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*Cover: Typical surface drill rig; solution mining well configuration; schematic of a heap leaching dump; blasting for in-situ leaching.*



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the highest water permeability measured was 0.26 md. Most samples had no detectable permeability. The pores of the rock are interconnected as demonstrated by the capillary pressure data and also by ready imbibition of water. This indicates that minerals within the rock can be leached only by diffusion processes.

5. High degrees of compaction can alter the capillary curves by fracturing and breaking down the larger particles. This produces smaller particles but apparently not many more fines. This can be seen by comparing sample 2 which was compacted under 100 psi with sample 5 which was compacted to 400 psi. Note the higher water retention at low capillary pressures in sample 5.

6. It is possible for a zone of high capillarity to appear as a perched water table. Field and laboratory tests can be used to determine whether it is a perched water table or a zone of high capillary water saturation.

## ACKNOWLEDGMENTS

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# Chapter 9

## A TRACER TECHNIQUE TO MEASURE THE DIFFUSIONAL ACCESSIBILITY OF MATRIX BLOCK MINERALIZATION

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## ABSTRACT

Fluid flow through an igneous rock formation will occur mainly through fractures. A non-diffusing or slowly diffusing tracer (such as .5μ silica spheres identifiable under electron microscope) will arrive at a monitor well when enough fluid has been injected to displace the volume of water in the flow fractures between the injection and monitor wells. A rapidly diffusing tracer (such as NaCl) will diffuse into the matrix blocks and so a volume of tracer nearly equal to the total fluid volume contained in the rock formation between injection and monitor wells must be injected before significant diffusing tracer arrival will be noted. The flow fracture porosity is typically one hundred times smaller than the total porosity of an igneous formation. The shift between diffusing and non diffusing tracer arrivals, together with the diffusional characteristics of the tracers, can define the diffusional accessibility of the matrix blocks of an igneous formation. A field test of these concepts and the problems encountered will be described.

## INTRODUCTION

Fluid flow through an igneous rock formation will occur mainly through fractures. Mineralization in the "matrix blocks" between fractures must be accessed by diffusion of chemicals from the flow fractures if metal values there are to be leached. This paper describes the theory behind a simple tracer test that can potentially measure the diffusional accessibility of matrix block mineralization and then describes field implementation of that theory.

## THEORY BEHIND TEST

The rationale of the test can best be explained by considering a non-diffusing tracer first. A non-diffusing tracer injected in one well will arrive at another well, a distance R away, approximately (neglecting mechanical mixing) when enough tracer has been injected to displace the intervening mobile pore fluids. By reference to Figure 1 it can be seen this volume must be about $V_A$, where

$$\underset{\text{Non-Diffusing}}{V_A} = \pi R^2 H \Phi_f \, . \quad (1)$$

For a diffusing tracer dilution may occur by diffusion of tracer components from the flow fractures into the "matrix blocks"*. One would expect** that for a diffusing tracer, the matrix blocks would have to be filled with tracer before much tracer would be observed at the monitor well. The criterion for diffusing tracer arrival then becomes:

$$\underset{\text{Rapidly Diffusing}}{V_A} = \pi R^2 H \Phi_T \quad (2)$$

Here, $\Phi_T$ is the total porosity of the formation tested.

$\Phi_f$ is generally about two orders of magnitude smaller than $\Phi_T$, so a measurable displacement in arrival time of tracers with different diffusion constants should be observable.

A more complete theory is sketched in Appendix I. There, account is taken of the diffusion constant of the tracer, D', the effective diffusional porosity of the matrix blocks, $\Phi$, and of the spacing of the fractures, $2D_{\frac{1}{2}}$, and their average thickness $2d_{\frac{1}{2}}$.

* Matrix blocks are the blocks of rock between flow fractures. Essentially no flow is thought to occur through these blocks.

** Chemical diffusion is directly analogous to thermal conduction. The tracer experiment with a diffusing tracer is thus similar to pushing pieces of hot paper between tightly fitting rock blocks and awaiting a thermal anomaly at 50 to 100 feet distance. Intuitively it is clear the blocks themselves must warm up before much of a thermal anomaly will be observed at the monitor well.



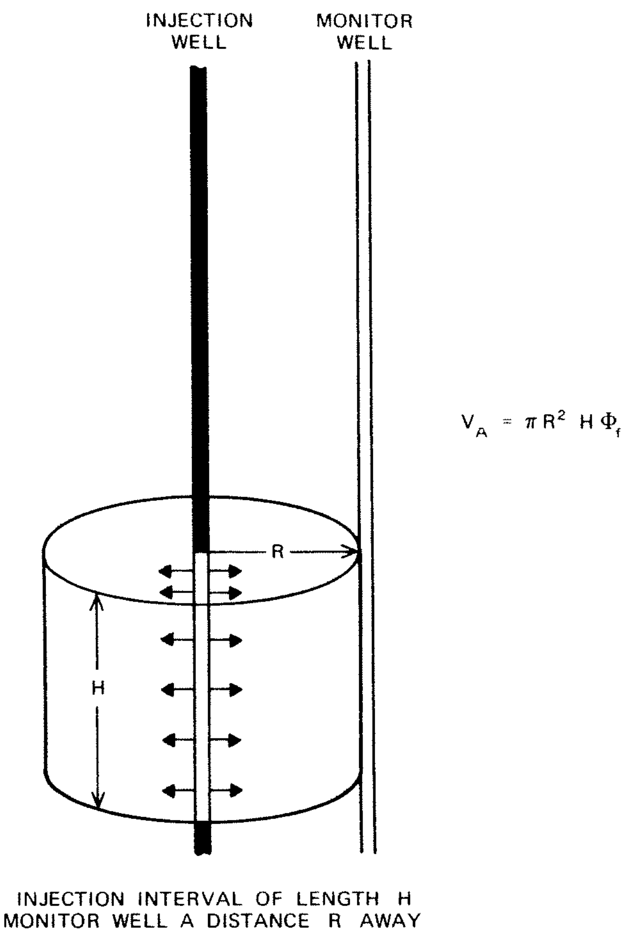



Figure 1. Geometry of injection and monitor wells. $\Phi_f$ is the flow channel porosity of the formation tested. $V_A$ is the volume of tracer injected when the monitor concentration is half the injected tracer concentration for a non-diffusing tracer.

## THE FIELD TEST

From September 8 to October 3, 1972, a dual component tracer was injected as shown in Figure 2 into well K-286 (see Figures 3, 4) at Kennecott's Ely Witch test site in Ely, Nevada. The tracer contained 41,000 ppm NaCl and 25 cc of .5μ silica dust from Union Carbide per gallon (see Figures 6, 9). The chloride level was monitored chemically. The silica spheres could be identified when samples were centrifuged, dried, mounted and examined under an electron microscope. The spherical shape of the sphere's, their size distribution, and their translucency were considered diagnostic for identification purposes.

The fluid flow was inferred from the water level in surrounding holes during the test and is shown in Figure 5. Flow was almost entirely through a supergene zone that had a total porosity of ~ 10% and a permeability of about 11 millidarcies (see Figure 4). Calculations (method of images) showed the underground workings should not distort the flow pattern. At least 5 - 10 gallons were bailed from all the monitor holes each day to prevent the water in the holes from unduly diluting the tracer.

After 28 days of injecting and monitoring the test was discontinued. No detectable NaCl anomaly had reached any of the monitor wells (see Table 1), but silica spheres had been detected in near injection concentrations (see Figures 6, 7, 8 and 9). Chemical alteration of the silica spheres to an iron-calcium-sulfate was observed but this appeared to be occurring in the sample bottles after recovery (see Figures 8 and 9).

## INTERPRETATION OF THE FIELD TEST

Although oxygen injection (see Figure 2) could have produced an iron-calcium-sulfate colloidal precipitate similar to that observed, the interpretations in this event would be similar to assuming arrival of the injected spheres. The non-diffusing tracer arrived, the diffusing tracer did not. Continued bailing of one monitor well after tracer injection had been stopped produced a drop in silica sphere concentration.

Assuming near injection concentration of silica spheres at K-277 after 3400 gallons injected (see Figures 2, 6 and 7) and an injection interval H = 50', from (1)

$$\Phi_f = 10^{-3}$$

The fracture spacing in the area of the test was observed to be about 1ft, so from App. I equation (6)



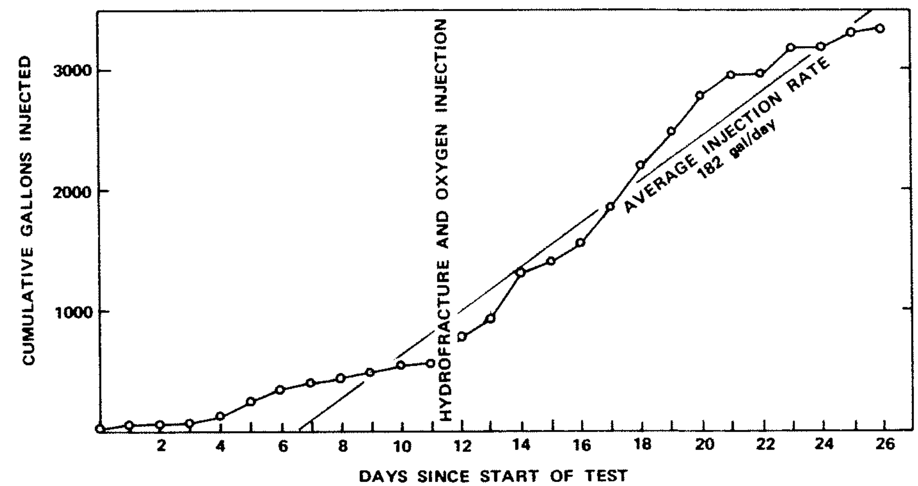



Figure 2: Test Injection History. Gallons of tracer injected into K-286 as a function of time (days) since start of test. The formation was hydrofractured and oxygen injected on the 11th day of the test.

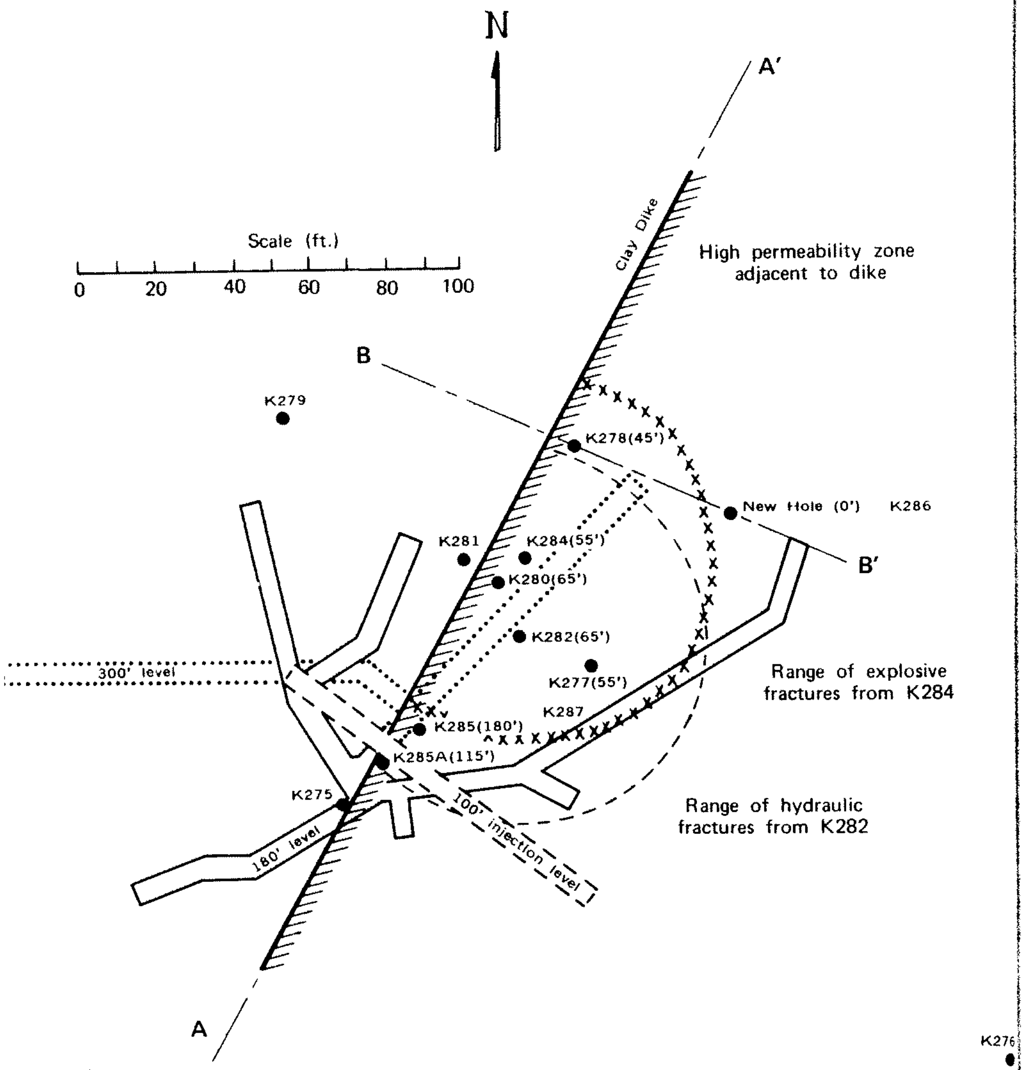



Figure 3: Well geometry at Ely Witch showing the proposed injection hole ("New Hole") and retrieval hole (K-278). Major influences on the permeability are also shown, such as the impermeable clay dyke with its adjacent high permeability zone, the radius of induced hydrofractures, the radius of induced explosive fractures, and the 180ft level workings.



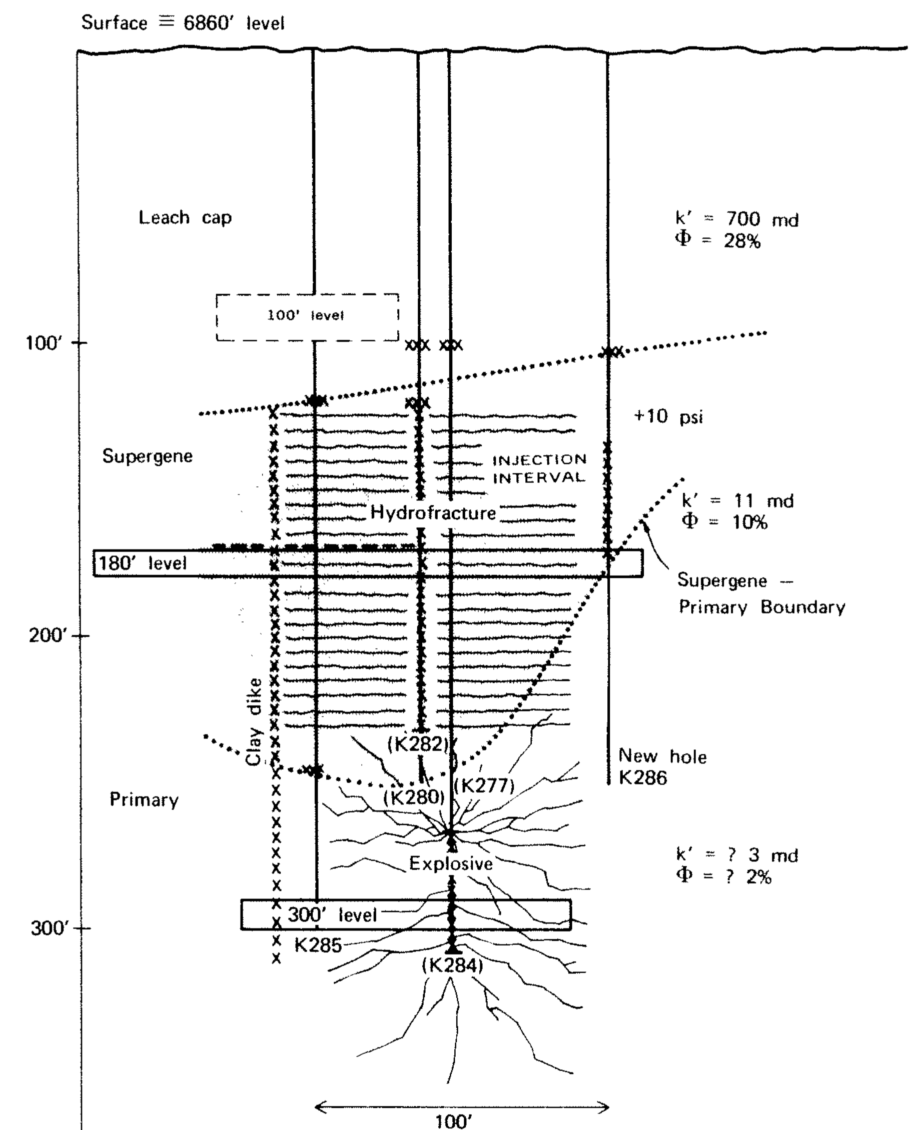



Figure 4: Cross-section AA' from Figure 1. Areas probably artifically fractured are shown as well as the Clay Dike.

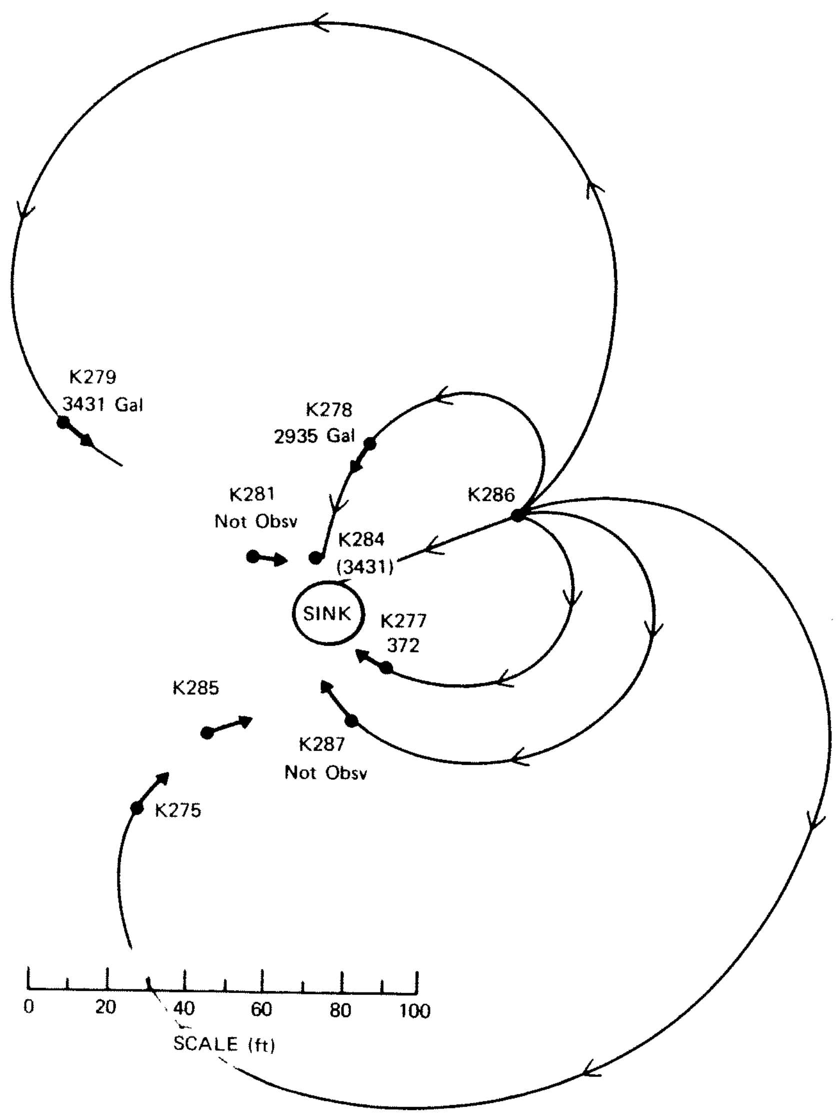


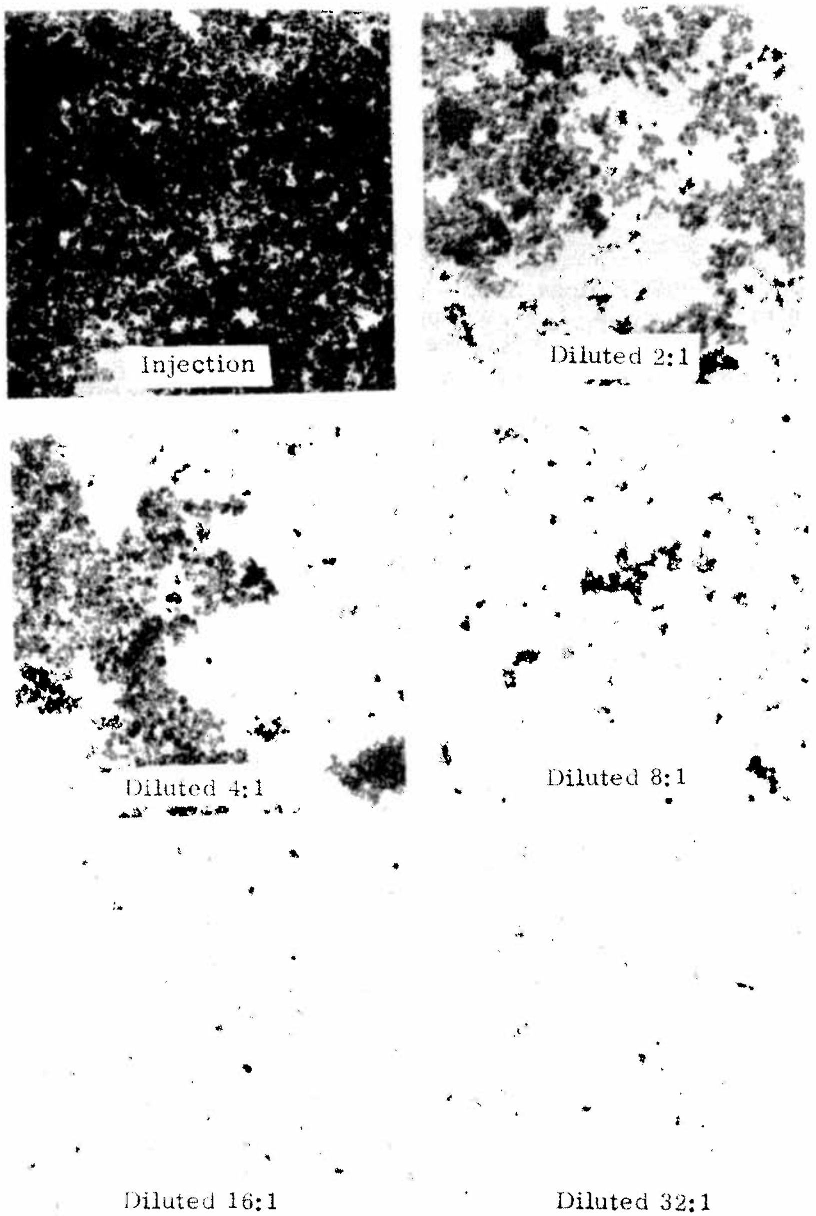

Figure 5: Number of gallons injected before first silica spheres detected. Parentheses indicate the first sample analyzed showed spheres and record the number of gallons injected at that sample. The arrival could be prior to this analysis. Superimposed are flowlines deduced from the water level in the wells during the test.



TABLE I

Chloride concentrations in ppm measured in various samples taken from monitor wells. 41,000 ppm chloride was injected in K-286 during the tracer test.

| | Gallons Injected | | | |
|---|---|---|---|---|
| Monitor Well | 0 | 350 | 1350 | 3462 |
| K-277 | 160 | 130 | 120 | 100 |
| K-278 | 40 | 43 | 39 | 39 |
| K-279 | 42 | 37 | 35 | 38 |
| K-281 | 42 | 40 | 41 | 38 |
| K-284 | 73 | 62 | 46 | 65 |
| K-285 | 21 | 18 | 20 | 19 |





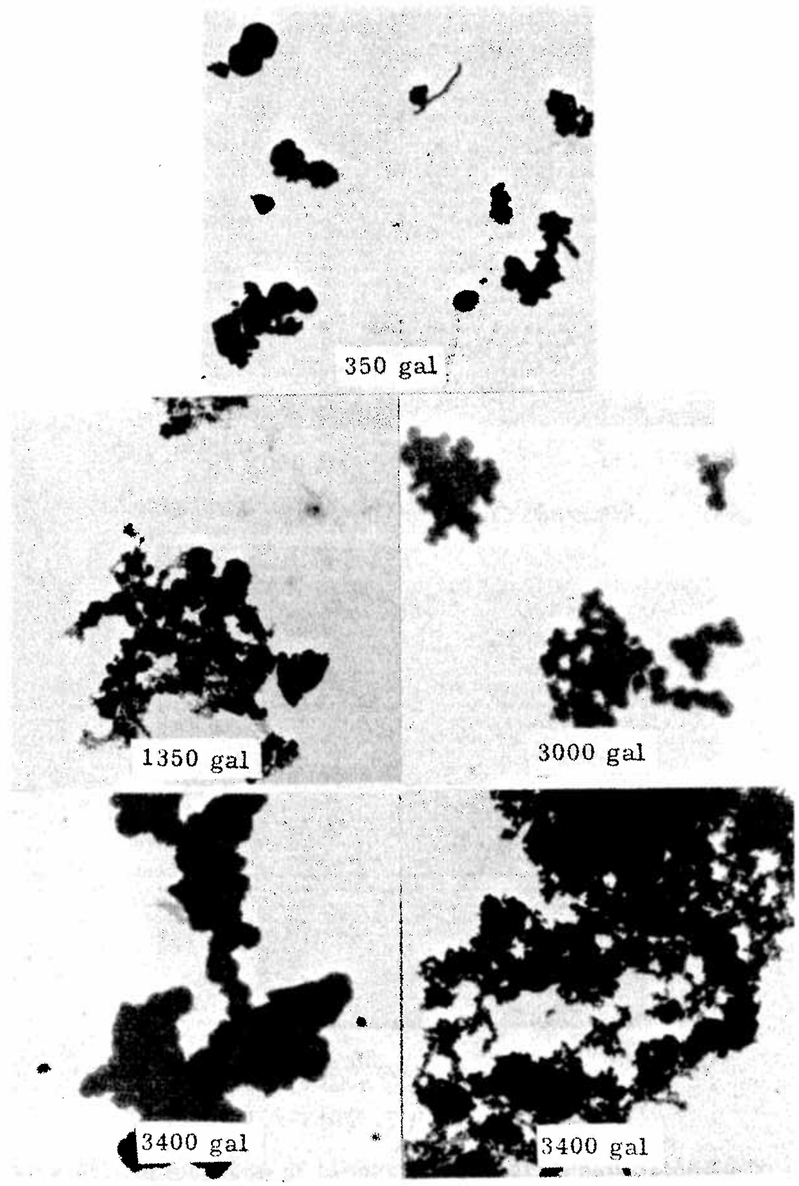
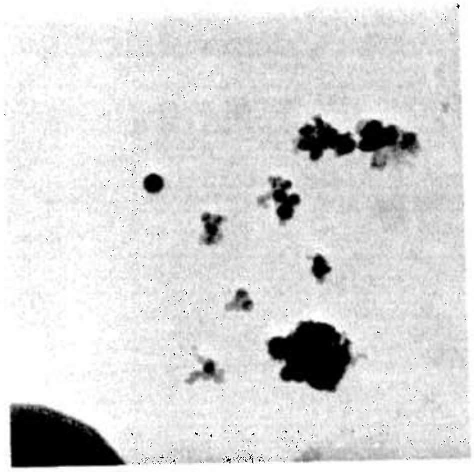
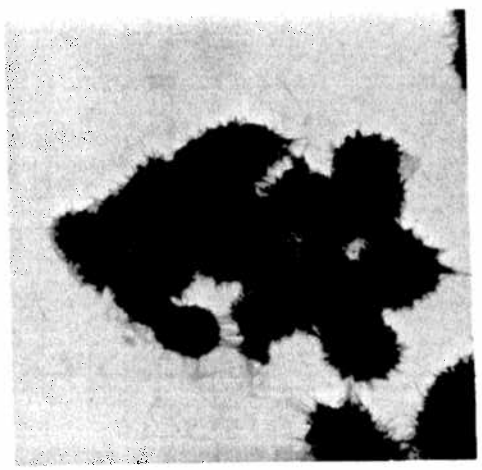




Figure 7: Analysis Sequence for K-277. Spheres first observed after 350 gal injected. 5-10 gals. bailed once per day. Bailing of ~63 gallons produced the difference between the last two figures.



K277-116 30,000X

Analyzed October 10. 1972

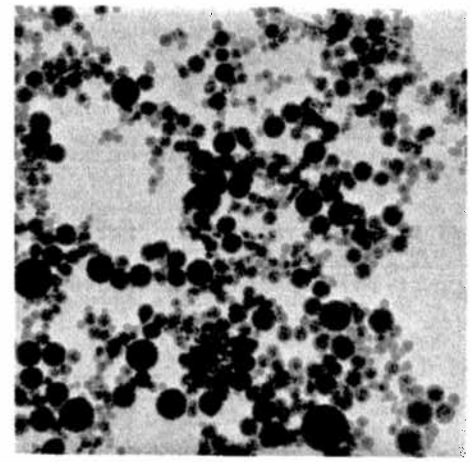


K277-116 30,000X

Analyzed March 7, 1973

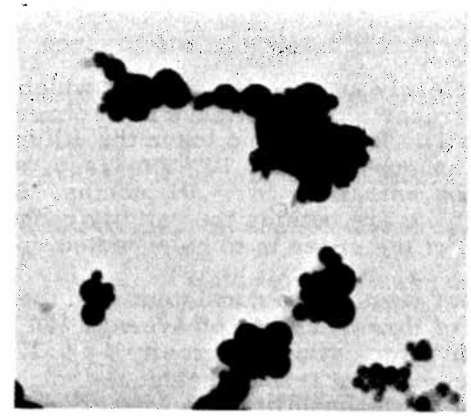
Figure 8: Comparison of first analyzed sample from 277 and a later analyzed sample. Note change in opacity of spheres.





Injected 30,000X

Analyzed without exposure to $Fe^{++}$, $Fe^{+++}$, $SO_4^{=}$



Aged Injection 30,000X

Analyzed after expsoure to $Fe^{++}$, $Fe^{+++}$, $SO_4^{=}$ at $50^{o}C$ for 43 days.

Figure 9: Comparison of laboratory spheres subjected to iron sulfate solution to spheres not so subjected. Opacity change is beginning to become evident. However, laboratory altered spheres would not dissolve in acid as spheres from aged sample bottles did.

$$d_{\frac{1}{2}} = \frac{\Phi_f D_{\frac{1}{2}}}{2} = 75\mu m .$$

(We assume two perpendicular sets of fractures in the flow direction. Hence the factor of ½).

41,000 ppm NaCl solution was injected. There was no anomaly within ± 4ppm. Thus $C/C_o$ after 1 month must have been less than $10^{-4}$. From Table App. I-1 this requires $\bar{t} < .035$ or

$$t < (.035) \frac{\Phi^2 D' X^2}{v^2 T d^2_{\frac{1}{2}}} \qquad (3)$$

Using $D' = 2 \times 10^{-5}$ $cm^2/sec$ (an appropriate value for $Na^+$ or $Cl^-$) $\Phi = .1$, X = 50 ft, T = 5 (found experimentally in laboratory to be appropriate), $d_{\frac{1}{2}} = 7.5 \times 10^{-3}$ cm, and $v = 10^{-3}$ cm/sec (calculated from average injection rate, Figure 2, $\Phi_f$, and taking R = 30 ft), (3) becomes:

$$t < 21.5 \text{ mo} \qquad (4)$$

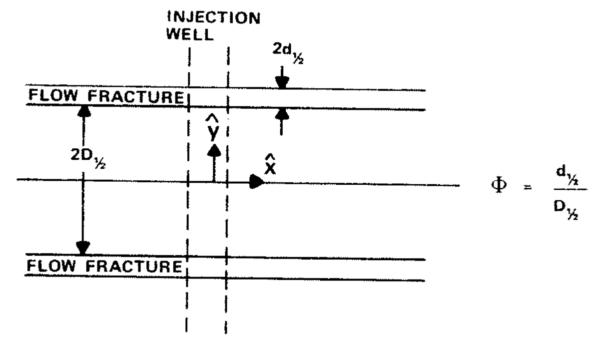
Condition (4) was clearly satisfied by the test which lasted ~1 month so the $Cl^-$ tracer should not have been observed as it indeed was not (Table 1). By the same token the diffusion constant of .5 μm silica spheres is about $10^{-8}$ $cm^2/sec$, so (3) would predict trace concentrations in ~.01 months. Since the test ran for ~1 month we are outside the validity range of (3), but it is clear arrival of the silica is to be expected.

We conclude the test results are consistent with theoretical predictions and a set of flow fractures on average 150 μm thick and spaced 1ft apart in a formation of porosity $\Phi = 0.1$. Further development of multicomponent tracer techniques might lead to a method of assessing the leachability of a formation in situ.



APPENDIX I

Let the geology be simplified:




Let C = concentration of tracer [ $gm/cm^3$ - fluid ]

D' = diffusion constant in the tracer [ $cm^2/sec$ ]

$\Phi$ = effective porosity of the matrix blocks - i.e. the porosity through which tracer can diffuse

T = tortuosity of the diffusion channels in the matrix block

$d_{\frac{1}{2}}$ = average thickness of the flow fractures [ cm ]

$D_{\frac{1}{2}}$ = half average spacing between fractures

v = velocity of fluid flow in flow fractures

Then

$$\frac{d(\Phi C)}{dt} = \frac{D' \Phi}{T} \nabla^2 C \qquad (1)$$

In the matrix where there is no flow, neglecting axial diffusion (1) becomes:

$$\frac{\partial C_m}{\partial t} = \frac{D'}{T} \frac{\partial^2 C_m}{\partial y^2} \qquad (2)$$

In the flow fracture, again neglecting axial diffusion, (1) becomes:

$$\frac{\partial C_f}{\partial t} + v\frac{\partial C_f}{\partial x} = D'\frac{\partial^2 C_f}{\partial y^2} \qquad (3)$$

Within the flow fracture transverse (to flow) diffusion is rapid enough to permit definition of an average tracer concentration:

$$C_{\bar{f}}(x, t) = \frac{1}{d_{\frac{1}{2}}}\int_{D_{\frac{1}{2}}}^{D_{\frac{1}{2}}+d_{\frac{1}{2}}} C_f(x, y, t)\, dy$$

Since $\left.\frac{\partial C_f}{\partial y}\right|_{y=D_{\frac{1}{2}}+d_{\frac{1}{2}}} = 0$ by symmetry considerations,

and the flux of tracer across the fracture boundary must be continuous, and

$$\left[\underline{j}\cdot\hat{n}\right]_-^+ = 0 \text{ where } \underline{j} = \frac{-D'\Phi\underline{\nabla}C}{T},$$

$$\frac{D'\partial C_f}{\partial y} = \frac{-D'\Phi}{T}\frac{\partial C_m}{\partial y},$$

(3) becomes:

$$\frac{\partial C_{\bar{f}}}{\partial t} + v\frac{\partial C_{\bar{f}}}{\partial x} = \frac{-D'\Phi}{T}\left.\frac{\partial C_m}{\partial y}\right|_{y=d} \qquad (4)$$

(4) and (2) may be solved by Laplace transform techniques, subject to the initial and boundary conditions:



$$C_{\bar{f}}(t<o, x) = o$$
$$C_m(t<o, x, y) = o$$
$$C_{\bar{f}}(t>o, o) = C_o$$
$$C_{\bar{f}}(t, x) = C_m(t, x, D_{\frac{1}{2}})$$

$$\left.\frac{\partial C_m}{\partial y}\right|_{y=o} = 0 \quad \text{by symmetry.}$$

The result is:

$$\bar{C}_{\bar{f}}(\bar{p}, \zeta) = \left(\frac{C_o}{\bar{p}}\, e^{-\zeta\bar{p}}\right)\left(e^{-\zeta\beta\sqrt{\bar{p}}\tanh\sqrt{\bar{p}}}\right) \qquad (5)$$

where

$$\zeta = \frac{x D'}{v D_{\frac{1}{2}}^2 T}$$

$$\beta = \frac{\Phi}{\Phi_f} = \frac{\Phi D_{\frac{1}{2}}}{d_{\frac{1}{2}}} \qquad (6)$$

$$\Phi_f = \frac{d_{\frac{1}{2}}}{D_{\frac{1}{2}}}$$

$$t = \frac{T D^2_{\frac{1}{2}}}{D'}\bar{t}$$

If $\zeta\beta \ll \mathrm{Re}\,|\sqrt{\bar{p}}\,|$, $\mathrm{Re}\,|\zeta\beta\sqrt{\bar{p}}\,|$ is small until $\mathrm{Re}\sqrt{\bar{p}}$ is large. $\tanh\sqrt{\bar{p}}$ can be approximated as 1, both parts of (5) can be inverted and the solution expressed by the convolution integral:

$$C(\bar{t}, \zeta) = C_o\int_o^{\bar{t}} H(\bar{t}-\zeta-\tau)\,\frac{\zeta\beta}{2\sqrt{\pi\tau^3}}\, e^{-(\zeta\beta)^2/4\tau}\, d\tau \qquad (7)$$

Since large $\bar{p}$ corresponds to small $\bar{t}$, (7) is valid for the first tracer arrivals.

The step function can be ignored since it just requires C to be zero until $t > x/v$. A diffusing tracer will arrive much later than this. Thus for small times (very dilute tracer arrival)

$$\frac{C}{C_o}(\bar{\bar{t}}) = \int_0^{\bar{\bar{t}}} \frac{1}{2\sqrt{\pi \tau^3}} e^{-1/4\tau} \, d\tau \qquad (8)$$

where $\bar{\bar{t}} = \bar{t}/(\zeta\beta)^2$. Table App. I-1 gives $C/C_o$ as a function of $\bar{\bar{t}}$.

| $\bar{\bar{t}}$ | $\frac{1}{2\sqrt{\pi \bar{\bar{t}}^3}} e^{-1/4\bar{\bar{t}}}$ | $C/C_o = \int_0^{\bar{\bar{t}}} \frac{1}{2\sqrt{\pi\tau^3}} e^{-1/4\tau} d\tau$ |
|---|---|---|
| .005 | $1.54 \times 10^{-19}$ | $2.2 \times 10^{-21}$ |
| .010 | $3.92 \times 10^{-9}$ | $5.2 \times 10^{-12}$ |
| .015 | $8.8 \times 10^{-6}$ | $1.3 \times 10^{-7}$ |
| .020 | $3.7 \times 10^{-4}$ | $7.9 \times 10^{-7}$ |
| .025 | $3.2 \times 10^{-3}$ | $9.5 \times 10^{-6}$ |
| .030 | $1.3 \times 10^{-2}$ | $5.1 \times 10^{-5}$ |
| .035 | $3.4 \times 10^{-2}$ | $1.7 \times 10^{-4}$ |
| .040 | $6.8 \times 10^{-2}$ | $4.4 \times 10^{-4}$ |
| .045 | $1.1 \times 10^{-1}$ | $9.1 \times 10^{-4}$ |

Table App. I-1 Normalized time and calculated tracer early arrival concentrations computed from (8).

If $\zeta\beta$ is large, Re $\sqrt{p}$ must be small for Re $(\zeta\beta\sqrt{p})$ to be small enough to allow a non-zero contribution to the inversion integral. In this case Tanh $\sqrt{\bar{p}} \rightarrow \sqrt{\bar{p}}$ and the second part of (5) becomes $e^{-\zeta\beta\bar{p}}$ whose inverse is $\delta(\bar{t} - \zeta\beta)$. The convolution of this delta function with the step function $H(\bar{t} - \zeta)$ in (6) gives:

$$\frac{C(t)}{C_o} = H\left(t - \frac{\Phi}{\Phi_f} \frac{x}{v}\right) \qquad (9)$$



This is equivalent to (2) in the text. It has been verified by numerical inversion of (5) that (7) melds into (9) when $\zeta\beta > 5$. These results are similar to those found by Coats, K.H., and Smith, B.D., Dead End Pore Volume Dispersion in Porous Media, Society of Petroleum Engineers Journal, March 1964, pp. 73-84.