressor to inflate packers that can isolate a variable length of perforated pipe within the borehole. The pipe is connected to a tank that is attached to a vacuum pump. When the packers are inflated, a vacuum is drawn, and the amount of water and air withdrawn from the borehole interval under study can be measured.

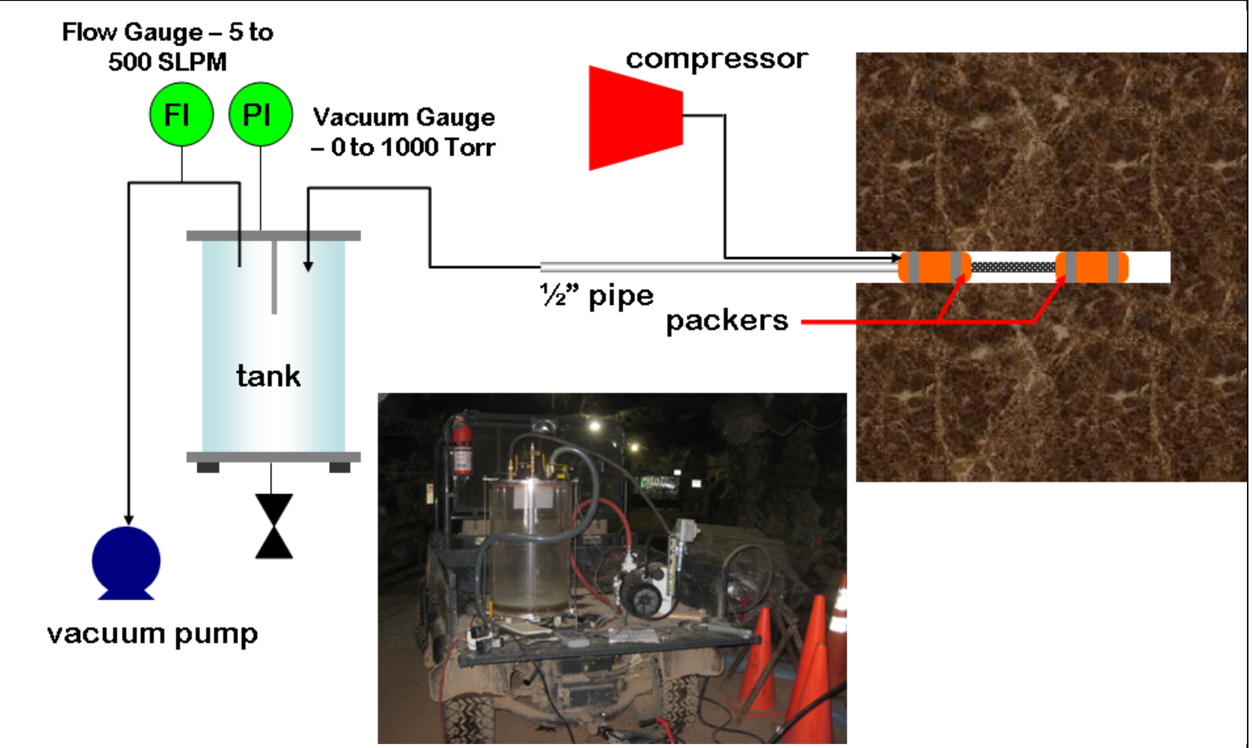


Figure 12. Custom built fracture permeability testing equipment.

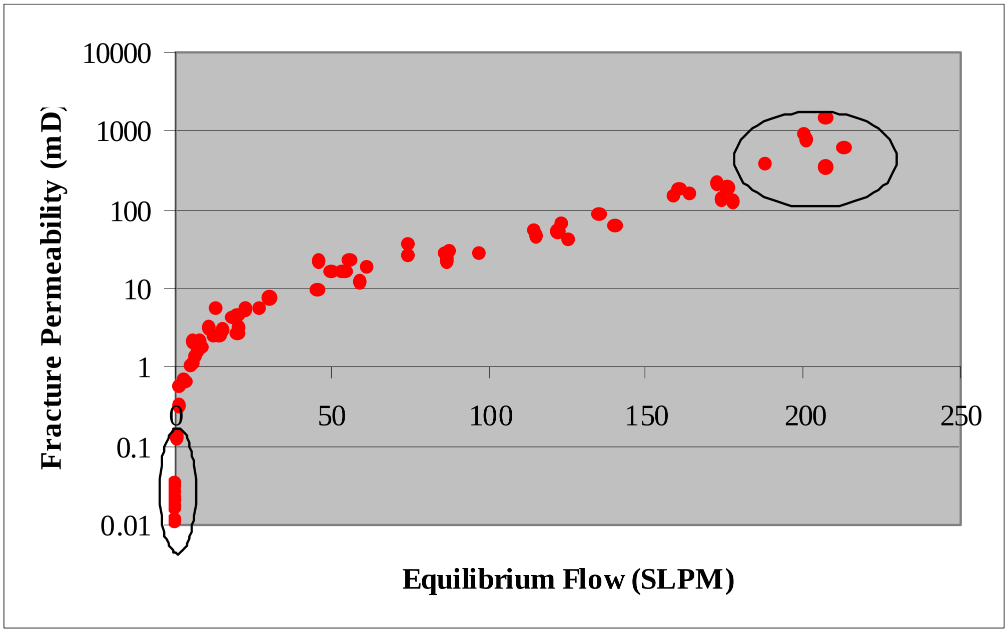


Figure 13. Summary results of vacuum system tests.

These flow rates can be expressed as permeability assuming volumes of rock mass measured and distances over which flow occurred. For this analysis, the rock mass and flow distances were determined based on the location of the tested interval within a borehole. This was determined by calculating the position of the tested interval relative to the nearest tunnel wall. Corrections were made to the measured pressures to account for frictional losses.

Basically, there are three classes of flow values for air:

1. Tight – essentially no or very low permeability (left side portion of **Figure 13**).
2. Open – extremely high permeability and flow rates as in upper right portion of **Figure 13**.
3. Intermediate – fractures and zones where flow rates were intermediate.

Water flow results indicate that flow through the mine pillars takes place quickly, probably in 12 weeks or less. In March 2010, 22% of the intervals tested produced water. The maximum flow rate for water production was over four barrels per day. However, in June 2010, only 7% of the intervals tested flowed water, and water rates were reduced to less than 0.1 barrels per day. In late June 2010, only 25% of the intervals that produced water earlier in the month continued to produce water at the lower flow rates. Seventy five percent of the water production intervals became dry.

From these observations it was concluded that over the majority of a year, most fractures within the pillars are dry and do not flow water. Water flow appears to be restricted to the snow melt portion of the year from February through early June.

Groundwater Flow at Colony

Based on this hydrogeology evaluation, water passing through or near the experimental volumes within the Mahogany ultimately flows downward to the B-Groove and/or laterally into the mine bench fill. Travel times along this flowpath could be as quick as 12 hours or as long as 70 years depending on the permeability of the fracture(s) within a specific rock volume, and upon the time of year during which an experiment is conducted. For example, water containing green dye was used during fracturing for the Electrofrac fractures. This water was encountered within the Mahogany over one year later during subsequent drilling.

Once water reaches the B-Groove aquifer, flow is into the alluvial fill or the mine bench fill. Flow time modeling indicates that flow through the B-Groove and lean zones of R6 is on the order of three years. This assumes a hydraulic conductivity of 2.7 feet per day and the existing hydraulic gradient.

Upon exiting the bedrock, water moves through the mine bench fill or the alluvial aquifer in a southward direction towards the southern Colony boundary. Movement of water through the alluvial aquifer to the property boundary south of MW12 is seven years at a minimum, based on the existing hydraulic gradient and hydraulic conductivity from local flow tests.

The estimated minimal time required to allow water to move from the Electrofrac volumes to the Colony property boundary is about 10 years, even if some of the fluid reaches the surface water system. Some water flowing through the experimental volumes may enter the surface water system from either the mine bench fill, the alluvial aquifer, or directly from the B-Groove at outcrops south of the mine area. However, all surface water is held in retention ponds and

Figure 14. Locations of new groundwater monitoring wells at Colony (in blue). Existing wells are shown in yellow. Inset is a picture of one of the retention ponds for capture of surface water.

evaporates or infiltrates to become part of the groundwater system. There has been no surface discharge from Colony since the mid 1990's. The retention ponds have been deepened and expanded somewhat since that time (**Figure 14**).

The amount of water contacting the Electrofrac experimental volume is relatively small compared with overall surface and groundwater volumes exiting the property. Dilution of any waters from the Electrofrac area by waters from Middle Fork and Davis Gulch, combined with the groundwater flow will result in dilution on the order of several thousand times.

Water Monitoring

Four new water monitoring wells are planned for Colony. Three wells are going to be drilled into the B-Groove between each Electrofrac volume and the mine bench fill. These wells will provide information on groundwater flow and chemistry within the B-Groove and the lower, lean portion of the Mahogany as experiments progress. A fourth well will be drilled in the alluvial valley fill near the base of the mine bench fill. This well will evaluate groundwater flow and chemistry of alluvial aquifer water leaving the mine bench area. Locations of these wells and other wells already used for water level monitoring and chemistry are shown in **Figure 14**.

Conclusions

Water flow within the Mahogany is dominated by fractures and the interconnected system within some beds of nahcolite dissolution vugs. The Mahogany has very low matrix porosity and permeability. Most flow is through a small number of fractures. Some fractures have radial flow characteristics equivalent to a permeability of 9 Darcy. However, most fractures do not flow water or only flow water during the spring. Overall permeability of the rock volumes around the Electrofrac fractures is interpolated to be approximately 100 mD.

The A and B-Grooves are the primary water flow units in the mine area. Both units are organically lean and have much higher fracture densities than the Mahogany.

The most likely minimum flow time is ten years for groundwater to travel from the Electrofrac fractures in the Mahogany to the Colony boundary. Actual rates from the Electrofrac experimental volumes through the Mahogany to the B-Groove are unknown at this time. They are estimated to be in the range of less than 1 day to 70 years. Travel time from the B-Groove to the alluvial aquifer or the mine bench fill will take approximately three years. Travel time through the alluvial aquifer to the southern Colony boundary will take approximately seven years due to low hydraulic gradients in this aquifer.

Any water volume from the Electrofrac experimental rock volume will be diluted by a factor of several thousand by the time that volume of water reaches the Colony boundary. This dilution applies to both ground and surface drainage. No surface drainage is discharged from Colony.

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