SOME QUESTIONS ON PICEANCE BASIN HYDROLOGY

Joseph H. Birman
Geothermal Surveys, Inc.
South Pasadena, California

ABSTRACT

Most of the ground water in the Piceance Creek basin, Colorado, may be in shallow aquifers (alluvium and Uinta Formation) and not in significant contact with deeper bedrock aquifers of the underlying Green River Formation. Ground-water movement in the deeper aquifers may be exceedingly slow.

INTRODUCTION

This paper presents a set of working hypotheses alternate to some of the concepts that seem to be held at present in Piceance basin hydrology. If these hypotheses are correct, mining in and beneath the Mahogany zone of the C-b Tract should be possible without hazard to the usable ground water, the springs, and the streams. We present these ideas not to teach but to learn. We hope to test them until we can accept them with confidence, or until we must reject them for better interpretations.

Very little of this interpretation is new. It is an extrapolation of some established concepts and a little modification of others using existing data. In brief, it holds that lateral ground-water migration within much of the Green River Formation is so slow as to be, in practical effect, nonmoving; that away from through-going faults, the deep ground water is not in significant communication with the near-surface water; that some of the water in the Green River Formation is ancient and is not being actively recharged now; and that some of the leaching of the Green River Formation may have occurred in ancient times, after which through-going continuity of open space was destroyed.

WORKING HYPOTHESES

The underlined statements which follow are tentative working hypotheses, followed by some explanatory discussion including some useful references. The geohydrologic setting of the Piceance basin has been described in many publications and need not be repeated here.

1. Lateral or intraformational migration of ground water may be extremely slow. Drill stem test data are available from drillhole SG-17 in the southeastern corner of the C-b Tract (Energy Consulting Associates, 1977). In 33 intervals over a total depth range of 1,638 feet (500 m), measured hydraulic conductivities range from 0.02 gal/day ft^2 (9.44×10^{-9} m/s) to 4.1 gal/day ft^2 (1.94×10^{-6} m/s).

On the C-b Tract, the hydraulic gradient for both the Upper Aquifer and Lower Aquifer is reported to be about 100 ft/mi (19 m/km) (Weeks, et al, 1974).

Substituting these values in Darcy's Law, $v = Ki$, where v is Darcy or discharge velocity (Todd, 1980), and i is hydraulic gradient, the range of Darcy velocities is 0.018 ft/yr (5.49×10^{-3} m/yr) to 3.79 ft/yr (1.16 m/yr).

These are the extreme limits, and if other things are held equal, are not real. To arrive at the actual velocities through the rock mass, the Ki function is divided by porosity as the Bernoulli Principle must apply. The real velocities are thus greater than the Darcy velocities by orders of magnitude depending on what values for porosity are used and assuming that discharge remains the same.

For the Piceance basin this seems too simple an approach. All the hydraulic factors are related--discharge, gradient, hydraulic conductivity, and porosity. Of these factors, effective porosity is one of the most difficult to assess, but ranges from 0.1 to less than 0.01 (Chestnut and Cox, 1977) have been used, and in very tight formations, the porosity can be extremely low. Although porosity does affect hydraulic conductivity (normally as porosity decreases, hydraulic conductivity also decreases), the relationship is highly complex (Scheidegger, 1957).

It seems unreasonable that an equivalent thickness of Mahogany will carry the same discharge and at faster rate than the A-Groove, especially as the potential (Domenico, 1972) to drive water through smaller and smaller pore spaces is limited by the elevation of the Roan Plateau, or whatever area is the principal source of recharge.

If most of the water is carried in the alluvium and the Uinta Formation, the deeper beds of the Green River Formation may be characterized by little discharge and low velocity.

For these reasons, it is worthwhile to examine the extent to which the limiting Darcy velocities may be approached in the real sense.

The drill stem tests provide the lowest Darcy velocity values. The highest Darcy velocity values were from transmissivity calculations based on data from a reinjection program at the C-b Tract in the spring of 1981. From the reinjection tests, the range of Darcy velocities derived in the Green River Formation is 0.55 ft/yr (.17 m/yr) to 16.4 ft/yr (5.00 m/yr) (Geothermal Surveys, Inc., 1981; Tiab, et al, 1980). The transmissivity values, which provide these velocities, are in reasonable agreement with or larger than transmissivity values based on other approaches such as test pumping on the C-b Tract (Tipton, et al, 1977).

2. Given the range of Darcy velocity values, the maximum time for water to travel across the Piceance basin within the deep bedrock aquifers of the Green River Formation might be measured in thousands of years or even greater orders of magnitude. Maps of the potentiometric surface for the Upper Aquifer and the Lower Aquifer are provided by the U.S. Geological Survey (Weeks, et al, 1974; Robson, et al, 1980).

It is about 30 miles (48 km) from the south or southeast rim of the Piceance basin to the White River, south of which the beds of the Green River Formation are exposed. The potentiometric surface is steeper at the C-b Tract than throughout most of the Piceance basin. Therefore velocity values derived for the C-b Tract should be reasonably representative and may be conservative.

Using the data, the shortest limiting time for ground water in the deep aquifers to move across the Piceance basin is 9,600 yrs (reinjection analysis). The longest limiting time is 8.8 million yrs (drill stem test SG-17). Again, the values represent extreme or limiting cases based on the Darcy velocity not the actual velocity. The actual velocities would be greater depending on what porosity values are used.

3. Except along through-going fault zones, vertical leakage across the stratigraphic units in the Green River Formation may be insignificant. There are several categories of evidence that bear this out.

Geologically the layered arrangement of strata, and the fact that the layers are arranged essentially horizontal, inhibits downward or upward ground-water migration. While it is true that the ground water is in the fractures, it is also true that the fractures are largely controlled by the rock type. Brittle marlstones are able to hold open fractures to some depth. Oil-rich shales are not.

Water in different strata show differences in chemistry. These differences do not change continously downward but increase and decrease with depth. This means that if vertical leakage is occurring it is not sufficient to smooth out or eliminate the differences in water chemistry.

During shaft sinking, large differences were found in rates of water production from different horizons. As with water chemistry, there was not a continuous change downward. There were increases and decreases in rate, and some intervals were completely dry.

There are well pairs at or near the C-b Tract in which wells completed in alluvium show no drawdown while companion wells completed in the bedrock show much drawdown. Such is the case with alluvial/bedrock pairs WA-06/SG-20 and WA-07/SG-19. If leakage downward from the alluvium is occurring into the deep bedrock, it is still too slight to be discerned after more than a year of observed drawdown in the bedrock wells.

In well 32X-12, completed in the Upper Aquifer, water stands about 800 feet (244 m) below the surface. Ninety feet (27 m) from this well are the Service Production Shafts, now about 1,800 feet (549 m) deep. These shafts have undergone dewatering since the beginning of sinking in March 1979. The shafts are lined but not sealed and are designed to leak. The fact that water still occurs in a "partially penetrating" observation well so close to the two great (more than 30 feet [9 m] diameter) "production wells" is strong evidence that both the horizontal and vertical hydraulic conductivities are extremely small.

Using a statistical approach (Fetter, 1980) and the hydraulic conductivity values from the drill stem tests of SG-17, the vertical permeability is about one-tenth the horizontal permeability. However, because this is based on horizontal permeability data, the true vertical permeability is likely to be even smaller.

Leakance studies using the Newman and Witherspoon (1972) equation were made by General Electric Company - Tempo in a study for the Environmental Protection Agency (1980). They report: "Leakance values, estimated from type-curve matching (table 5-7), were small, showing that the water level in any aquifer was not affected by pumping any other aquifer. A computer solution of the Neuman and Witherspoon leaky aquifer equation was developed which indicated that the vertical hydraulic conductivity was less than $5x10^{-7}$."

Perhaps, the most striking evidence of non-communication between shallow aquifers and the deep bedrock is that some horizons encountered during shaft sinking were absolutely dry (Stellavato, 1981), even though the overlying bedrock contained water. These dry horizons must be considered as not reached by either vertical leakage nor by horizontal migration from vertical leaky zones elsewhere.

4. The leached zone may represent an ancient event. During sinking of the shafts, large vugs were found, some of which were dry and some of which contained water that flowed strongly for a short time and then stopped.

If the vugs are interconnected from source to outlet, and if there is active recharge to the deep formations; they should still contain water, and the water should continue to flow into the open shaft. That some vugs were found to be dry and that others flowed strongly and then stopped, suggests that the vugs are not interconnected from recharge source to outlet; but that at least some of the water in the deeper formations, if not connate, may have been trapped there for a very long time.

Donnell (1961) shows unconformable relationships among some of the formations. This implies erosion, and therefore leaching may have occurred shortly after the depositing of any of the saline deposits. If so, later blanketing by the overlying formations would tend to seal off and isolate some of the leached zones.

Such processes would provide today, long after the Eocene, a system of partially interconnected vugs and channels showing the effects of earlier activity, able to contain water but not able to transmit water for long distances.

This would also provide high-transmissivity values for short-term tests, but this would not necessarily indicate that through-basin flow at high velocity is going on.

5. Some upward leakage does occur from the deep aquifers to the shallow formations in the stream bottoms in the northern part of the basin; this leakage is likely controlled by major faults. Through-going faults are mapped (Donnell, 1961) across Black Sulphur Creek and across Piceance Creek near the mouth of Ryan Gulch. Recent mapping by Beard (1981) shows faulting in the north rim of the basin, with directional trends across Piceance and Yellow Creeks.

It is in such localities that upward leakage could occur and may have been occurring for a long time. In such areas, soils with higher salinities may be due to upward leakage and deposition at the surface.

In these localities, the salines are not excessively thick even though they have been exposed for a very long time (except for stream alluvium there are no post-Eocene deposits). This implies that unless flushing at the surface is going on, the upward leakage to the surface is either a very recent event or it goes on at an extremely slow rate.

6. Most of the springs may be from very shallow sources. Many of the springs in the C-b Tract area show very short-term changes in flow rates, are along exposed stratigraphic horizons in the bedrock, or are along the bedrock-alluvial contact.

If the slow ground-water migration rates as described in the foregoing paragraphs are correct, it is difficult to believe that short-term changes in flow rates can occur in springs that are outlets of the deep aquifers.

The C-b area springs may be derived from two shallow sources. One source, from the high-peripheral areas may provide water to the major springs via the shallow formations. In addition, some of the springs may be fed by water that infiltrates into the near-surface fractures in the bedrock ridges, maintains high mounds of saturated storage during wet periods, and feeds the springs along adjacent slopes and valley bottoms. During dry periods, these storage mounds are lowered, and the springs may reduce in flow or go dry.

In this concept, some of the springs are controlled very locally by bedrock, by near surface fracture distribution, and by short-term changes in climate. Others are substrained by long term and long distance migration in the shallow formation.

7. The Uinta Formation may contain both unconfined and confined ground water in the C-b area, and may be responsible for much of the recharge to Piceance Creek and its tributaries. Recent geologic mapping (Beard, 1981a) shows that the Black Sulphur Tongue subcrops beneath the alluvium of Piceance Creek north of the C-b Tract

and dips southerly beneath the tract. The layers above and below the Black Sulphur Tongue are thus in position to receive infiltration from (or provide water to) Piceance Creek in the north, from surrounding areas in the south and east, and by downward seepage from above. The Black Sulphur Tongue appears to be the uppermost significant confining layer, and above this the water is unconfined.

It seems likely that confined water occurs in the Uinta Formation between the Black Sulphur Tongue and the Thirteen Mile Creek Tongue at the base, and that it is this confined water in the lower Uinta Formation, recharged from the higher slopes to the south, the north, and the east that can provide significant recharge to Piceance Creek.

In this concept, the flow of Piceance Creek and its tributaries near the C-b Tract is derived mostly from surface runoff, from shallow-source springs, and from the Uinta aquifers.

8. <u>That the potentiometric contours bend around Piceance Creek is not necessarily due to upward leakage from the bedrock aquifers.</u> An interpretation held by many is that this configuration of the potentiometric surface shows that the deep bedrock aquifers discharge into Piceance Creek along most of its length. Piceance Creek is thus acting as a drain for the deep aquifers and thus depresses the potentiometric surface. This is reasonable, but there may be another explanation.

The potentiometric contours closely resemble any set of structure contours in the Piceance basin. The Piceance Dome north of Piceance Creek is quite well defined by the potentiometric contours, and Piceance Creek flows almost along the structural downwarp axis of the basin.

The potentiometric configuration may reflect a combination of structural control of the ground water and very slow migration not upward into Piceance Creek, but outward into the White River through the Green River outcrops. We agree with the U.S. Geological Survey (Weeks, et al, 1974) that fracturing should be greatest along the structural axis of the basin. If fractures are more abundant in the competent beds and less abundant in the incompetent (oil-rich) beds, the entire axial zone should thus drain laterally more efficiently than the limbs (Stearns, et al, 1972) toward the outlet region south of the White River, while maintaining confining integrity in the vertical direction, except where locally cut by faults.

We suggest this concept to explain the configuration of the potentiometric surface because it appears to explain why the major tributaries to Piceance Creek do not similarly have to be interpreted as drains for upward leakage, nor does Yellow Creek which, second to Piceance, is the largest drainage in the Piceance basin. Zones of upward ground-water potential (Robison, et al, 1980) are indicated in the lower and upper Yellow Creek system, yet the published maps do not show the potentiometric contours bending around this stream.

9. <u>The deep bedrock aquifers in the Piceance basin may have experienced relatively little flushing since the end of Uinta time.</u> If the ground-water migration rates are very long as suggested in this interpretation (Item 2), the ground water does not course rapidly through the deep formations, and at least in some of the formations there may have been few or no transits through the system.

10. <u>Of the recharge that does occur to the deep bedrock, a significant proportion may enter the upturned Green River Beds along the eastern rim of the basin.</u> At least for the Piceance Creek part of the Piceance basin, the deep bedrock aquifers are exposed along the eastern margin. It would seem that the easiest way for water to enter these formations is along the upturned eroded edges of the beds, and from infiltration from uppermost Piceance Creek and its tributaries which flow directly upon them or where the alluvium is coarse grained and thin.

11. <u>At the C-b Tract, vertical leakage if it occurs as a result of mining, would be downward.</u> Based on many wells, the head elevations for the Lower Aquifer horizons are slightly lower than are the heads in the Upper Aquifer horizons.

Therefore, we would expect that during and after mining and abandonment of retorts, there should be no leakage upward from the retorts into the shallower formations, if the overlying aquicludes have not been broken, and the shallow aquifers have not been dewatered.

12. <u>From the mining zone at the C-b Tract, lateral migration, if it occurs, should have no effect on quantity and quality of the usable ground water.</u> From the C-b Tract, it is 8 miles (13 km) to the nearest expected zone of upward leakage to the surface. This is where through-going faults intersect the structural axis of the basin near the

mouth of Ryan Gulch (Weeks, et al, 1974).

The fastest Darcy velocities (our own work based on reinjection) and the slowest Darcy velocities (drill stem tests, SG-17) if used as limits and extrapolated across this distance give indicated times of 2,600 yrs and 3,250,000 yrs respectively to reach this locality. The actual times, of course, would depend on what values are used for the other hydraulic parameters. The Darcy velocities are so slow; however, that even if the average linear real velocities are higher by an order of magnitude or more, and if the drill stem test results are more accurate than our own interpretations, the time to reach the locality may be measured in thousands to tens of thousands of years or even more.

Some criticisms of this interpretation are that with fracture porosity, discharge can be quite large because it varies with the cube of fracture width (Witherspoon, et al, 1980). A second is that fingering (Verma, 1970) that can occur in a cracked porous medium may take place locally in some of the formations.

However, there is another aspect of the problem that should be considered. What we are largely concerned with is not simply the established steady-state transport condition, but the time for first arrival from a source of potential contamination to where it can become a hazard. In a region as large as the Piceance basin, a mining area even as large as the C-b Tract can be considered more or less a point source. Flows emanating from such areas after abandonment should be subject to the laws of dispersion (Hubbert, 1940) and the processes of matrix diffusion (Grisak, et al, 1980). It would seem that the time for first arrival of a contaminant could be extremely long.

In summary, the foregoing analysis contains some surprisingly large numbers in regard to the migration time of water through the Piceance basin. The times are so large that they appear unrealistic, and they probably are. Yet they are based on observed data, and their validity can be tested. It seems reasonable to consider the time ranges stated here as extreme limits, and that what actually occurs is at some intermediate value.

Whatever the final results, the time for water migration through the Piceance basin seems to be long, and the geohydrologic setting seems to favor protection of the environment. These conditions appear to occur widely throughout the Piceance basin, and this should be of interest to other developers of oil from shale in the Piceance basin.

Finally, the excellent work by the U.S. Geological Survey and by other organizations (Fox, 1981; Mehran, et al, 1980), in developing models for ground-water flow and solute transport are based on the best data available to them at the time. By responding to their repeated requests for data, we can greatly help them in improving their models. Their willingness to do this and their receptivity to new ideas is obvious to any of us who have worked in the Piceance basin.

REFERENCES

Beard, T. N., 1981, Geologic framework, Tract C-b area, Rio Blanco County, Colorado: Report to Cathedral Bluffs Shale Oil Company: p. 1-13 with maps and tables.

______1981a, Personal communication.

Chestnut, D., and Cox, D., 1977, The dependence of aquifer storage coefficients on porosity in low porosity media: Report to Occidental Oil Shale, Inc., Denver, Colorado, unpublished: p. 1-14.

Dagan, G., 1979, The generalization of Darcy's Law for nonuniform flows: Water Resources Research, v. 15, p. 1-7.

Domenico, P., 1972, Concepts and models in ground water hydrology: McGraw Hill, p. 1-405.

Donnell, J. R., 1961, Tertiary geology and oil-shale resources of the Piceance Creek basin between the Colorado and White Rivers, northwestern Colorado: U.S. Geological Survey Bulletin 1082-L, p. 835-891.

Energy Consulting Associates, 1977, Drill Stem Test Analysis, Tract C-b: Report to Occidental Oil Shale, Denver, Colorado, unpublished: p. 1-81.

Fetter, C., 1980, Applied hydrogeology: Charles E. Merrill, p. 1-488.

Fox, J. P., 1981, Water-related impacts of in-situ oil-shale processing: Lawrence Berkeley Laboratory Report No. LBL-6300.

Freeze, R., and Cherry, J., 1979, Ground water: Prentice-Hall, p. 1-604.

General Electric Company - Tempo, 1980, Monitoring ground-water quality, the impact of in-situ oil-shale retorting: Contract No. 68-03-2449, for Environmental Monitoring Systems Laboratory, Office of Research and Development, U.S. EPA, Las Vegas, Nevada: p. 1-280.

Geothermal Surveys, Inc., 1981, Geohydrologic study of reinjection, Tract C-b, Piceance basin, Colorado: Report to Occidental Oil Shale, unpublished, p. 1-82.

Grisak, G., and Pickens, J. 1980, Solute transport through fractured media; 1. The effect of matrix diffusion: Water Resources Research, v. 16, p. 719-730.

Hubbert, M. K., 1940, The theory of ground-water motion: Journal of Geology, v. 48, p. 785-944.

Mehran, M., Narasimhan, T., and Fox, J. P., 1980, An investigation of dewatering for the modified in-situ retorting process, Piceance Creek basin, Colorado: Lawrence Berkeley Laboratory Report No. LBL-11819, 105 p.

Neuman, S., and Witherspoon, P. 1972, Field determination of the hydraulic properties of leaky multiple aquifer systems: Water Resources Research, v. 8, p. 1284-1298.

Robson, S., and Saulnier, G., 1980, Hydrogeochemistry and simulated solute transport, Piceance basin, northwestern Colorado: U.S. Geological Survey Open-File Report 80-72, p. 1-89.

Scheidegger, A. E., 1957, The physics of flow through porous media: MacMillan Company, p. 1-231.

Stearns, D., and Friedman, M., 1972, Reservoirs in fractured rock, in Fracture-Controlled Production, American Association of Petroleum Geologists, Reprint No. 21, Kostura, J. R., and Ravenscroft, J. H., eds.: p. 174-206.

Stellavato, N., 1981, personal communication.

Tiab, Djebbar, and Anil Kumar, 1980, Application of the p' function to interference analysis: Journal of Petroleum Technology, p. 1465-1470.

Tipton and Kalmbach, Inc., 1977, Hydrology, mine dewatering, water use, and augmentation: Report to Occidental Oil Shale, Inc., Denver, Colorado, unpublished.

Todd, D. K., 1980, Ground water hydrology: John Wiley, p. 1-535.

Verma, A., 1970, Fingero imbibition in artificial replenishment of ground water through cracked porous media: Water Resources Research, v. 6, p. 906-911.

Weeks, J., and others, 1974, Simulated effects of oil-shale development on the hydrology of Piceance basin, Colorado: U.S. Geological Survey Professional Paper 908, 84 p.

Witherspoon, P., and others, 1980, Validity of cubic law for fluid flow in a deformable rock fracture: Water Resources Research, v. 16, p. 1016-1024.