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An Assessment of Drilling Fluid Tracers Used to Monitor Borehole Development for Hydrochemical Sampling

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David L. Graham
Basalt Waste Isolation Project

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ABSTRACT

Until recently, boreholes have been drilled for the Basalt Waste Isolation Project using water-based drilling fluids. Three drilling fluid tracers are used to monitor borehole development for hydrochemical sampling at the Basalt Waste Isolation Project. The tracers used are fluorescein dye, total organic carbon, and tritium. Used in concert, these tracers yield useful information regarding the degree to which a zone has been developed prior to final sample collection.

The adequacy of these tracers in assessing borehole development has been examined using data collected from five zones within three boreholes across the Hanford Site. Field data indicate that fluorescein and total organic carbon perform well in helping to assess borehole development. Tritium data from these examples indicate that final samples collected are greater than or equal to 98 percent groundwater.

Limited ionic data were available for one field example. These data indicate that certain species are affected by the introduction of drilling fluids. After the removal of approximately 9.5×10^4 liters of fluid, most species appear to stabilize. However, tracer data indicate that components of drilling fluid were still present in the zone at this time. A field test is in progress to better quantify the relationship between drilling fluid tracer behavior and major chemical and isotopic species dissolved in basaltic groundwaters.

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1.0 INTRODUCTION

The Basalt Waste Isolation Project (BWIP) began in 1976 to evaluate the suitability of the Columbia River basalts for a potential nuclear waste repository. A major part of the site characterization is understanding the natural hydrologic and hydrochemical properties of the groundwater flow systems within the basalts.

Groundwater hydrochemistry and isotopic data are useful tools when used in conjunction with hydrologic and geologic information to evaluate the origin and movement of groundwater. It is imperative that samples collected from boreholes reflect formation groundwater conditions if hydrochemistry data are to be fully utilized.

Most boreholes that have been drilled by the BWIP are multipurpose and provide geologic, hydrologic, and hydrochemical information. These boreholes are continuously cored to total depth. This normally requires the use of drilling fluids to obtain maximum drilling efficiency. Special additives are used in drilling fluids to adjust the fluid mixture to lubricate and cool the bit, maximize removal of cuttings from the boreholes, remove cuttings from the drilling fluid at the surface, control drilling fluid pH, and provide borehole stability. During the drilling process, drilling fluids may invade transmissive formations. If drilling fluids are not sufficiently removed from a zone within a borehole prior to sampling, analyses may produce misleading hydrochemical data.

Drilling fluids typically used by the BWIP begin as a mixture of bentonite and water. Additional soluble components may be added to this base to enhance the performance of the fluids. Thus, there is a need for obtaining information related to the water used to mix the drilling fluid as well as the solid or particulate matter added in order to determine when drilling fluids have actually been removed from a borehole. Tracers can be added to drilling fluids to monitor the removal of both components.

Parameters such as temperature, specific electrical conductance, and pH have been monitored routinely in hydrologic investigations to determine when a groundwater sample should be collected. Once these parameters have stabilized, it is thought that formation conditions have been reached and a representative sample can be collected (Wood, 1976). Basalt Waste Isolation Project experience has shown that in the deep basalts these parameters are not sufficiently sensitive to determine when drilling fluids have been removed from a borehole. This was also observed by Apps et al. (1979) in early work conducted in the deep Columbia River basalts beneath the Hanford Site.

Additives are used when mixing drilling fluids to maintain a fluid pH of ~8.5 to 9.5. This range is similar to the pH of the groundwaters in the deep basalts. Therefore, changes of only a few tenths of a pH unit may result from the introduction of drilling fluids in a borehole. The field measurement of pH is plagued by several uncertainties that include the degassing of the sample as it is brought up the borehole, instrumental and

sampling error, and temperature effects encountered in the field. These uncertainties, coupled with the pH of the drilling fluids, make this parameter insensitive for determining drilling fluid removal.

Groundwater cools significantly as it is brought from depth in a borehole. In very deep zones, the measured uphole temperature does not reflect in situ conditions. The temperature of groundwater discharging at land surface is also affected by air temperature. Thus, groundwater temperature measured at land surface provides little information relative to determining development of a deep horizon in a borehole.

Conductivity may be the most useful of these three parameters for determining when drilling fluids have been removed from a particular zone within a borehole. However, the utility of this parameter depends on the mixture and amount of drilling fluid used to drill a zone. In some instances, changes in conductivity are imperceptible because the volume of drilling fluid introduced into the system is small or the conductivity of the drilling fluid is less than or equal to the conductivity of the formation water. Thus, this parameter is not sufficiently sensitive to give reliable development information in all drilling situations.

It is necessary, therefore, to monitor parameters that are indicative of the fluid introduced into a borehole during drilling. Tracers can be added to the drilling fluids or components of the drilling fluids can be monitored to determine when a zone has been sufficiently developed.

2.0 TRACERS USED IN HYDROLOGIC STUDIES

Many types of tracers have been used in hydrologic studies. Most tracer studies have attempted to determine groundwater flow direction and/or velocity. A good summary of groundwater tracers and their application is given by Davis et al. (1980). The use of tracers to monitor borehole clean-up has been given relatively little attention until recently. This is probably because small diameter boreholes drilled relatively deep (>1,000 m) have not been used routinely for groundwater sampling.

No ideal tracer exists for all hydrologic or drilling applications; however, some are more appropriate than others depending upon the particular information to be obtained. In general, tracers can be broken down into several categories as shown in Table 1. Basically, anionic tracers are the least sorbed solute species on natural aquifer materials. This is because minerals tend to have net negative surface charges and, thus, repel anionic tracers (Davis et al., 1980). However, many of the negatively charged species, such as Cl^-, Br^-, and I^-, are not recommended as drilling fluid tracers because of their importance in characterizing groundwater chemistry. These species must be evaluated for each individual situation before a particular tracer or suite of tracers is determined. Cations, on the other hand, have a strong affinity for sorption and tend to be retarded quite readily on aquifer materials.

TABLE 1. Tracers Commonly Used in Hydrologic Studies (modified from Thompson, 1980). (Sheet 1 of 4)

Type of tracer	Characteristics	Comments
<u>Ionic tracers</u>		
Halides Cl^-	Nonsorptive, inexpensive, density problems when used in high concentrations, measured by titration methods, selective ion electrode, ion chromatography.	Not recommended for use in groundwaters with high background Cl^- concentrations.
Br^-	Very slight sorption, measurable using selective ion electrode, (practical sensitivity ~0.5 p/m), or HPLC.	Normally very low background concentrations in groundwaters. A very good general purpose groundwater tracer.
I^-	Moderate sorption, measured by selective ion electrode, sensitivity ~0.5 p/m	Very low natural background concentrations in most groundwaters.
^{131}I	Radioisotope $t_{1/2}$ - 8.2 d, detected by emmission (β and γ).	Useful for short-term tests, most common application in oil reservoir studies.
Dyes Rhodamine WT	Red dye, moderate sorption, moderately stable, low background fluorescence, most frequently used in surface water and in karst tracing, use in highly permeable sand and gravel aquifers, detected by fluorimetry, sensitivity ~1 to 0.1 μg/L.	Fluorescent dyes are easily detected in the field. They are inexpensive and easy to handle.
Fluorescein[a]	Yellow dye, similar properties as rhodamine WT but stronger sorption on aquifer materials.	Can be used as a drilling fluid tracer to give indication of how well particulate component has been removed from borehole.

TABLE 1. Tracers Commonly Used in Hydrologic Studies (modified from Thompson, 1980). (Sheet 2 of 4)

Type of tracer	Characteristics	Comments
Chelates EDTA-^{51}Cr EDTA-IN	The EDTA complexes with heavy metals or radioisotopes, detected by radiation by postneutron activation, some complexes unstable in presence of other cations in water, numerous chelated tracers have been developed and tested with varying results, mostly in oil reservoir studies, good sensitivity.	
Thiocyanate[b] SCN^-	Sodium, potassium, or ammonium salts of thiocyanate, most commonly used chemical tracer of the oil industry, low sorption in reducing conditions.	Works well as a drilling fluid tracer. Can be detected by colorimetry or HPLC down to ~0.1 mg/L.
Organic anions[b] sodium benzoate pentafluorobenzoic acid	Unlimited variety of good tracers possible, very low sorption, stability improved by fluorine substitution, can be measured with high precision using HPLC, detectable in low pg/L range.	Expensive. However, they can be concentrated in the lab prior to being introduced into a borehole making them cost effective.
<u>Uncharged tracers</u>		
Fluorocarbons CCl_2F_2 CBr_2F_2 $C_2Cl_3F_3$ $C_2Br_2F_4$ etc.	All fluoromethanes and fluoroethanes with chlorine and/or bromine substitutions, slight to moderate sorption on silicate or carbonate material, strong sorption by organic materials such as coal and peat, nondegradable, nontoxic, volatile, low solubility, difficult handling, measurement by gas chromotography with electron capture detection. Most are detectable to 1 p/T.	If drilling fluid has organic polymer additive, adsorption could be quite strong. [illegible]y work quite well to determine removal of particulate material in drilling fluid. Detection method not generally suited to field application.

TABLE 1. Tracers Commonly Used in Hydrologic Studies (modified from Thompson, 198[illegible]). (Sheet 3 of 4)

Type of tracer	Characteristics	Comments
Aldehydes and alcohols	Used in oil reservoir studies, degradable, detectable at parts per million level with gas chromatography.	
Tritium[a] HTO, CH_3T	Radioisotope of hydrogen, low sorption on most aquifer materials, very restricted use in shallow aquifers due to radiation hazard. common use in oil reservoirs, $t_{1/2}$ = 12.3 yr, measurement by weak β radiation.	Can be very useful tracer in drilling fluid. Background levels must be low in aquifer being drilled. Makeup water for drilling fluid must have a high activity relative to aquifer. Works well when aquifer water is older than 100 yr. Turnaround time for analysis is normally quite long. Provides good "after the fact" information about final sample integrity. Low-level counting techniques are expensive.
<u>Particulate tracers</u>		
Lycopodium spores	No chemical sorption, ~50 μm dia., multiple tracers possible by dying spores different colors, collected by trapping on plankton nets followed by microscope identification and counting, used almost exclusively for tracing karst conduits.	Most types of particulate tracers are not well suited for rapid field analysis. Analysis normally has to be done in a laboratory situation by culturing and counting.
Microorganisms yeasts, coliform bacteria	Smaller than spores (1-3 μm dia.) most useful for testing permeability of aquifer to transport of organisms, movement primarily through fractures in sediment or rock, organisms may sink or float in still water, measured by filtration followed by incubation and counting colonies.	

TABLE 1. Tracers Commonly Used in Hydrologic Studies (modified from Thompson, 1980). (Sheet 4 of 4)

Type of tracer	Characteristics	Comments
Viruses	0.02-0.05 μm, many types sorbed on media due to positive charge on organism, bacteriophage (virus infecting E. Coli) shows potential as good tracer due to negative charge on organism, detection by culturing and colony counting.	
Organic polymers		
Natural or synthetic polymers (components of certain drilling fluids)	Compounds have a strong affinity for water (hydrophilic colloids), sorbed by clays, certain polymers are produced by modifying natural starches and gums, others synthetically produced by interaction of selected units or monomers.	These carbon compounds serve as good tracers in drilling fluid. Yields relatively good information regarding particulate material in drilling fluids. Can be monitored by measuring TOC of groundwater. Detection is by means of a non-dispersive infrared detector. The TOC can be measured to 0.5-1.0 mg/L. Samples can be analyzed relatively quickly giving quick information during the cleanup phase. Particularly good drilling fluid tracer if it is a component of the drilling mud.

NOTE: EDTA = Ethylenediamenetetraacetic acid
HPLC = High performance liquid chromatography
TOC = Total organic carbon.

[a]Drilling fluid tracers currently being used by the BWIP.

[b]Tracers being considered for use.

Tracers should be chosen to obtain as much information as possible about the drilling fluids being introduced into a borehole. To achieve adequate information about borehole development, multiple drilling fluid tracers should be used. Both conservative and nonconservative tracers may be required to obtain adequate information. For example, anionic species work well for tracing the removal of the liquid used to mix drilling fluids since they are conservative and only slightly sorbed. Similarly, tracers such as tritium may work well as indicators of makeup water removal. Since tritium is part of the water molecule, it appears to move with the fluid and has been demonstrated to be sorbed only slightly on most aquifer materials. Conversely, cationic species can be used to monitor the removal of the bentonitic portion of the drilling fluid since they are readily sorbed by the negatively charged clay particles.

Compounds that are part of the drilling fluid may also prove to be good drilling fluid tracers. As shown in Table 1, the addition of organic polymers to drilling fluids allows total organic carbon (TOC) to be used to trace the removal of this component of the drilling fluid.

3.0 TRACERS USED DURING DRILLING OF DEEP BOREHOLES BY THE BASALT WASTE ISOLATION PROJECT

As mentioned earlier, collection of representative hydrochemical samples is necessary to chemically characterize groundwater. Drilling fluid tracers have been used by the BWIP to monitor borehole development for this reason. The tracers currently being used were selected for various reasons, including:

- Tracer cost
- Tracer availability
- Tracer stability
- Analytical methodology
- Turnaround time for analyses
- Relative ease in handling and collection of tracer
- Relationship of tracer to particulate or liquid component of drilling fluid.

Three tracers have been used in the deep boreholes at the Hanford Site. These include fluorescein dye, TOC, and tritium. All three tracers have both advantages and disadvantages. However, used in concert, they yield valuable information regarding the representativeness of a particular hydrochemical sample.

Fluorescein dye has been employed as a drilling fluid tracer since mid-1981. Total organic carbon was examined as early as 1979, but has only been routinely monitored since mid-1982. Tritium has been collected from each zone sampled within the basalts since 1979.

3.1 FLUORESCEIN DYE

Fluorescein, Colour Index 45350 (Society of Dyers and Colourists, 1971), is a fluorescent dye that is visually detectable in low concentrations. It has very low stability under sunlight and, thus, must be collected in amber bottles and not subjected to sunlight for long periods of time prior to analysis. Because of this characteristic, it is best to sample for fluorescein directly from a discharge line and not from a weir box or other standing body of water that may be subjected to long exposure to sunlight.

As mentioned, fluorescein can be detected visually, making it very easy to monitor borehole development in early stages. Fluorescein can be detected in very low concentrations ($\sim$1 µg/L) by using a filter fluorometer. These instruments are simple to use, relatively inexpensive, and hold up well under field operations. The particular instrument used in this study (Turner Model 111) can also be equipped with a flowthrough door and recorder for continuous sampling throughout the development phase.

The fluorometer gives a relative measure of the intensity of light emitted by a fluorescent substance such as fluorescein. The intensity of fluorescent light detected is proportional to the amount of fluorescent substance present in a sample. The value obtained from the fluorometer is not a concentration of dye in the sample, but simply a measure of the light emitted by a fluorescent compound. The intensity of fluorescent light detected from a sample depends on many variables such as the natural fluorescence in the aquifer, the amount of fluorescent tracer injected into a zone, dilution, temperature, and pH. Thus, values obtained from one zone should not be compared directly to those collected from another. The relative change in fluorescence for an individual zone, however, serves as a useful indicator of borehole development for that zone.

Fluorescein is used by the BWIP in a qualitative manner to determine when a zone has been sufficiently developed for sampling. An initial spike of dye is added to each batch of drilling fluid mixed during the drilling of a zone. Normally a spike of $\sim$1.0 mg/L is added to the fluid. This represents $\sim$40 g of fluorescein per 37,810 L of drilling fluid. Fluorescein sorbs on the bentonite clay particles in the drilling fluid as well as the clayey materials in the aquifer. As a result, fluorescein serves as a good indicator of the amount of particulate matter remaining in groundwater pumped from the zone.

Samples are routinely collected every 1 to 2 h during the development phase prior to final sampling. Sampling of fluorescence is determined qualitatively in the field using a filter fluorometer. The instrument is

zeroed using an opaque blank. The sample is collected from the discharge line and placed in the instrument, and the intensity of the fluorescence is read directly from the dial. This reading is plotted versus time or cumulative volume of fluid removed (Fig. 1) during the development phase of testing. These data are used in conjunction with other tracer data to determine when a final groundwater sample should be collected.

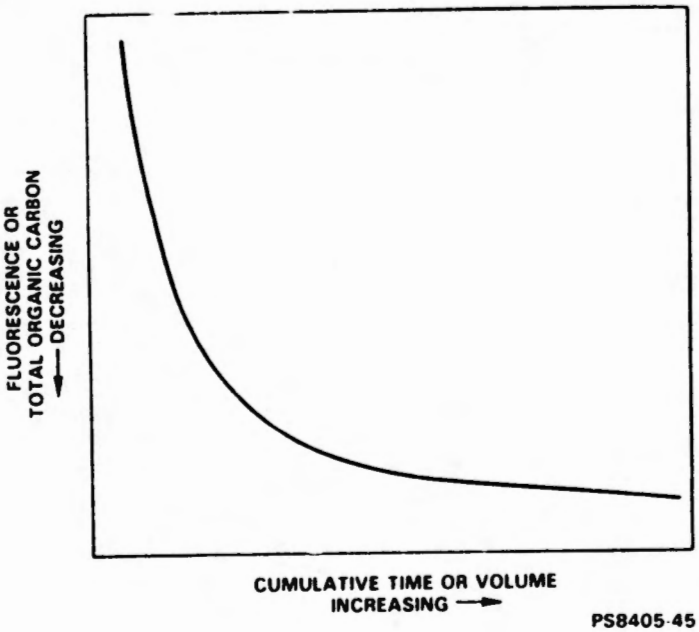


FIGURE 1. Idealized Curve for Borehole Tracers Used to Monitor Borehole Development.

3.2 TOTAL ORGANIC CARBON

Most drilling fluids used for coring deep boreholes at the Hanford Site have an organic carbon component. This additive is usually an organic polymer which, as shown in Table 1, may be a natural or synthetic product. The behavior of polymeric compounds on clay surfaces is very complex and only semiquantitatively understood. An in-depth discussion of clay-polymer interactions is well beyond the scope of this report; however, a brief description of the clay-polymer relationship is probably warranted. A more precise and detailed discussion is given by Gray and Darley (1981), Theng (1982), and Alther (1984).

Polymeric compounds used in drilling fluids are macromolecules formed by joining repeated single chemical building blocks called monomers. Polymers that dissociate in water are referred to as polyelectrolytes and may be cationic, anionic, or uncharged. Most polymers are biodegradable and breakdown with time. However, their main function has usually been

accomplished long before this occurs. Polymers may be tailored to fit nearly any drilling application by varying the length of the chain and the number of functional groups attached to the chain (Alther. 1984).

Polymeric compounds are important in drilling fluids because of their interaction with the clay minerals in these fluids. They are highly hydrophilic colloids and are readily sorbed on the surface of clay platelets. Electrostatic attraction, anion exchange, hydrogen bonding, Van der Waals forces, and ligand exchange are mechanisms proposed for clay-polymer interactions (Theng, 1982). When a clay-polymer mixture is hydrated, both components begin to swell. The polymer prevents agglomerates from forming on the edges of the clay platelets, thus allowing more clay surface area and greater swelling (Theng, 1982).

An understanding of the background levels of TOC in the aquifer is needed if this tracer is to be used with some degree of confidence. This baseline concentration can be established by sampling other boreholes that have not been drilled with a fluid containing an organic polymer. However, natural TOC levels may vary from point to point within an aquifer. Depending on the zone being sampled in the Columbia River basalts, background TOC concentrations range from ~0.5 to 2.0 mg/L. Natural TOC levels sampled from various locations across the Hanford Site are listed in Table 2.

TABLE 2. Natural Total Organic Carbon Concentrations in Groundwaters from the Columbia River Basalts Across the Hanford Site.

Source	Formation	TOC[a] (mg/L)
Lower Snively Spring	Saddle Mountains Basalt	0.48
Rattlesnake Springs	Lower Saddle Mountains/ Upper Wanapum Basalt	1.75
Borehole DC-14[b]	Grande Ronde Basalt	0.64
McGee Well[c]	Wanapum Basalt	0.42

[a]Total organic carbon.

[b]Borehole was originally drilled with an organic polymer fluid. However, the zone was flowing for ~1 yr prior to sampling.

[c]Borehole was not drilled with an organic polymer fluid.

Unfiltered samples are collected every 4 h from the discharge line during the development phase. These samples are analyzed in the laboratory on a total carbon analyzer (Dohrman Model DC-80). The resulting TOC values are plotted in a fashion similar to the fluorescence data (see Fig. 1). With this instrumentation, the detection limit for TOC is ~0.5 to 1.0 mg/L.

3.3 TRITIUM

Tritium is a radioactive isotope of hydrogen. It has a half-life of 12.3 yr and is produced in the upper atmosphere by cosmic-ray bombardment of nitrogen nuclei. This cosmic-ray flux results in the steady-state production of tritium in the atmosphere that falls to the earth's surface as precipitation. Tritium content of groundwater is commonly reported in tritium units (TU) or pCi/L. One tritium unit is equivalent to a concentration of 1 atom of tritium in 10^{18} atoms of hydrogen and is equal to 3.23 pCi/L.

In the early 1950s, atmospheric tritium concentration increased dramatically with the advent of open-air thermonuclear-weapons testing. Tritium concentrations in precipitation increased two to three orders of magnitude during this period. Tritium concentrations peaked in 1963 and have been declining ever since.

This decline has been observed in Columbia River water collected in the vicinity of the Hanford Site. LaSalla and Doty (1971) reported tritium activity in Columbia River water in 1969 to generally range between 300 to 600 TU. Apps et al. (1979) reported average tritium activities around 80 TU that are consistent with those reported by Eddy and Wilbur (1981) and the U.S. Department of Energy (DOE, 1982) of 40 to 80 TU.

In groundwater studies, the following generalities are commonly made concerning tritium.

- Tritium levels $\leq$5 TU indicate groundwater was recharged prior to 1953.

- Groundwater having high tritium concentrations (i.e., 100 TU) indicates that the recharge entered the flow system after 1953.

Tritium exists in groundwater as part of the water molecule and, thus, normally moves with the groundwater through an aquifer. Groundwater older than ~100 yr should have virtually no detectable tritium activity. Groundwaters from the Columbia River basalts that have not been contaminated by tritiated water during drilling have tritium activities that are virtually undetectable by low-level counting techniques. LaSalla and Doty (1971), LaSalla et al. (1972), Apps et al. (1979), and DOE (1982) all discuss the use of tritum as an indicator of drilling fluid contamination at the Hanford Site. Drilling fluids used in boreholes at the Hanford Site are made up using Columbia River or "system" water as a base. System water is Columbia River water treated for domestic use. This provides a spike of tritium that is incorporated each time a batch of drilling fluid is mixed. The use of a natural tritium spike in drilling fluids serves as a very sensitive indicator of the degree of drilling fluid removal.

Low-level tritium analyses are relatively expensive and normally have a long turnaround time. Therefore, tritium is only sampled and measured when a final hydrochemical sample is collected. A 1-L sample (glass bottle) is collected under a heavy argon envelope to reduce contamination from the atmosphere. This sample is then sent to the University of Miami for low-

level counting. Tritium, unlike fluorescein and TOC, gives after-the-fact information regarding final sample integrity. In this respect, tritium is not truly used to monitor borehole development but, instead, is a final check to determine the degree of borehole development.

In the past, the BWIP has considered a sample to be representative if the tritium activities are $\leq$1.0 TU. This criterion seems to be quite adequate for a sample collected for major inorganic constituents, stable isotopes, and dissolved gas data. However, this criterion may not be stringent enough for some trace elements and certain stable and radioactive isotopes. Tritium values may need to be within two counting standard deviations (i.e., $\pm 2\sigma$) of 0 TU to ensure a high confidence in the reliability of such parameters. This criterion will be examined closely in a test designed specifically to address the problem of borehole development related to the collection of hydrochemistry data.

4.0 HYDROLOGIC TESTING AND HYDROCHEMICAL SAMPLING

Before examining actual field examples, it is appropriate to discuss briefly the field testing and sampling methodology used by the BWIP for collection of data from deep basalt core holes. In most instances, samples are collected from specific isolated zones within a borehole during a progressive drilling and testing sequence. A single packer system is commonly used to isolate a particular zone in this testing mode. This arrangement is used to test and sample major interflows and interbeds within the basalt as a borehole is drilled. The packer arrangement consists of either a pneumatic or tensional compression packer attached to steel tubing of sufficient diameter to conduct pump, air-lift, swab, and displacement tests. A typical single packer arrangement is shown in Figure 2.

Straddle packers are routinely used to test open zones within a borehole after drilling has been completed. This system consists of a downhole probe capable of monitoring temperatures and pressures above, below, and in the straddled interval. These data are transmitted via a single conductor cable and recorded and/or printed at the surface. The configuration of a dual packer system is also illustrated in Figure 2. For a more detailed discussion of these packer assemblies and hydrologic testing, refer to Jackson (1980) and Strait et al. (1982).

The general hydrologic testing and sampling sequence used by the BWIP is illustrated in a flow chart in Figure 3. Once a zone has been isolated using a given packer system, the interval is developed for $\sim$24 h. The zone is then allowed to recover, and the static water level is determined. Subsequently, longer aquifer tests are initiated, and drilling fluid tracers are monitored. The zone is once again allowed to recover. Tracer data are evaluated during this recovery phase, and a decision is made whether the zone requires additional development. If additional development is required, the zone is pumped with continual monitoring of drilling fluid tracers. Based on the drilling fluid tracers and borehole development

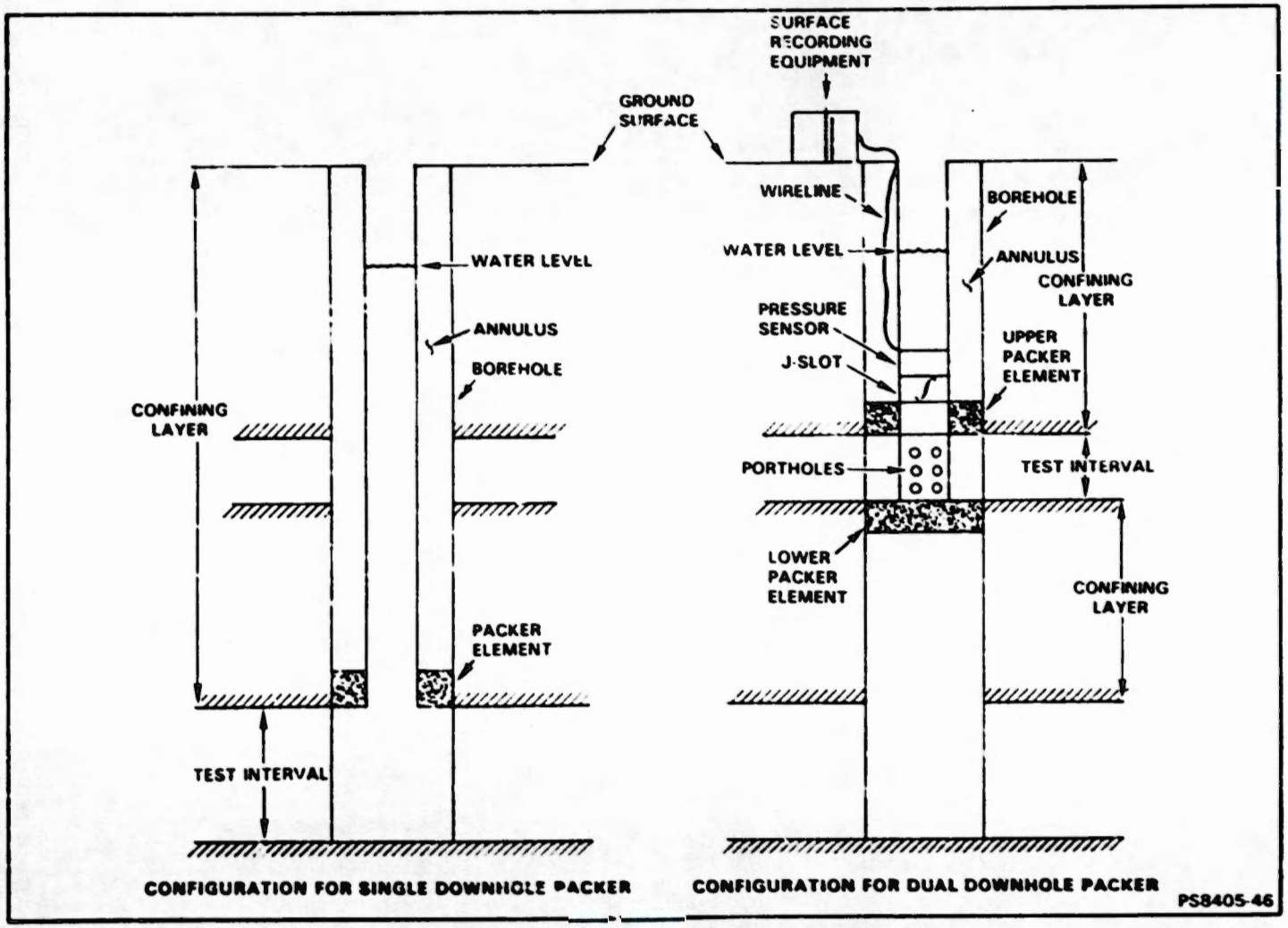


FIGURE 2. Typical Downhole Packer Installations.

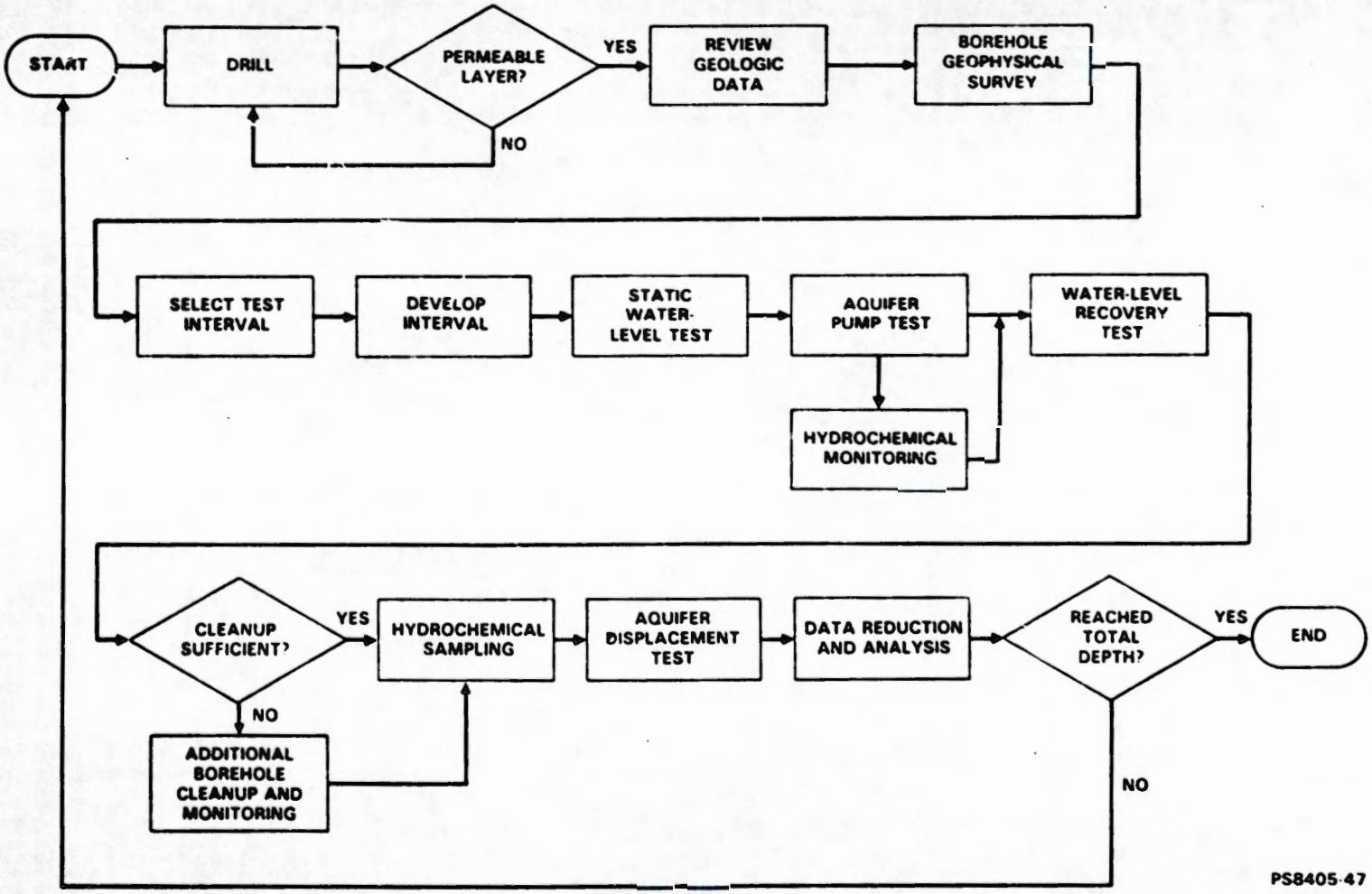


FIGURE 3. Generalized Hydrologic Testing and Hydrochemical Sampling Procedures.

ratio, a decision is reached to collect a final sample. Additional hydrologic testing is conducted, and the zone is grouted or left open depending on the particular horizon. The borehole is then deepened to the next permeable zone.

5.0 FIELD EXAMPLES FROM BOREHOLES AT THE HANFORD SITE

Five examples will be discussed from three boreholes at the Hanford Site. The boreholes are DC-15, DC-16A, and RRL-2. The data are from zones in the Wanapum Basalt and Grande Ronde Basalt Formations of the Columbia River basalts. The location of these boreholes is shown in Figure 4. The generalized stratigraphy of the Columbia River basalts is illustrated in Figure 5. The field data used to construct the development curves are listed in Appendix A.

Reference will be made to a ratio that will informally be called the "development ratio" in the following discussion. This value is the ratio of the volume of fluid removed during the development of a zone divided by the volume of fluid lost in a particular zone during drilling. The volume of fluid removed during development is well known. However, the volume of fluid lost to a zone in some cases can only be roughly estimated, making the development ratio a qualitative estimate of borehole development. Ideally, this ratio should be as large as possible. This value serves as an indicator of how well a zone has been developed prior to final sampling. For example, a ratio of 20 would indicate that 20 times the volume of fluid lost in a zone had been removed prior to sampling. The development ratios for the examples given below range from 2 to 18.

The development ratio is particularly useful for evaluating the degree of borehole development when the drill and test procedure is used in a borehole. Normally, one zone is open to receive fluids at any one time during this process. However, in some instances, the cement grout used to isolate previous zones tested in a borehole may leak, allowing some drilling fluid to enter more than one zone. In this case, the borehole development ratio is conservative because it is assumed that all drilling fluid lost during the drilling of a particular zone was lost to that zone. This is especially true in the case of Grande Ronde Basalt. During the drilling of Grande Ronde Basalt, all zones are left open after testing in most boreholes to allow low permeability testing to be conducted in the deep basalts at a later date. After testing is completed, drilling resumes and the hole is deepened. It becomes increasingly difficult to assess which zone or zones are taking the majority of the drilling fluids lost once several zones have been penetrated in this manner. Determination of the actual fluid losses in each zone depends on the hydraulic head differentials and transmissivities of each zone penetrated and left open in the borehole. Again, the calculated development ratio for a zone will be conservative if more than one zone was responsible for the fluid lost during drilling. This results in the zone being developed to a greater degree than indicated by the ratio. This conservative approach has been followed in the examples discussed below for Grande Ronde Basalt.

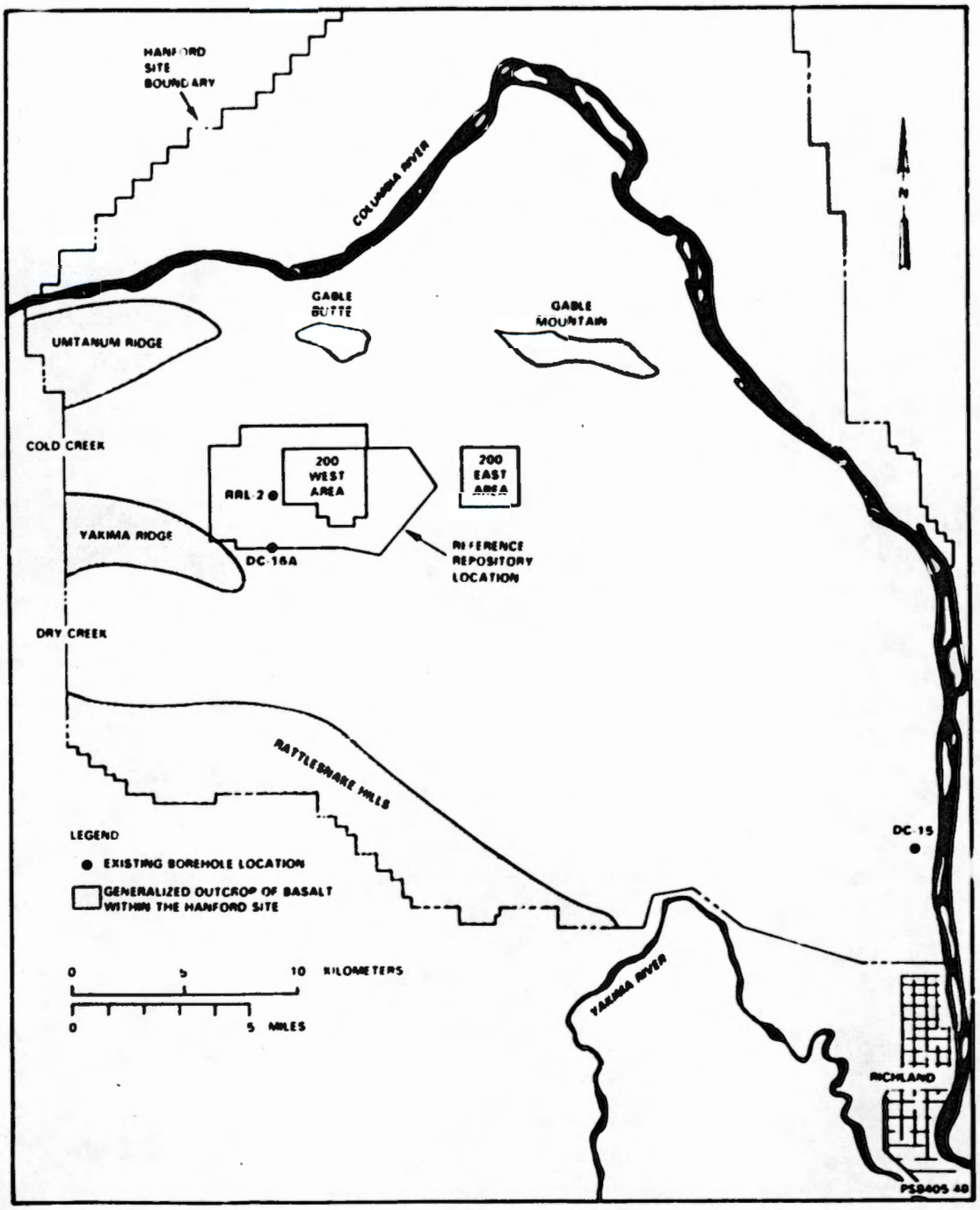


FIGURE 4. Location of Boreholes Used in this Analysis.

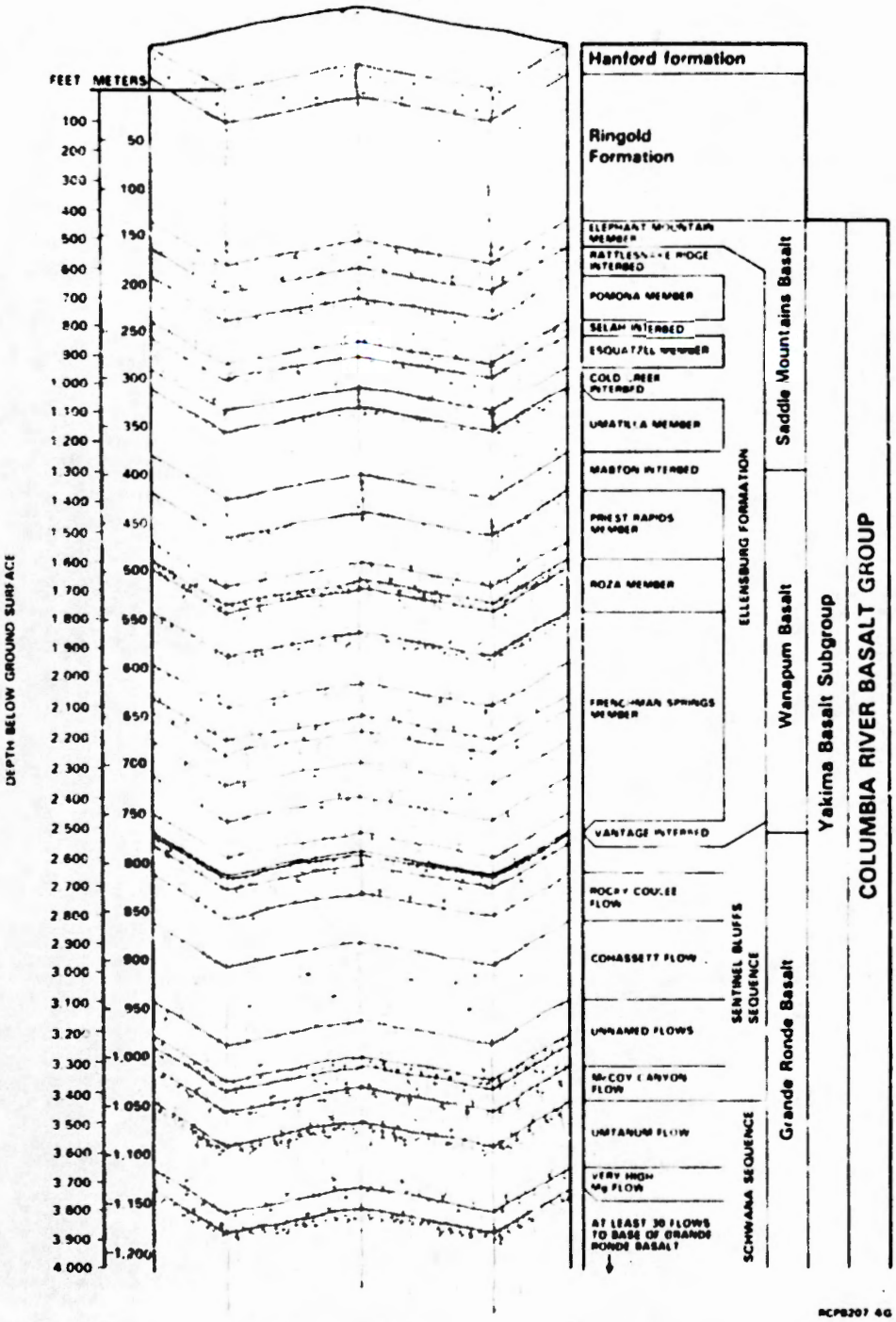


FIGURE 5. Generalized Stratigraphy of the Columbia River Basalts in the Vicinity of the Hanford Site.

Table 3 is a summary of pertinent data from five field examples. Figures 6 and 7 are plots of drilling fluid tracer data from the various field examples. Data from boreholes DC-15 and RRL-2 are presented in Figure 6. Fluorescein was the only tracer monitored in these particular zones because the analytical capability for TOC had not been established by the BWIP at the time these zones were drilled. Plots for data from three zones within borehole DC-16A are shown in Figure 7; both fluorescein and TOC data are shown.

In all cases, the data show a general decrease in tracer with increased fluid removed from a zone. The curves in Examples 1 and 3 (see Fig. 6 and 7) have a somewhat different shape than those of the other tests. This is due to the fact that the initial samples collected during the development phase reflect water introduced into the system to set the packers. This water is usually Columbia River water that has a very low natural fluorescence level. As this fluid is removed from the system, fluorescence increases as drilling fluids tagged with fluorescein are brought up the hole. This behavior is not observed in the other examples because samples were not collected early enough in the development to allow this to be observed.

A common phenomenon is observed in all five examples analyzed. This is an increase in tracer concentration when an air-lift test is terminated and restarted some time later. While the precise cause is unknown at present, it may be due to the fact that when the air-lift or pumping test is resumed, the shock exerted by the restart of the test releases drilling fluid or tracer that is loosely bound to the sides of the borehole and/or aquifer. This results in a pulse of tracer being brought into the borehole and eventually detected at the surface. These pulses may then indicate that particulate material related to drilling fluid is still in the zone and removal of this material is slower than the dissolved constituents in the drilling fluid. Other phenomena such as sorption-desorption processes are also being considered to explain these observed fluctuations.

As mentioned above, the development ratio is an indicator of the degree of borehole development. A high ratio should be associated with low tracer concentrations. This is not always the case, as illustrated by the data in Table 3. The three highest development ratios (Examples 1, 3, and 5) all have the highest levels of tracer at the time of sampling. This can possibly be attributed to several factors such as the geologic nature of the isolated zone (e.g., sedimentary interbed, flow top, and degree of secondary mineralization), the sorptive properties of the particular zone, the duration of the cleanup phase, the total concentration of tracer introduced into the hole, and the uncertainties associated with the fluid loss estimates. However, the actual cause of this relationship is not fully understood. It is hoped that a field test designed specifically to monitor borehole development and drilling fluid tracer responses will provide further insight into this behavior.

Tritium is a good indicator of how well the liquid portion of the drilling fluid has been removed from a borehole. Tritium data for all zones indicate that the majority of the river water used to mix the fluids had

TABLE 3. Borehole Development Information for Five Zones within the Columbia River Basalts.

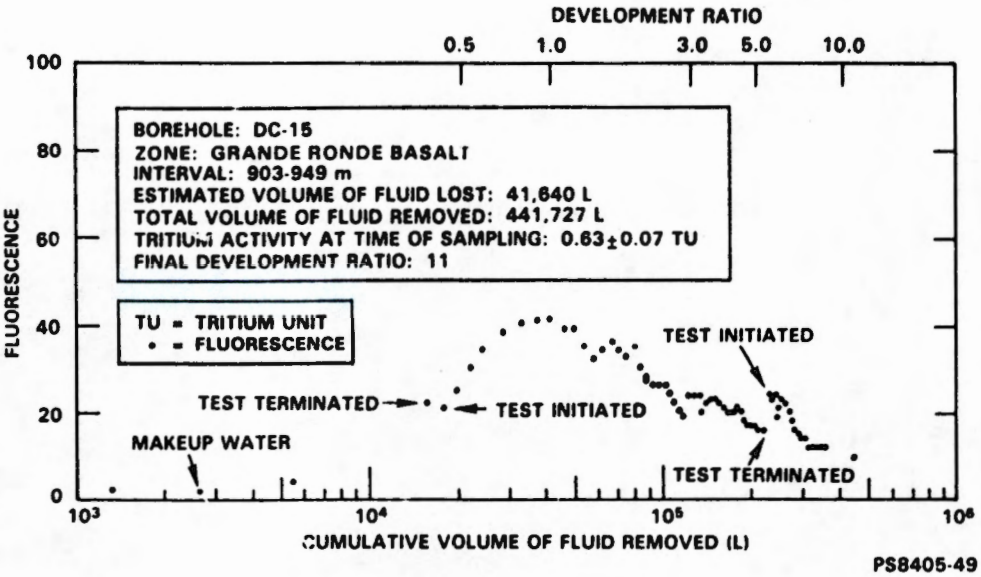
Field example	Borehole	Zone	Interval (m below land surface)	Estimated volume lost (L)[a]	Volume removed (L)	Development ratio	Final fluorescence	Final TOC[b] (mg/L)	Final tritium (TU)[c]	Tritium remaining[d] (%)
1	DC-15	Grande Ronde Basalt	903-949	41,640	441,727	11	10	--	0.63±0.07	1.1
2	RRL-2	Grande Ronde Basalt	829-889	62,459	241,899	4	7	--	0.90±0.10	1.5
3	DC-16A	Vantage interbed	814-832	23,848	334,610	14	15	17.2	0.85±0.07	1.4
4	DC-16A	Rocky Coulee flow	864-898	141,953	264,301	2	9	9.2	0.70±0.07	1.2
5	DC-16A	Frenchman Springs 3	671-689	18,927	346,358	18	15	8.6	0.46±0.08	0.8

[a]This volume is a best estimate of fluid lost in a particular zone. In some instances this total volume was not lost to a single zone. Using this maximum value results in a conservative estimate of borehole development.

[b]Total organic carbon.

[c]Tritium units.

[d]Based on an average tritium activity for Columbia River water of 60 TU.



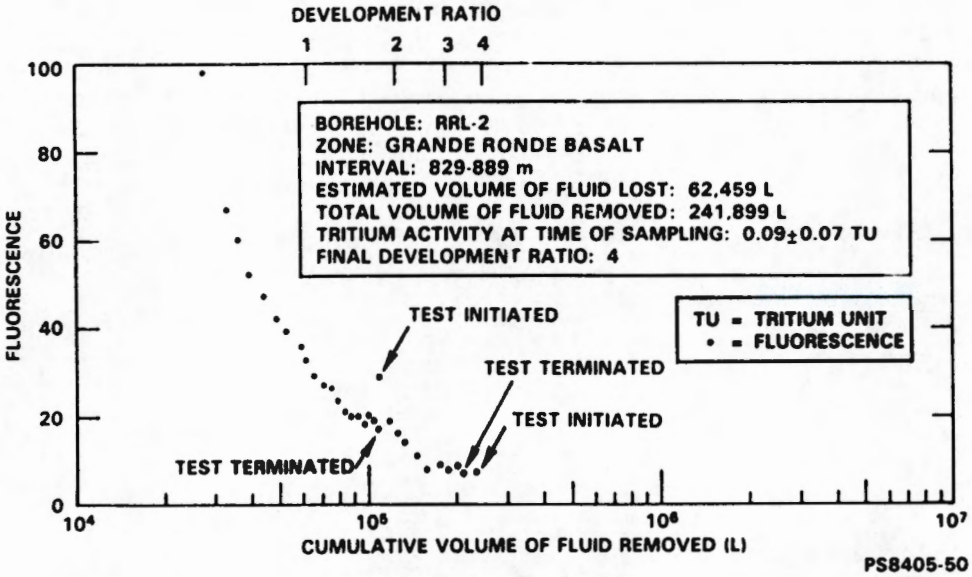
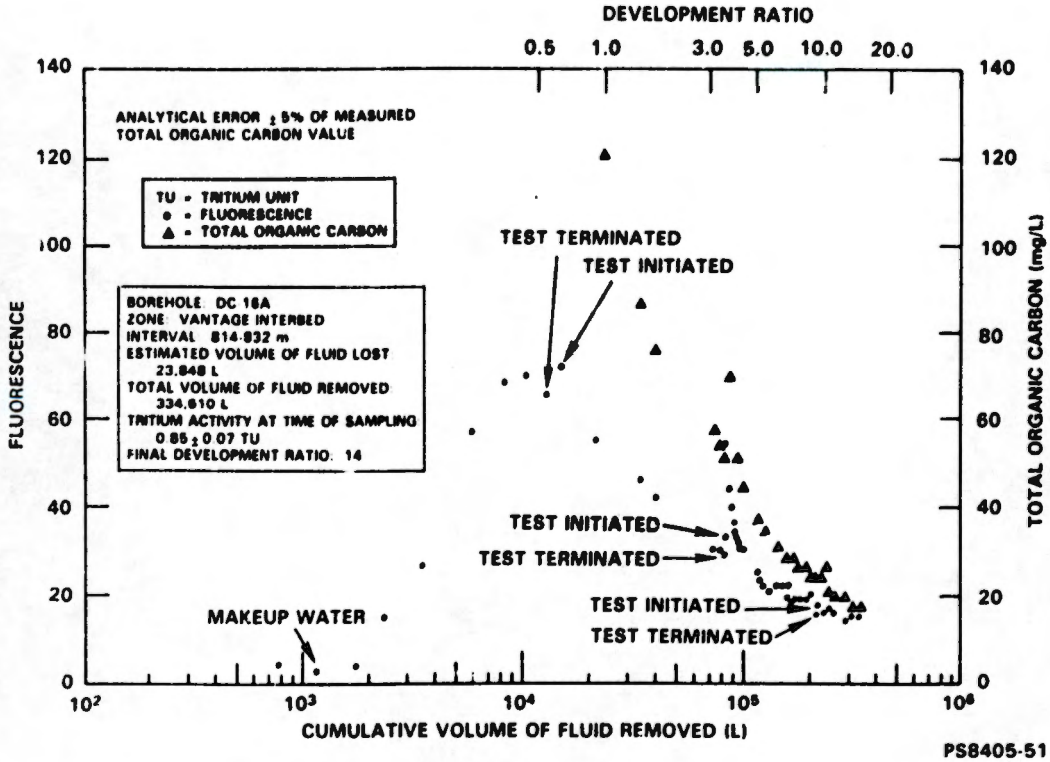


FIGURE 6. Plots of Fluorescence Versus Cumulative Volume of Fluid Removed and Borehole Development Ratio from Zones within Boreholes DC-15 and RRL-2.



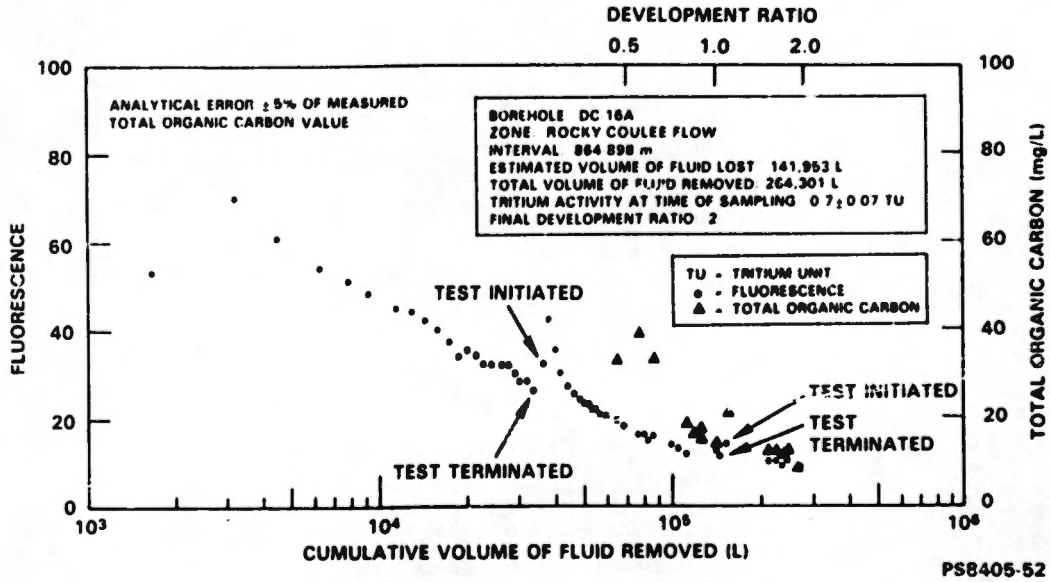


FIGURE 7. Plots of Fluorescence and Total Organic Carbon Versus Cumulative Volume of Fluid Removed and Borehole Development Ratio from Zones within Borehole DC-16A. (Sheet 1 of 2)

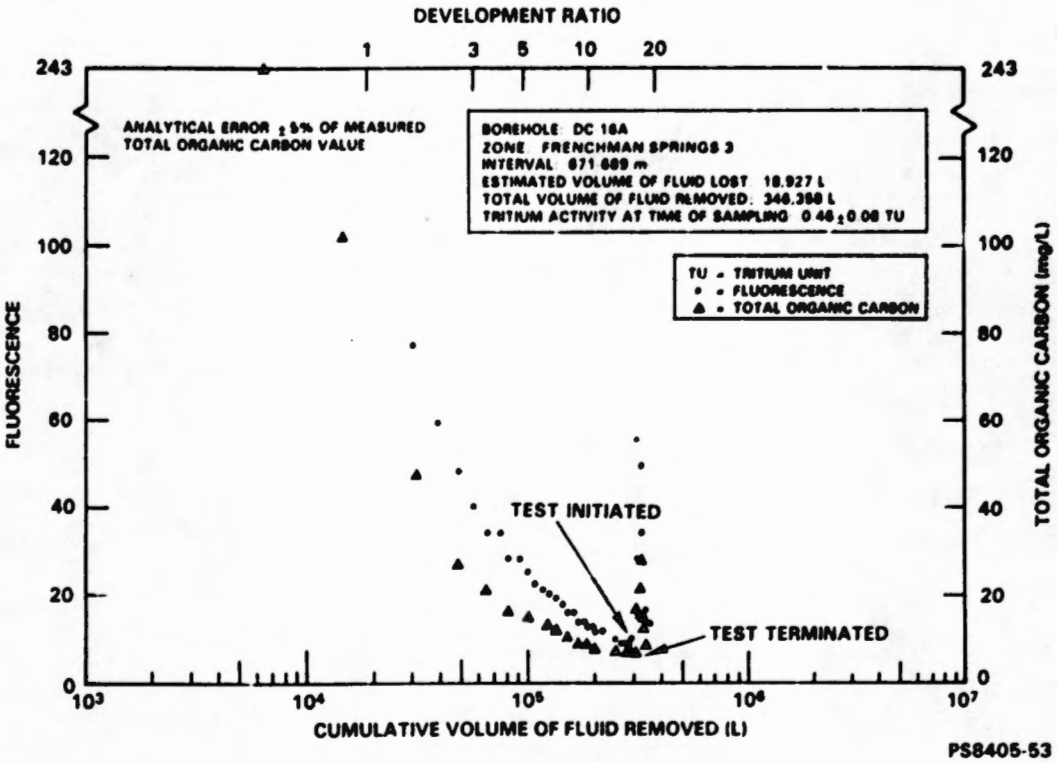


FIGURE 7. Plot of Fluorescence and Total Organic Carbon Versus Cumulative Volume of Fluid Removed and Borehole Development Ratio from Zones within Borehole DC-16A. (Sheet 2 of 2)

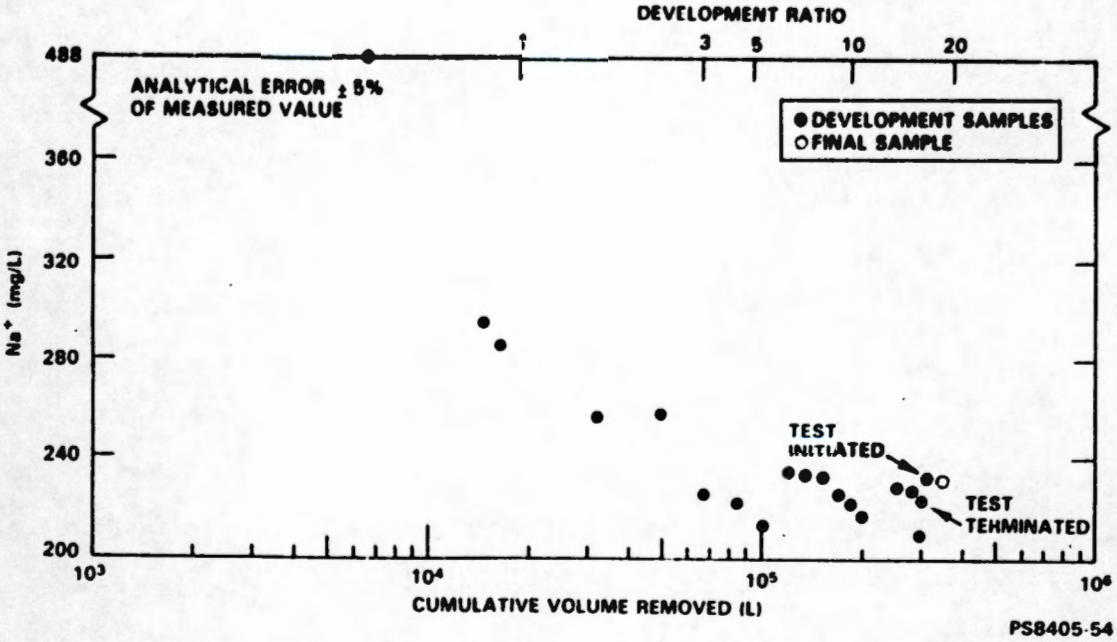
been removed during the development of each zone (see Table 3). Assuming an average tritium concentration of 60 TU for Columbia River water, the percentage of tritium remaining in a zone can be calculated (see Table 3). In all cases, the tritium activity of the sampled water was <2% of the injected fluid, indicating that the samples collected are ≥98% formation water.

Example 5 is unique in comparison to the other four examples in that a limited amount of major cation and anion data were also analyzed during portions of this test. These data are listed in Table 4. The species analyzed included Na^+, Ca^{+2}, K^+, Cl^-, F^-, Br^-, and SO_4^{-2}. Figures 8 and 9 are plots of concentration versus volume removed for the various chemical species. The data in Figure 8 demonstrate that these parameters (Na^+, SO_4^{-2}, Ca^{+2}, and K^+) are initially affected by the use of drilling fluids. In all cases, the concentrations of the parameters are initially elevated and decline rapidly to an apparent steady-state concentration with time. It is assumed that the steady-state concentrations represent natural formation conditions.

TABLE 4. Cation and Anion Data Collected during Development Phase at Borehole DC-16A, Frenchman Springs 3 (Field Example 5).

Date	Time	Cumulative flow (L)	Na^+	Ca^{+2}	K^+	Cl^-	F^-	Br^-	SO_4^{-2}
5/21/82	1730	6,541	488	55.0	61.3	231	7.2		174.0
	2000	14,718	295	15.9	39.7	293	10.2		81.0
5/22/82	1630	16,164	285	19.8	39.2	266	9.2		65.0
	2000	31,347	257	7.2	35.3	288	9.0	0.43	36.5
	2400	48,699	257	6.9	35.4	310	9.9	0.46	21.9
5/23/82	0400	66,052	226	6.0	31.6	299	9.7	0.46	15.8
	0800	83,404	222	6.6	32.3	307	10.0	0.45	13.1
	1205	100,756	214	5.5	30.9	310	10.3	0.46	11.4
	1600	118,109	235	5.4	34.3	307	10.3	0.46	9.7
	2000	135,461	233	5.7	34.4	311	10.8	0.48	8.9
	2400	152,813	232	5.5	34.2	309	9.7	0.52	8.1
5/24/82	0400	170,166	226	5.3	33.4	313	9.8	0.50	7.3
	0800	187,518	222	4.8	32.6	313	9.8	0.46	6.5
	1200	204,870	217	4.7	32.1	307	10.1	0.50	6.0
5/25/82	0030	258,373	228	5.1	34.1	310	10.3	0.50	4.9
	0600	282,233	227	4.8	34.0	311	11.2	0.50	4.5
	1000	299,585	209	4.5	31.4	314	11.2	0.54	4.0
	1155	308,261	224	4.6	33.8	296	10.9	0.51	4.3
5/28/82	1000	315,957	232	4.9	34.6	339	9.2	0.46	6.2
Final sample									
6/03/82	1000	346,358	232	4.9	34.6	309	10.8	0.46	6.5

NOTE: Concentrations are in mg/L.



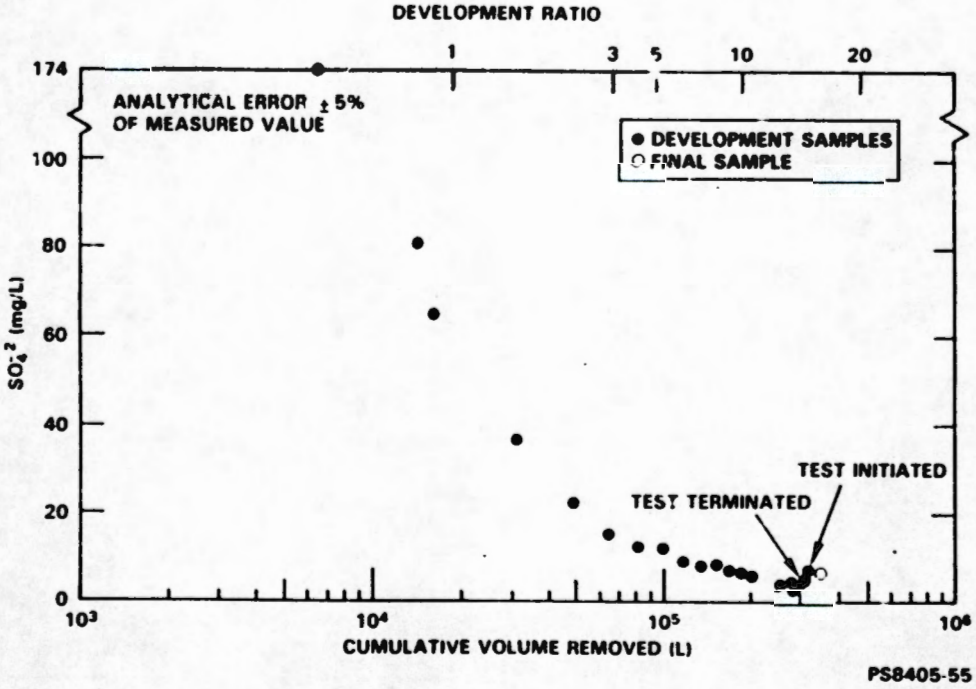
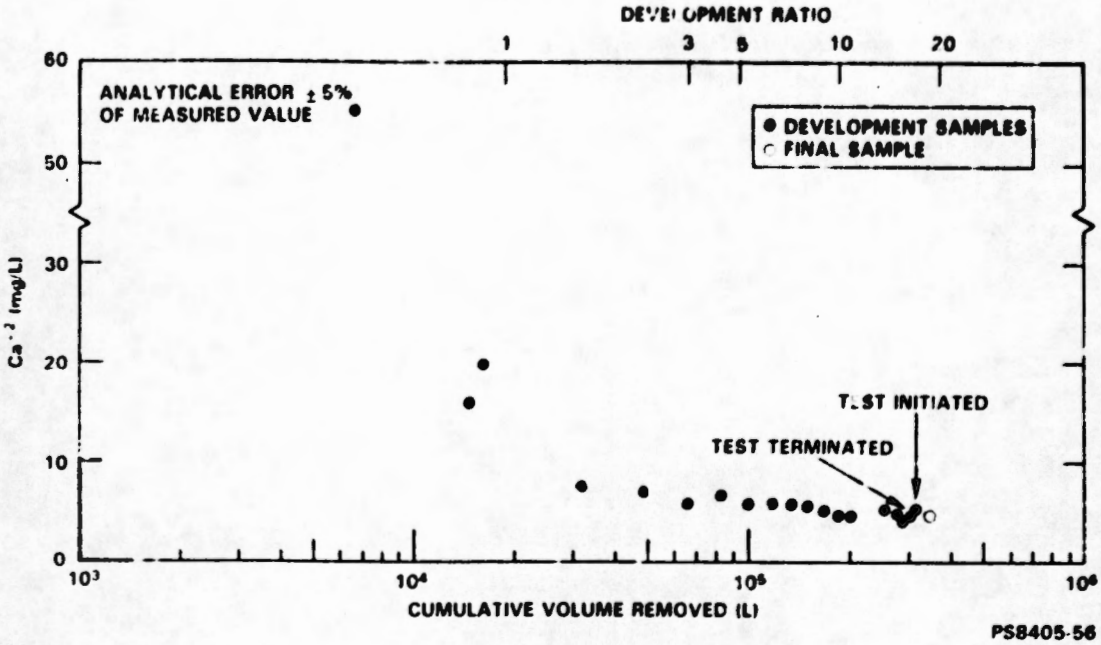


FIGURE 8. Plots of Concentration Versus Cumulative Volume of Fluid Removed and Borehole Development Ratio for Na^+, SO_4^{-2}, Ca^{+2}, and K^+ from the Frenchman Springs 3 in Borehole DC-16A. (Sheet 1 of 2)



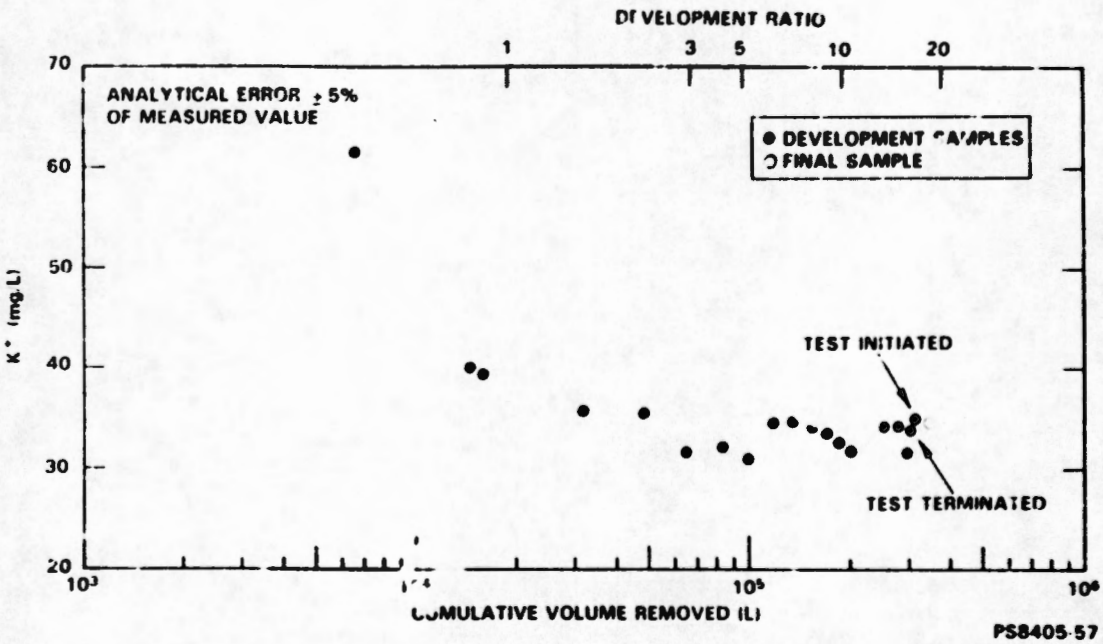
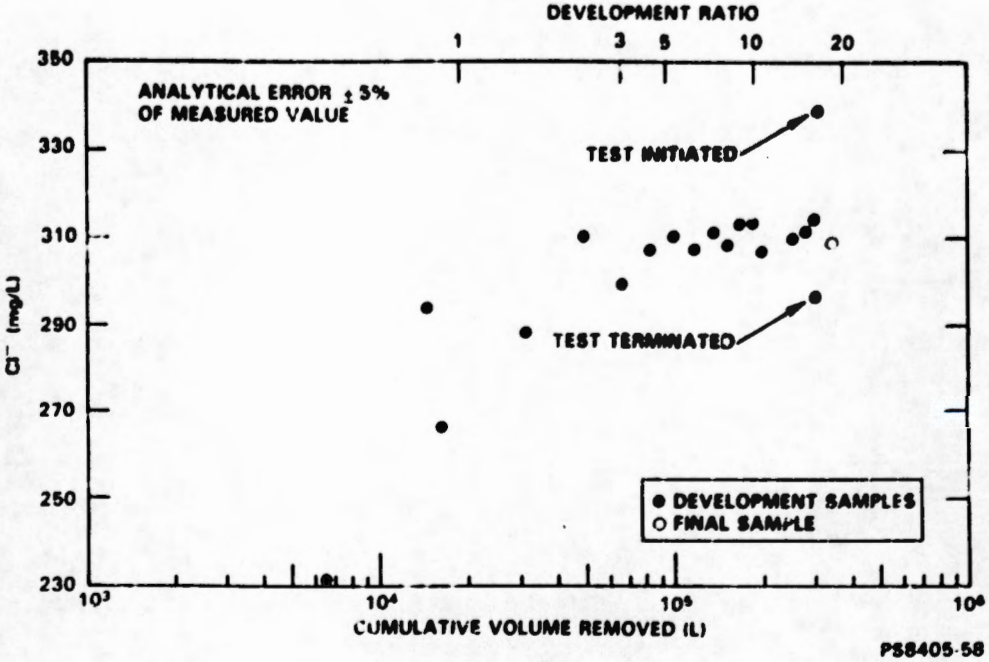


FIGURE 8. Plots of Concentration Versus Cumulative Volume of Fluid Removed and Borehole Development Ratio for Na^+, SO_4^{-2}, Ca^{+2}, and K^+ from the Frenchman Springs 3 in Borehole DC-16A. (Sheet 2 of 2)



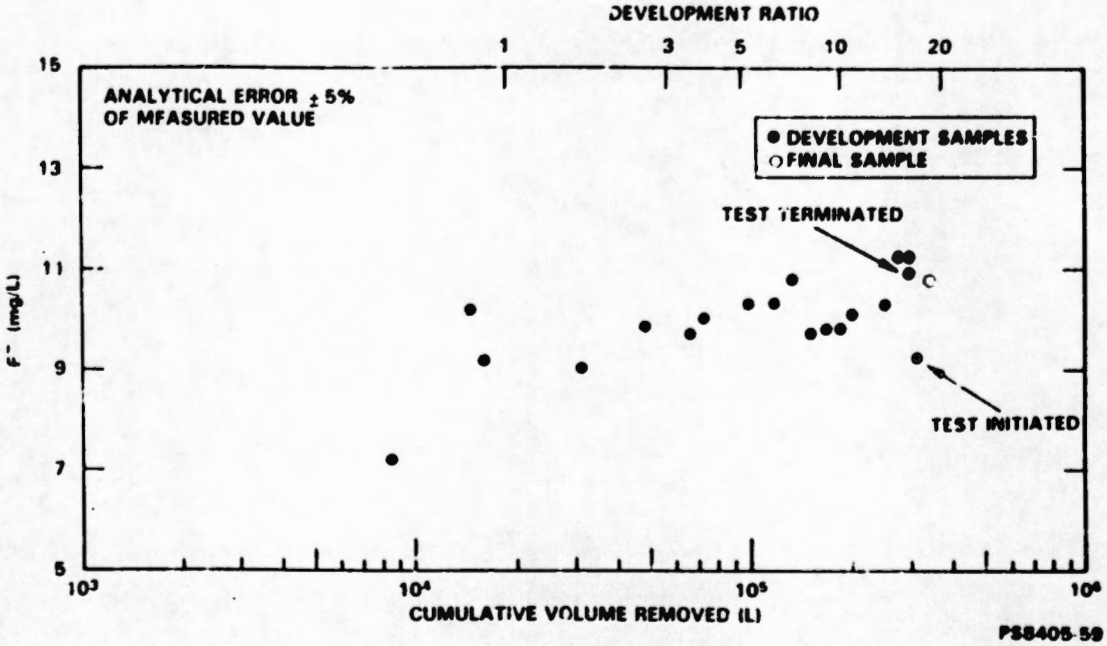


FIGURE 9. Plots of Concentration Versus Cumulative Volume of Fluid Removed and Borehole Development Ratio for Cl^-, F^-, and Br^- from the Frenchman Springs 3 in Borehole DC-16A. (Sheet 1 of 2)

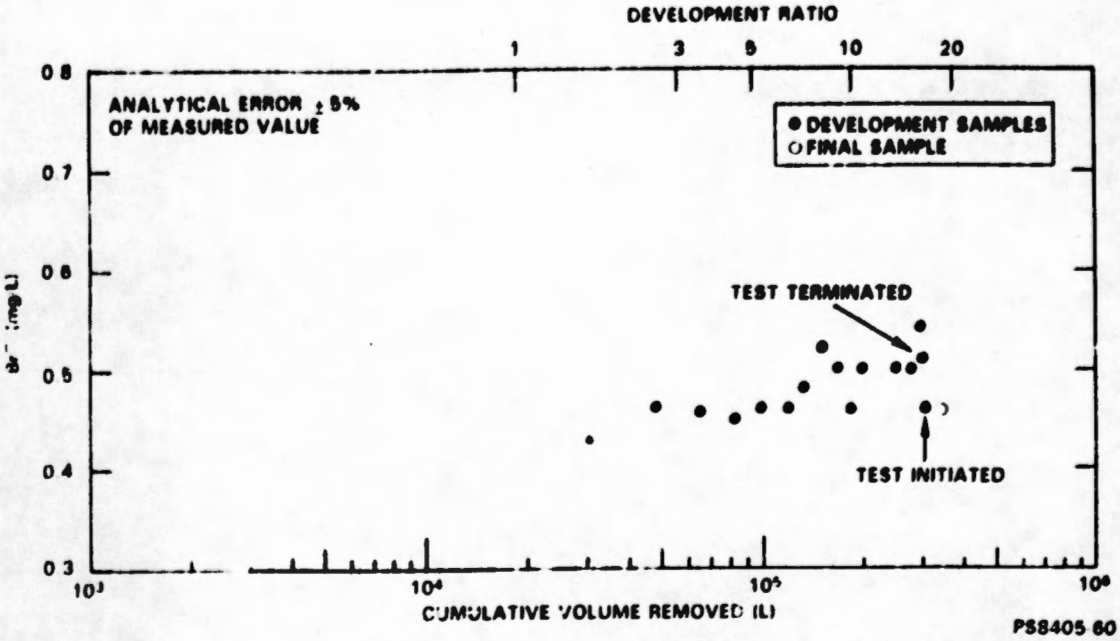


FIGURE 9. Plots of Concentration Versus Cumulative Volume of Fluid Removed and Borehole Development Ratio for Cl^-, F^-, and Br^- from the Frenchman Springs 3 in Borehole DC-16A. (Sheet 2 of 2)

The Na^+ and K^+ curves show considerable scatter after ~3.8 x 10^4 L of fluid were removed from the zone. The reason for this is not fully understood; however, the analytical techniques used to analyze the sample may provide one explanation for this behavior. An inductively coupled plasma spectrophotometer is used to analyze the basaltic groundwater for cations. The inductively coupled plasma spectrophotometer uses a high-energy electron plasma to dissociate the sample down to the atomic level. Field samples are routinely filtered through a 0.45 µm filter. If colloidal material smaller than 0.45 µm and high in Na^+ and/or K^+ was in suspension in the sample, this material would be dissociated and erratic fluctuations in Na^+ and K^+ could result.

Considerable fluctuations are observed in nearly all data after the removal of ~3 x 10^5 L of fluid. This appears to correspond to the major increases in tracer concentrations in Figure 7, Example 5. These variations may be the result of intermittent terminations of the test for various reasons. Also, the flow rate was changed significantly when a low-volume pump was installed prior to final sampling (see Appendix A, Example 5).

The halogen data plotted in Figure 9 result in a much different trend than the data in Figure 8. All three parameters are initially diluted when drilling fluids are introduced into the borehole. Concentrations increase with time as fluid is removed from the zone until formation conditions are approached. Dilution of these constituents indicates that drilling fluids

contain little, if any, of these specific species. Selected chemistry data collected from the Columbia River are listed in Table 5. This water is routinely used to mix drilling fluids used to drill boreholes for the BWIP. As can be seen, concentrations of Cl^-, F^-, and Br^- are all below those associated with basalt groundwater, indicating that there is no source of these constituents in the water used to mix the drilling fluids.

TABLE 5. Chemistry of Selected Constituents from the Columbia River Adjacent to Borehole DC-14.

pH	Electrical conductivity	Temp. (°C)	Alkalinity (HCO_3^-)	Na^+	K^+	Ca^{+2}	Cl^-	F^-	Br^-	SO_4^{-2}
6.8	150	6.9	79	2.40	0.90	20.29	0.82	0.12	ND*	11.54

NOTE: Concentration of ionic species in mg/L.
*ND = Not detected.

The data from Example 5 (see Fig. 8 and 9) clearly indicate that drilling fluids do affect certain ionic species present in the basaltic groundwaters. Most data available for this zone appear to stabilize reasonably after the removal of ~9.5 x 10^4 L of fluid (development ratio of 5). However, due to the limited data available for this zone, it is not safe to assume that all chemical and isotopic species of interest to hydrochemical characterization behave in a similar manner. The components in drilling fluids responsible for changes in groundwater chemistry need to be examined more closely. A controlled test designed specifically to assess the effects of drilling fluids upon groundwater chemistry is currently under way at borehole DC-14 in the deep Grande Ronde Basalt. The test will examine, in detail, drilling fluid effects on major inorganics, minor and trace elements, dissolved gases, and stable and radioactive isotopes and determine the utility of drilling fluid tracers to a greater degree.

6.0 CONCLUSIONS

From data presented in this report, it appears that fluorescein, TOC, and tritium are satisfactory tracers for evaluating the degree of borehole development for hydrochemical sampling purposes from boreholes currently being drilled by the BWIP. Fluorescein and TOC supply information regarding the particulate portion of the drilling fluids, whereas tritium yields useful information relative to the liquid used to mix the drilling fluids.

Based on the data available, it appears that certain ionic species in basaltic groundwaters are affected by drilling fluids. Concentrations of species such as Na^+, Ca^{+2}, K^+, and SO_4^{-2} are elevated while those of Cl^-, F^-, and Br^- are diluted.

The hydrochemical data presently available are insufficient to adequately assess the effects of drilling fluids on all chemical and isotopic parameters important for chemical characterization of basaltic groundwater. A test specifically designed to address this topic is in progress at borehole DC-14 and results will be presented in a future report.

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APPENDIX

Borehole Development Data from Five Field Examples

APPENDIX

Borehole Development Data from Five Field Examples

Borehole: DC-15
Zone: Grande Ronde Basalt
Interval: 903 to 949 m
Estimated volume of fluid lost: 41,640 L
Total volume of fluid removed: 441,727 L
Final development ratio: 11

EXAMPLE 1
(Sheet 1 of 8)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC[a] (mg/L)
2/5/81	1315	1.47	1,325	2	b
	1330	1.47	2,646	2	
	1400	1.47	5,292	4	
Test terminated	1600	1.47	15,876	22	
2/6/81	0830	1.19	18,022	21	
	0900	1.19	20,169	25	
	0930	1.19	22,315	30	
	1000	1.19	24,461	34	
	1030	1.19	26,608		
	1100	1.19	28,754	38	
	1200	1.19	33,047	40	

Borehole: DC-15

Zone: Grande Ronde Basalt

Interval: 903 to 949 m

Estimated volume of fluid lost: 41,640 L

Total volume of fluid removed: 441,727 L

EXAMPLE 1

(Sheet 2 of 8)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC[a] (mg/L)
2/6/81	1300	1.19	37,339	41	
	1400	1.19	41,632	41	
	1500	1.19	45,925	39	
	1600	1.19	50,217	39	
	1700	1.19	54,510	35	
	1800	1.19	58,803	32	
	1900	1.19	63,095	34	
	2000	1.19	67,388	36	
	2100	1.19	71,681	34	
	2200	1.19	75,973	33	
	2300	1.19	80,266	35	
	2400	1.19	84,559	30	

Borehole: DC-15

Zone: Grande Ronde Basalt

Interval: 903 to 949 m

Estimated volume of fluid lost: 41,640 L

Total volume of fluid removed: 441,727 L

EXAMPLE 1

(Sheet 3 of 8)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC[a] (mg/L)
2/7/81	0100	1.19	88,851	28	
	0200	1.19	93,144	26	
	0300	1.19	97,437	26	
	0400	1.19	101,729	26	
	0500	1.19	106,022	24	
	0600	1.19	110,315	22	
	0700	1.19	114,607	20	
	0800	1.19	118,900	19	
	0900	1.19	123,192	24	
	1000	1.19	128,621	24	
	1100	1.19	131,271	24	
	1200	1.19	136,070	20	

EXAMPLE 1
(Sheet 4 of 8)

Borehole: DC-15
Zone: Grande Ronde Basalt
Interval: 903 to 949 m
Estimated volume of fluid lost: 41,640 L
Total volume of fluid removed: 441,727 L

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC[a] (mg/L)
2/7/81	1300	1.19	140,363	22	
	1400	1.19	144,656	23	
	1500	1.19	148,948	23	
	1600	1.19	153,241	22	
	1700	1.19	157,534	22	
	1800	1.19	161,826	21	
	1900	1.19	166,119	20	
	2000	1.19	170,412	20	
	2100	1.19	174,704	20	
	2200	1.19	178,997	21	
	2300	1.19	183,290	20	
	2400	1.19	187,582	18	

Borehole: DC-15

Zone: Grande Ronde Basalt

Interval: 903 to 949 m

Estimated volume of fluid lost: 41,640 L

Total volume of fluid removed: 441,727 L

EXAMPLE 1

(Sheet 5 of 8)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC[a] (mg/l)
2/8/81	0100	1.19	191,875	18	
	0200	1.19	196,168	17	
	0300	1.19	200,460	17	
	0400	1.19	204,753	17	
	0500	1.19	209,046	16	
	0600	1.19	213,338	16	
Test terminated	0700		218,009	16	
2/15/81	1400	1.24	231,433	24	
	1500	1.24	235,907	21	
	1600	1.24	240,381	22	
	1700	1.24	244,856	19	

Borehole: DC-15

Zone: Grande Ronde Basalt

Interval: 903 to 949 m

Estimated volume of fluid lost: 41,640 L

Total volume of fluid removed: 441,727 L

EXAMPLE 1

(Sheet 6 of 8)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC[a] (mg/L)
2/15/81	1800	1.24	249,330	21	
	1900	1.24	253,804	23	
	2000	1.24	258,279	21	
	2100	1.24	262,753	22	
	2200	1.24	267,227	21	
	2300	1 24	271,702	20	
	2400	1.24	276,176	18	
2/16/81	0100	1.24	280,650	16	
	0200	1.24	285,125	16	
	0300	1.24	289,599	15	
	0400	1.24	294,074	14	
	0500	1.24	298,548	14	

Borehole: DC-15

Zone: Grande Ronde Basalt

Interval: 903 to 949 m

Estimated volume of fluid lost: 41,640 L

Total volume of fluid removed: 441,727 L

EXAMPLE 1

(Sheet 7 of 8)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC[a] (mg/L)
2/16/81	0600	1.24	303,022	14	
	0700	1.24	307,497	12	
	0800	1.24	311,971	12	
	0900	1.24	316,445	12	
	1000	1.24	320,920	12	
	1100	1.24	325,394	12	
	1200	1.24	329,868	11	
	1300	1.24	334,343	12	
	1400	1.24	338,817	12	
	1500	1.24	343,291	12	
	1600	1.24	347,766	12	
	1700	1.24	352,240	12	

Borehole: DC-15

Zone: Grande Ronde Basalt

Interval: 903 to 949 m

Estimated volume of fluid lost: 41,640 L

Total volume of fluid removed: 441,727 L

EXAMPLE 1

(Sheet 8 of 8)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC[a] (mg/L)
2/16/81	1800	1.24	356,715	12	
	1900	1.24	361,189	12	
2/17/81 Test terminated	0945	1.24	441,727	10	

[a]Total organic carbon.

[b]TOC data not available for this test.

Borehole: RRL-2

Zone: Grande Ronde Basalt

Interval: 829 to 889 m

Estimated volume of fluid lost: 62,459 L

Total volume of fluid removed: 241,899 L

Final development ratio: 4

EXAMPLE 2
(Sheet 1 of 5)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC[a] (mg/L)
5/6/82	1555	0.83			c
	1855	0.83	9,062[b]		
5/7/82	1415	0.62			
	1630	0.62	14,070	off scale	
	1730	0.62	16,296	off scale	
	1830	0.62	18,522	off scale	
	2030	0.62	22,974	off scale	
	2230	0.62	27,425	98	
5/8/82	0053	0.62	32,706	65	
	0220	0.62	35,958	60	
	0400	0.62	39,667	52	
	0600	0.62	44,119	47	

Borehole: RRL-2

Zone: Grande Ronde Basalt

Interval: 829 to 889 m

Estimated volume of fluid lost: 62,459 L

Total volume of fluid removed: 241,899 L

EXAMPLE 2

(Sheet 2 of 5)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC[a] (mg/L)
5/8/82	0800	0.62	48,571	42	
	1000	0.62	53,022	39	
	1215	0.62	58,030	36	
	1405	0.62	62,111	33	
	1606	0.62	66,597	29	
	1806	0.62	71,048	27	
	2005	0.62	75,466	26	
	2205	0.62	79,918	23	
	2400	0.62	84,184	21	
5/9/82	0210	0.62	89,006	20	
	0410	0.62	93,079	20	
	0610	0.62	97,910	18	

Borehole: RRL-2

Zone: Grande Ronde Basalt

Interval: 829 to 889 m

Estimated volume of fluid lost: 62,459 L

Total volume of fluid removed: 241,899 L

EXAMPLE 2

(Sheet 3 of 5)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC[a] (mg/L)
5/9/82	0810	0.62	102,361	20	
	1010	0.62	106,813	19	
	1100	0.62	108,668	17	
Test terminated	1115	0.62	109,224		
5/11/82	1245	0.49			
	1230	0.49	109,667		
	1305	0.49	110,852	29	
	1800	0.49	119,585	19	
	2200	0.49	126,686	16	
5/12/82	0225	0.49	134,534	14	
	1130	0.49	150,667	11	

Borehole: RRL-2

Zone: Grande Ronde Basalt

Interval: 829 to 889 m

Estimated volume of fluid lost: 62,459 L

Total volume of fluid removed: 241,899 L

EXAMPLE 2

(Sheet 4 of 5)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC[a] (mg/L)
5/12/82	1730	0.49	161,323	8	
	1880	0.49	164,877	8	
	2410	0.49	173,164	9	
	0400	0.49	179,974	9	
	0930	0.49	189,740	8	
	1330	0.49	196,845		
5/13/82	2045	0.51			
5/14/82	0223	0.51	207,134	9	
	0520	0.51	212,611	7	
	0800	0.51	217,472	7	
Test terminated	0900	0.51	219,312		

Borehole: RRL-2

Zone: Grande Ronde Basalt

Interval: 829 to 889 m

Estimated volume of fluid lost: 62,459 L

Total volume of fluid removed: 241,899 L

EXAMPLE 2

(Sheet 5 of 5)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC[a] (mg/L)
5/17/82	0045	0.64			
	0800	0.64	236,107	7	
Test terminated	1030	0.64	241,899		

[a]Total organic carbon.

[b]Initial development, no tracer data collected.

[c]TOC data not available for this test.

EXAMPLE 3
(Sheet 1 of 6)

Borehole: DC-16A
Zone: Vantage interbed
Interval: 814 to 832 m
Estimated volume of fluid lost: 23,848 L
Total volume of fluid removed: 334,610 L
Final development ratio: 14

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC* (mg/L)
8/27/82	1718	0.66			
	1750	0.66	791	4	
	1800	0.66	1,189	3	
	1815	0.66	1,779	4	
	1830	0.66	2,373	15	
	1900	0.66	3,558	26	
	2000	0.66	5,936	57	
	2100	0.66	8,309	68	
	2200	0.66	10,682	70	
	2300	0.66	13,056	66	
	2350	0.66	15,032	72	

Borehole: DC-16A

Zone: Vantage interbed

Interval: 814 to 832 m

Estimated volume of fluid lost: 23,848 L

Total volume of fluid removed: 334,610 L

EXAMPLE 3

(Sheet 2 of 6)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC* (mg/L)
Test terminated	2400	0.66	15,137		
9/2/82	1400	0.80			
	1620	0.80	21,814	55	123.0
	2045	0.80	34,454	46	86.2
	2300	0.80	40,893	42	76.1
9/3/82	0800	0.80	66,649		
	1042	0.80	74,280	30	57.3
	1253	0.80	80,481	30	54.8
Test terminated	1340	0.80	82,865	29	

Borehole: DC-16A

Zone: Vantage interbed

Interval: 814 to 832 m

Estimated volume of fluid lost: 23,848 L

Total volume of fluid removed: 334,610 L

EXAMPLE 3

(Sheet 3 of 6)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC* (mg/L)
9/7/82	1300	0.52			
	1330	0.52	83,793	33	51.0
	1400	0.52	84,717	54	
	1500	0.52	86,568	44	
	1605	0.52	88,574	40	70.0
	1730	0.52	91,193	36	
	1800	0.52	92,348	34	
	1900	0.52	93,972	33	
	2000	0.52	95,823	32	50.6
	2100	0.52	97,674	31	
	2200	0.52	99,525	30	
	2300	0.52	101,376	30	

Borehole: DC-16A

Zone: Vantage interbed

Interval: 814 to 832 m

Estimated volume of fluid lost: 23,848 L

Total volume of fluid removed: 334,610 L

EXAMPLE 3

(Sheet 4 of 6)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC* (mg/L)
9/7/82	2350	0.52	102,921	30	44.8
9/8/82	0745	0.52	117,574	25	
	0830	0.52	118,963	25	36.9
	1010	0.52	122,044	23	
	1210	0.52	125,750	22	34.4
	1330	0.52	128,215	22	
	1520	0.52	131,610	21	
	2020	0.52	145,185	22	31.1
	2330	0.52	146,725	22	32.0
9/9/82	0322	0.52	153,884	22	
	0620	0.52	159,376	22	28.5
	0810	0.52	162,772	19	
	1015	0.52	167,519	18	

Borehole: DC-16A

Zone: Vantage interbed

Interval: 814 to 832 m

Estimated volume of fluid lost: 23,848 L

Total volume of fluid removed: 334,610 L

EXAMPLE 3

(Sheet 5 of 6)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC* (mg/L)
9/9/82	1200	0.52	169,866	18	28.7
	1435	0.52	174,647	19	
	1835	0.52	182,051	19	26.6
	2350	0.52	191,768	19	26.3
9/10/82	0320	0.52	198,249	19	
	0625	0.52	203,957	20	24.3
	0935	0.52	209,817	17	
	1120	0.52	213,057	16	24.3
Compressor off/restarted	1300		213,985	18	
	1515	0.52	218,149	18	
	1715	0.52	221,851	18	23.4
	2015	0.52	227,400	17	22.0

Borehole: DC-16A

Zone: Vantage interbed

Interval: 814 to 832 m

Estimated volume of fluid lost: 23,848 L

Total volume of fluid removed: 334,610 L

EXAMPLE 3

(Sheet 6 of 6)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC* (mg/L)
9/10/82	2315	0.52	232,957	16	26.2
9/11/82	0815	0.52	249,617	17	20.8
	1805	0.52	267,817	16	19.6
9/12/82	0615	0.52	290,340	14	19.5
	0829	0.52	294,470	15	19.7
	1750	0.52	311,781	15	17.7
	2225	0.52	322,115	14	18.3
9/13/82	0620	0.52	334,610	15	17.2
Test terminated	0630				

*Total organic carbon.

Borehole: DC-16A

Zone: Rocky Coulee flow

Interval: 364 to 398 m

Estimated volume of fluid lost: 141,953 L

Total volume of fluid removed: 264,301 L

Final development ratio: 2

EXAMPLE 4
(Sheet 1 of 6)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC[a] (mg/L)
11/4/82	1000				
	1110	0.40	1,696	53	
	1222	0.40	3,441	70	
	1307	0.40	4,531	61	
	1423	0.40	6,371	54	
	1524	0.40	7,851	50	
	1624	0.40	9,305	48	
	1758	0.40	11,580	45	
	1900	0.40	13,086	44	
	2000	0.40	14,536	42	
	2100	0.40	15,990	40	
	2210	0.40	17,685	37	

Borehole: DC-16A

Zone: Rocky Coulee flow

Interval: 864 to 898 m

Estimated volume of fluid lost: 141,953 L

Total volume of fluid removed: 264,301 L

EXAMPLE 4

(Sheet 2 of 6)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC[a] (mg/L)
11/4/82	2300	0.40	18,897	34	
11/5/82	0000	0.40	20,350	35	
	0100	0.40	21,804	34	
	0200	0.40	23,258	32	
	0300	0.40	24,711	32	
	0400	0.40	26,165	32	
	0500	0.40	27,618	32	
	0600	0.40	29,072	30	
	0700	0.40	30,526	29	
	0800	0.40	31,979	28	
	0900	0.40	33,433	26	
Test terminated	1000		34,886		

Borehole: DC-16A

Zone: Rocky Coulee flow

Interval: 864 to 898 m

Estimated volume of fluid lost: 141,952 L

Total volume of fluid removed: 264,301 L

EXAMPLE 4

(Sheet 3 of 6)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC[a] (mg/L)
11/8/82	1520	0.45			
	1636	0.45	36,934	32	
	1733	0.45	38,471	42	
	1833	0.45	40,091	35	
	1937	0.45	41,681	30	
	2106	0.45	44,217	27	
	2245	0.45	46,886	25	
	2345	0.45	48,502	24	
11/9/82	0010	0.45	49,176	24	
	0100	0.45	50,524	23	
	0200	0.45	52,144	23	
	0300	0.45	53,760	22	
	0400	0.45	55,381	22	

Borehole: DC-16A

Zone: Rocky Coulee flow

Interval: 864 to 898 m

Estimated volume of fluid lost: 141,953 L

Total volume of fluid removed: 264,301 L

EXAMPLE 4

(Sheet 4 of 6)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC[a] (mg/L)
11/9/82	0500	0.45	56,997	21	
	0600	0.45	58,613	21	
	0650	0.45	59,965	20	
	1030	0.45	65,896	19	32.3
	1200	0.45	68,323	18	
	1745	0.45	77,624	16	38.9
	1900	0.45	79,649	16	
	2000	0.45	81,265	16	
	2100	0.45	83,400	15	
	2200	0.45	84,502	16	
	2300	0.45	86,118	16	33.2
11/10/82	0825	0.45	101,354	14	
	1115	0.45	105,598	13	

Borehole: DC-16A

Zone: Rocky Coulee flow

Interval: 864 to 898 m

Estimated volume of fluid lost: 141,953 L

Total volume of fluid removed: 264,301 L

EXAMPLE 4

(Sheet 5 of 6)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC[a] (mg/L)
11/10/82	1500	0.45	112,007	12	18.7
	1830	0.45	117,666		17.3
	2230	0.45	124,139		17.8
11/11/82	0241	0.45	125,127		15.7
	0820	0.45	140,049	12	14.2
	0915	0.45	141,529	11	
Test terminated	0950		142,472		
	b				
11/12/82	1230	0.45			
11/13/82	1320	0.45	154,736	14	21.5
11/14/82	0240	0.45	215,787	10	12.5

Borehole: DC-16A

EXAMPLE 4

Zone: Rocky Coulee flow

(Sheet 6 of 6)

Interval: 864 to 898 m

Estimated volume of fluid lost: 141,953 L

Total volume of fluid removed: 264,301 L

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC[a] (mg/L)
11/14/82	0840	0.45	225,599	10	12.6
	1320	0.45	233,503	9	11.8
	2026	0.45	244,840	10	12.9
11/15/82 Test terminated	0820	0.45	264,301	9	9.6

[a]Total organic carbon.

[b]Pump actuator was installed and a total of 10,889.28 L removed. Actuator failed and the air line was installed again. Air lift was resumed at 1,230 h.

Borehole: DC-16A
Zone: Frenchman Springs 3
Interval: 671 to 689 m
Estimated volume of fluid lost: 18,927 L
Total volume of fluid removed: 346,358 L
Final development ratio: 18

EXAMPLE 5
(Sheet 1 of 7)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC* (mg/L)
5/21/82	1530	0.91			
	1540	0.91	545		
	1550	0.91	1,090		
	1600	0.91	1,635		
	1630	0.91	3,271		
	1700	0.91	4,906		
	1730	0.91	6,541	off scale	242.8
	1800	0.91	8,176		
	1830	0.91	9,812		
	1900	0.91	11,447		
	1930	0.91	13,082	off scale	
Test terminated	2000	0.91	14,718	off scale	102.0

Borehole: DC-16A

Zone: Frenchman Springs 3

Interval: 671 to 689 m

Estimated volume of fluid lost: 18,927 L

Total volume of fluid removed: 346,358 L

EXAMPLE 5

(Sheet 2 of 7)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC* (mg/L)
5/22/82	1630	1.20	16,164		
	1730	1.20	20,502		
	2000	1.20	31,347	77	47.7
	2200	1.20	40,023	59	
	2400	1.20	48,699	48	27.2
5/23/82	0200	1.20	57,375	40	
	0400	1.20	66,052	34	21.0
	0600	1.20	74,728	34	
	0800	1.20	83,404	28	16.7
	1000	1.20	92,042	28	
	1200	1.20	100,756	25	15.1
	1400	1.20	109,432	22	
	1600	1.20	118,109	21	

Borehole: DC-16A

Zone: Frenchman Springs 3

Interval: 671 to 689 m

Estimated volume of fluid lost: 18,927 l

Total volume of fluid removed: 346,358 L

EXAMPLE 5

(Sheet 3 of 7)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC* (mg/L)
5/23/82	1800	1.20	126,785	20	13.7
	2000	1.20	135,461	19	12.0
	2200	1.20	144,137	18	
	2400	1.20	152,817	16	10.5
5/24/82	0200	1.20	161,489	16	
	0400	1.20	170,166	14	9.7
	0600	1.20	178,842	14	
	0800	1.20	187,518	13	9.6
	1000	1.20	196,194	13	
	1200	1.20	204,870	12	8.6
	1400	1.20	213,546	12	
5/25/82	0030	1.20	258,373	10	7.8
	0300	1.20	269,218	9	

Borehole: DC-16A

Zone: Frenchman Springs 3

Interval: 671 to 689 m

Estimated volume of fluid lost: 18,927 L

Total volume of fluid removed: 346,358 L

EXAMPLE 5

(Sheet 4 of 7)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC* (mg/L)
5/25/82	0500	1.20	277,895	9	
	0600	1.20	282,233	9	7.4
	1000	1.20	299,585	10	6.5
Test terminated	1200	1.20	308,223		6.6
Pump actuator installed 5/27/82					
5/27/82	2000	0.11	311,721	55	
	0100	0.11	313,742	28	
	0415	0.11	315,056	22	
	0800	0.11	316,593	22	
	1000	0.11	317,407		17.5
	1100	0.11	317,819	20	

Borehole: DC-16A

Zone: Frenchman Springs 3

Interval: 671 to 689 m

Estimated volume of fluid lost: 18,927 L

Total volume of fluid removed: 346,358 L

EXAMPLE 5

(Sheet 5 of 7)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC* (mg/L)
5/27/82	1200	0.11	318,595	20	
	1300	0.11	318,190	19	
	1600	0.11	319,807	17	
5/28/82	1900	0.11	321,022	15	
Test terminated	2200		322,233		
6/01/82	0015	0.11	322,468	17	
	0200	0.11	323,074	16	
	0400	0.11	323,986	16	
	0600	0.11	324,792	49	
	0700	0.11	325,197	40	
	0800	0.11	325,602	34	
	0900	0.11	326,007	31	28.1

Borehole: DC-16A

Zone: Frenchman Springs 3

Interval: 671 to 689 m

Estimated volume of fluid lost: 18,927 L

Total volume of fluid removed: 346,358 L

EXAMPLE 5

(Sheet 6 of 7)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC* (mg/L)
6/01/82	1000	0.11	326,458	30	
	1100	0.11	326,814	27	
	1200	0.11	327,219	26	
	1300	0.11	327,624	25	21.7
	1405	0.11	328,063	24	
	1500	0.11	328,434	23	
	1600	0.11	328,771	23	
	2000	0.11	330,387	19	
6/02/82	0130	0.11	332,609	19	
	0533	0.11	334,248	19	
	0800	0.11	335,236	16	14.7
	0900	0.11	335,641	15	
	1000	0.11	336,046	16	

Borehole: DC-16A

Zone: Frenchman Springs 3

Interval: 671 to 689 m

Estimated volume of fluid lost: 18,927 L

Total volume of fluid removed: 346,358 L

EXAMPLE 5

(Sheet 7 of 7)

Date	Time (h)	Average flow rate (L/s)	Cumulative flow (L)	Fluorescence	TOC* (mg/L)
6/02/82	1100	0.11	336,519	17	
	1200	0.11	336,856	16	
	1303	0.11	337,250	15	13.2
	1400	0.11	338,336	16	
	1500	0.11	338,741	16	
	1600	0.11	339,078	15	
	2000	0.11	340,695	14	
6/03/82	0100	0.11	342,716	16	
	0500	0.11	344,332	15	
	0800	0.11	345,544	11	
	0900	0.11	345,953	15	
	0940	0.11	346,221	15	
Test terminated	1000	0.11	346,358		8.6

*Total organic carbon.

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