

**WORK PLAN
PHASE 3 GROUNDWATER SITE CONCEPTUAL MODEL
SANTA SUSANA FIELD LABORATORY**

VENTURA COUNTY, CALIFORNIA

Prepared For:

**The Boeing Company
The National Aeronautics and Space Administration
The United States Department of Energy**

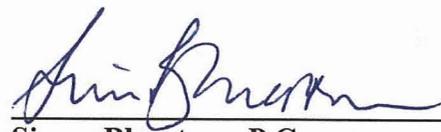
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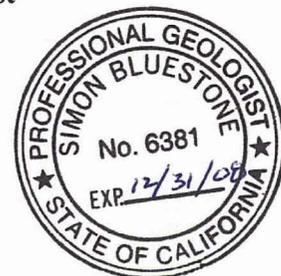


TABLE OF CONTENTS

| | | |
|------------|--|-------------|
| 1.0 | INTRODUCTION..... | 1-1 |
| 1.1 | WORK PLAN OBJECTIVE..... | 1-1 |
| 2.0 | DATA NEEDS, METHODS AND WORK TO BE PERFORMED..... | 2-1 |
| 2.1 | METHODS..... | 2-1 |
| 2.2 | FLUTE™ LINER HYDRAULIC CONDUCTIVITY PROFILING | 2-2 |
| 2.3 | STRADDLE PACKER TESTING..... | 2-4 |
| 2.3.1 | Straddle Packer Testing at a Location with Spraying Fractures | 2-4 |
| 2.4 | BOREHOLE GEOPHYSICAL LOGGING..... | 2-5 |
| 2.5 | HIGH-RESOLUTION FLUID TEMPERATURE LOGGING | 2-5 |
| 2.6 | COLLECTION AND ANALYSIS OF ROCK CORE SAMPLES..... | 2-7 |
| 2.6.1 | Physical Measurements of Fractures in Rock Core..... | 2-7 |
| 2.6.2 | Chemical Analysis of Rock Core Samples for Chloride..... | 2-7 |
| 2.6.3 | Rock Core Samples for Additional TCE Degradation Studies | 2-8 |
| 2.7 | COLLECTION AND ANALYSIS OF WATER SAMPLES | 2-9 |
| 2.7.1 | Collection and Analysis of Samples from Springs and Seeps..... | 2-10 |
| 2.7.2 | Collection and Analysis of Samples from Wells..... | 2-11 |
| 2.8 | IDENTIFICATION AND REVIEW OF SCIENTIFIC LITERATURE ON CHEMICAL DEGRADATION..... | 2-11 |
| 3.0 | SCHEDULE AND DELIVERABLES..... | 3-1 |
| 4.0 | SUMMARY | 4-1 |
| 5.0 | REFERENCES..... | 5-1 |

LIST OF TABLES

- 1 Data Needs and Collection Methods, Phase 3 Groundwater Site Conceptual Model Work Plan

LIST OF FIGURES

- 1 Santa Susana Field Laboratory Regional Map
- 2 Proposed Work for Phase 3 of Groundwater Site Conceptual Model
- 3 Locations of Springs/Seeps Sampled August 2006 through March 2007
- 4 Project Schedule

LIST OF APPENDICES

- A Background Information on the SSFL Groundwater Characterization Program
- B Groundwater Site Conceptual Model Overview and Fundamental Elements of Groundwater Flow System as Embodied in the Three-Dimensional Flow Model
- C FLUTE™ Hydraulic Conductivity Profiling and Associated Data Analysis Methods
- D Core Sample Selection, Testing and Analysis Methods, Fracture Closure Due to Lithostatic Loads
- E Analysis of Rock Core Samples for Chloride Content – Sampling and Analysis Procedures
- F Groundwater Sampling Methods for Analysis of Dissolved Gases

ACRONYMS AND ABBREVIATIONS

| | |
|-----------------|---|
| bgs | below ground surface |
| Boeing | The Boeing Company |
| C ¹⁴ | carbon-14 |
| CDCE | cis-1,2-dichloroethene |
| CFOU | Chatsworth Formation Operable Unit |
| DOE | U.S. Department of Energy |
| DTSC | Department of Toxic Substances Control |
| FLUTE™ | Flexible Liner Underground Technology |
| HRFT | high-resolution fluid temperature |
| NASA | National Aeronautics and Space Administration |
| NSR | non-strippable residue |
| Panel | Groundwater Advisory Panel |
| RCRA | Resource Conservation and Recovery Act |
| RFI | RCRA Facility Investigation |
| SCM | Site Conceptual Model |
| SSFL | Santa Susana Field Laboratory |
| TCE | trichloroethene |
| TD | total depth |
| VOC | volatile organic compounds |

1.0 INTRODUCTION

This Resource Conservation and Recovery Act (RCRA) Facility Investigation (RFI) work plan presents activities toward completing the characterization of the Chatsworth Formation Operable Unit (CFOU) of the Santa Susana Field Laboratory (SSFL). In particular, this work plan presents an approach for obtaining field data to be used in confirming and providing additional lines of evidence for specific elements of the groundwater site conceptual model (SCM). The SSFL is jointly owned by The Boeing Company (Boeing) and the federal government (administered by the National Aeronautics and Space Administration [NASA]) and is operated by Boeing. The U.S. Department of Energy (DOE) used a portion of the SSFL. However, there are no longer any active DOE operations and the facilities are undergoing decommissioning and demolition.

The SSFL is located in the southeast corner of Ventura County, 29 miles northwest of downtown Los Angeles, California. The location of the SSFL and its surrounding vicinity is shown on Figure 1. Previous environmental investigations have shown that the Chatsworth formation beneath portions of the SSFL has been impacted by historic releases of chemicals from operational activities, with trichloroethene (TCE) being the compound detected at the highest concentration and with the greatest frequency. This work plan has been prepared by MWH on behalf of Boeing, NASA and DOE and was developed jointly by staff from Boeing, the Groundwater Advisory Panel (Panel), consisting of Dr. John Cherry, Professor Emeritus from the University of Waterloo, Dr. David McWhorter, Professor Emeritus from Colorado State University, Dr. Beth Parker, Professor at the University of Guelph, and MWH. Additional background information about the Chatsworth formation characterization project is provided in Appendix A.

1.1 WORK PLAN OBJECTIVE

The objective of this Phase 3 groundwater SCM work plan is to present an approach for collecting data that will provide confirming and additional lines of evidence for various elements of the groundwater SCM. These data will also be useful in helping to define specific boundary conditions and other elements of the three-dimensional groundwater flow model. A summary of

the groundwater SCM for contaminant transport and an overview of the fundamental elements of the SSFL groundwater flow system as embodied in the three-dimensional model are provided in Appendix B.

This work plan is being prepared in partial fulfillment of the requirement to characterize groundwater that has been established in the corrective action provisions of existing post-closure or operating permits (Department of Toxic Substances Control [DTSC], 1995) and the 1992 stipulated enforcement order (DTSC, 1992).

2.0 DATA NEEDS, METHODS AND WORK TO BE PERFORMED

The key elements of the groundwater site conceptual model for flow and contaminant transport were reviewed against existing site data to identify the additional data that are needed to complete the confirmation of the groundwater SCM. This evaluation showed that field or laboratory test data should be collected to provide:

- Additional estimates of effective hydraulic apertures and confirmation of the number of active fractures
- Confirmation of the base of the active freshwater flow system beneath the SSFL
- Confirmation of the reduction in the permeability of the Chatsworth formation with depth due to increasing lithostatic loads
- Confirmation of the estimates of groundwater recharge
- An assessment of the composition of the groundwater discharging at seeps and springs
- Confirmation of the mechanisms that are completely dechlorinating TCE

2.1 METHODS

A number of both direct and indirect methods of collecting measurements to fill the data needs identified above are available. The best methods that were identified and will be used to complete the work outlined in this work plan include the following:

- FLUTE™ liner hydraulic conductivity profiling
- Straddle packer testing
- Borehole geophysical logging
- Borehole high-resolution fluid temperature logging
- Collection and analysis of rock core samples
- Collection and analysis of water samples

Table 1 cross-references the data needs identified in Section 2.0 with the methods identified in this section. Note that a single method alone or in combination with another method can provide data that fills multiple needs (e.g., FLUTE™ hydraulic conductivity profiling can provide data useful for evaluating the number of hydraulically active fractures, assessing a reduction in the

permeability with depth, and calculating fracture hydraulic apertures). The remainder of this section will present the work to be performed using each of the methods identified above. Further descriptions of the methods to be used to collect these data are presented in the following sub-sections.

2.2 FLUTE™ LINER HYDRAULIC CONDUCTIVITY PROFILING

Blank FLUTE™ liners have been used for several years at the SSFL to seal coreholes after drilling. During that time, FLUTE™ developed measurement and data recording technologies that can be used during blank liner installation to provide data that can be analyzed to yield a continuous hydraulic conductivity profile for the corehole. The conductivity profiling will be performed within existing coreholes to provide further estimates of hydraulic conductivity that will be used to:

1. Calculate additional hydraulic aperture values,
2. Confirm the number of hydraulically-active fractures, and
3. Assess the reduction in permeability with depth, and
4. Confirm the base of the active groundwater flow system.

FLUTE™ conductivity profiling data were recorded during the installation of the blank liners to seal coreholes C-10, RD-35C, and RD-39C in the Northeast area (Phase 2 Northeast Area Work Plan, [MWH, 2005]; see Appendix C) in anticipation of also using this technique in coreholes located in other areas of the site. The profiling data collected in these coreholes has not yet been reduced, but will help to assess spatial variation in vertical conductivity profiles when combined with the conductivity profiling data that will be collected during the Phase 3 SCM work.

The conductivity profiling will initially be performed in corehole C-6, which is located in Area II of the SSFL near the former Delta test stands. The location is shown on Figure 2. Corehole C-6 is scheduled to be deepened from its current depth of 898 feet to a depth of approximately 1,400 feet during the summer/fall of 2007 as part of the 2000 work plan scope (Montgomery Watson, 2000b). Thus, this corehole will present the best opportunity to collect measurements

such that a decreasing trend in the permeability of the Chatsworth formation with depth can be evaluated. Although existing water supply wells at the SSFL extend to greater depths, their borehole diameter is too large and variable to facilitate efficient testing using blank liners (or straddle packers).

FLUTE™ conductivity profiling will provide data throughout the entire saturated length of the corehole, which is estimated to be about 1,280 feet. Unlike straddle packer testing, FLUTE™ profiling is not limited to a fixed test interval or by various factors that can limit the positions where packers could be placed in the corehole to create an effective seal. The blank liner drives a fixed volume of water into formation per unit length of descent, and seals off more and more flow zones in the corehole as it descends with a resultant slowing of the liner descent velocity. The velocity profile can be analyzed in combination with other data recorded during the liner's descent to identify flow zones in the corehole and associated hydraulic conductivity estimates. Additional descriptions of the testing and data analysis methods are presented in Appendix C. The hydraulic conductivity estimates from the C-6 FLUTE™ conductivity profiling will be evaluated for trends with depth, and will be used in conjunction with the core log and available geophysical data (geophysical logging was performed to the current C-6 corehole depth of approximately 898 feet) to calculate hydraulic apertures using the cubic law (Snow, 1968).

If the conductivity profiling at corehole C-6 (and at northeast area coreholes C-10, RD-35C and RD-39Cs) provides meaningful results, this testing program will also be performed at coreholes C-7 (total depth [TD] of 419 feet below ground surface [bgs]) and C-8 (TD of 400 feet bgs) to help evaluate spatial variation. Locations of C-7 and C-8 are shown on Figure 2. If FLUTE™ profiling is performed at C-8, the existing FLUTE™ multi-level monitoring system will first have to be removed from the corehole. Also, for coreholes where no geophysical data were previously collected (i.e., the deepened portion of C-6, and C-7), geophysical logging will be performed to support hydraulic aperture estimates from those locations.

2.3 STRADDLE PACKER TESTING

Straddle packer tests were performed in coreholes RD-35B and RD-46B in the late 1990s to provide estimates of hydraulic conductivity and hydraulic apertures (Montgomery Watson, 2000a). Additional hydraulic tests using straddle-packers may be performed at limited target intervals of interest within existing coreholes to corroborate the results of the FLUTE™ conductivity profiling. These test intervals would be selected based on the results of the FLUTE™ profiling, coring logs, and on other hydrogeologic or geophysical data, if available.

The smallest straddle packer test interval would be approximately 7.2 feet, but some test intervals might exceed three times this length depending upon the locations of fractures, wash-out zones, and other factors that could limit the positions where packers can be placed such that an effective seal can be created in the corehole. The straddle packer tests may include constant head injection tests, constant or transient rate injection tests, or shut-in pulse tests. Quality control measures would largely depend upon the specifics of the equipment used to perform the testing, and data analysis would be completed using standard methods for the tests performed. The approach to performing these tests would generally be as outlined in Chapter 17 of the Handbook of Groundwater Engineering (CRC Press, 1999).

2.3.1 Straddle Packer Testing at a Location with Spraying Fractures

Borehole video logs have revealed a few wells and coreholes at the SSFL where water is flowing from fractures that lie above the water level in the open hole. These fractures transmit water into the open hole at sufficient velocity such that the water sprays from the fracture into the hole. At first glance, this behavior appears contrary to the relatively small hydraulic apertures that have been calculated to date (i.e., ranging from the tens of microns to a few hundreds of microns). It is likely that a number of these features exist within other wells and coreholes at the SSFL, but that they exist below the water level in the open hole and so are not as dramatic in appearance. It should be recognized that these features are purely the result of the well or corehole, which provides direct flow pathways from fractures at higher hydraulic head to others at lower head that do not occur in the natural system. For example, in any well with such a spraying fracture, there must be outflow zones deeper in the hole that accept the flow from the spraying fracture. Yet, it is difficult to reconcile the visual impact of these spraying fractures and

the suggestion that the apertures of such fractures must be larger than the current estimates in order to conduct water at such an apparent velocity.

FLUTE™ conductivity profiling is effective only below the level of the water surface in the open hole, and thus cannot be used to evaluate a spraying fracture. Therefore, at least one spraying fracture will be targeted for straddle packer testing, which would provide a hydraulic conductivity value that could then be used to calculate the fracture aperture using the cubic law. This testing will be performed at corehole C-2 (TD of 400 feet bgs). The location of C-2 is shown on Figure 2. A spraying fracture in another well or corehole would be selected if placement of the packers is inhibited by a poor quality well bore (e.g., highly fractured and washout zones). After inflating the packers, the test interval will be allowed to fill with water from the spraying fracture while monitoring the head in the test interval. After the head in the test interval has stabilized, straddle packer testing and analysis methods similar to those described previously will be applied.

2.4 BOREHOLE GEOPHYSICAL LOGGING

Borehole geophysical logs will be collected to support hydraulic aperture estimates from the deepened portion of corehole C-6 (i.e., from 898 feet to the target depth of 1400 feet) and from corehole C-2 (if a corehole other than C-2 is selected for straddle packer testing of a spraying fracture, then that corehole will be geophysically logged rather than C-2). The string of packers or blank liner, if present, will be removed from the corehole prior to geophysical logging, and will be reinstalled at the conclusion of the work. Borehole geophysical logging will include the collection of caliper logs, natural gamma logs and optical or acoustic televiewer logs.

2.5 HIGH-RESOLUTION FLUID TEMPERATURE LOGGING

High-resolution fluid temperature (HRFT) logging will be performed at the same coreholes as those planned for FLUTE™ conductivity profiling, namely C-6 (after deepening), C-7 and C-8. HRFT logging has already been performed at coreholes C-10 and deepened RD-31 in the northeast area to provide information on spatial variation throughout the site. The HRFT logging

will be used to provide information on the number of hydraulically active fractures, to determine their relative number and flow contribution, and to estimate groundwater recharge. At corehole C-6, these data will also provide additional information on the base of the active groundwater flow system beneath the SSFL.

Multiple logging runs will be made in each corehole after first being sealed by a blank liner (FLUTETM conductivity profiling data has been or will have been collected during the installation of the blank liners). Following the installation of each blank liner, each corehole will be allowed to stabilize for a minimum of 48 hours before logging is initiated. At a minimum, the sequence of HRFT logging at each of the coreholes will be:

1. Passive temperature in the FLUTETM-lined hole
2. Active temperature in the FLUTETM-lined hole

It is anticipated that the HRFT logging activities will be led by Peter Pehme of Waterloo Geophysics Inc., who has performed this type of logging previously at the SSFL. An additional test that Mr. Pehme has developed over the past few years involves monitoring of the thermal recovery following active logging. He has found that although the active logging process is more sensitive to flow in the fractures, the recovery data provides a more stable estimate of the thermal properties of the rock mass. Two to three logging runs are required to provide the data needed to perform the decay calculations. Thermal decay logging may be performed at one or more of the selected coreholes at the SSFL.

The high-resolution fluid temperature logs will also be reviewed and evaluated to determine if they can be used to obtain a further understanding of the groundwater recharge. The passive temperature logs from the sleeved holes may provide information on the change in the geothermal gradient that can then be used to estimate a recharge rate.

2.6 COLLECTION AND ANALYSIS OF ROCK CORE SAMPLES

Samples of existing rock core will be subjected to chemical analysis for chloride, and will be used in additional TCE degradation studies. These analyses and studies are expected to provide additional information on groundwater recharge and further the understanding of the mechanisms and rates of TCE degradation. Additional descriptions of this work are provided below.

2.6.1 Physical Measurements of Fractures in Rock Core

Samples of existing fractured rock core were collected by Dr. Tariq Cheema of the University of Waterloo and tested to assess the magnitude of fracture closure resulting from increasing loads and their corresponding stresses. Fracture closure with depth due to increasing lithostatic loads is believed to be responsible for the anticipated reduction in permeability with depth in the Chatsworth formation. The data from this testing are currently being reduced and evaluated. Details regarding the core sample selection basis, and the testing and analysis methodologies are presented in Appendix D.

2.6.2 Chemical Analysis of Rock Core Samples for Chloride

Samples of existing rock core from both the vadose zone and the saturated zone will be analyzed for chloride. Vadose zone rock core samples are expected to provide information on groundwater recharge while rock core samples from the saturated zone will provide information regarding the base of the active freshwater flow system. Each of these sampling activities is further described below.

Vadose Zone Samples

Vadose zone rock core samples from corehole C-4 have been previously analyzed for chloride. Samples between the depths of approximately 10 and 50 feet bgs were collected and analyzed for chloride from this location. Corehole C-4 is located in Area I of the SSFL near the former Bowl test stands. Additional existing vadose zone rock core samples will be analyzed for chloride using the same method to further bound the estimates of groundwater recharge. Samples of existing vadose-zone rock core from coreholes C-1, C-6, C-8 and C-10 will be collected at

approximately 5-foot intervals. This collection interval will provide approximately 17 samples from C-1, 24 samples from C-6, 33 samples from C-8, and 16 samples from C-10.

As with the previous SSFL core samples analyzed for chloride, these samples will be split and analyzed with an ion-specific electrode and with a Dionex DX 500 Chromatography System by the Chemical Engineering Analytical Lab at the University of Waterloo. Details of the sample collection and preparation procedures, which were used previously at the SSFL for core samples from C-4 that were analyzed for chloride, as well as details of the laboratory equipment, analyses and techniques are presented in Appendix E.

Saturated Zone Samples

Rock core samples from the saturated zone between the depths of approximately 406 and 898 feet bgs were previously collected and analyzed for chloride. Samples of rock core from depths greater than 900 feet in corehole C-6 will also be collected and analyzed for chloride. The chloride analytical results from these rock core samples will be used to evaluate the position of the freshwater/saltwater interface, if encountered, and will help to define the base of the active groundwater flow system. Core samples will be collected at approximately 10-foot intervals between depths of 900 and 1,400 feet for a total of approximately 50 samples. The core sample collection, preparation, and analysis will be as described above for the vadose zone samples, and as detailed in Appendix E.

2.6.3 Rock Core Samples for Additional TCE Degradation Studies

The first phase of the laboratory microcosm studies of potential TCE degradation in saturated Chatsworth formation bedrock showed complete transformation of TCE to non-hazardous byproducts (Freedman and Darlington, 2006). A number of additional laboratory studies will be performed using rock core as described below to provide further evidence and enhance the understanding of the occurrence and rate of TCE transformation in Chatsworth formation groundwater.

Five additional activities will be performed to further evaluate the transformation of TCE in laboratory microcosms. These activities include:

1. Conducting a new set of microcosms focusing just on carbon 14-labeled cis-1,2-dichloroethene, or ^{14}C [cDCE], with the intent of increasing the chances of detecting a statistically significant transformation rate that could be used in contaminant transport models.
2. Establishing a new set of microcosms to which no ^{14}C [cDCE] compounds will be added, so that they could be used for analysis of ^{13}C [cDCE] to document a potential isotopic shift associated with the abiotic transformation pathway.
3. Combining iron (II) oxidizing anaerobes with chlororespiring microbes and SSFL rock core, with and without groundwater, to establish that the reduction of TCE to cDCE is sustainable by identifying the source of electron donor.
4. Continuing the molecular characterization of SSFL sediment with the intent of identifying the likely TCE dechlorinating microbe and the iron (II) oxidizer. This will be accomplished by enriching the TCE dechlorinator by making repeated additions of TCE to microcosms that exhibit activity, at least as long as the supply of electron donor lasts.
5. Further characterizing the non-strippable residue (NSR) from the microcosms described above. At higher concentrations of cDCE, a sufficient mass/concentration of NSR products is expected so that the constituents can be identified and quantified by gas chromatography, mass spectrometry or other analytical methods. Once the identity of the compounds in the NSR is known, it may be possible to better predict the transformation pathway leading to NSR and CO_2 from cDCE. Furthermore, these compounds may be identifiable in groundwater samples collected from the site, such that additional field data indicating the complete dechlorination of TCE could also be collected.

Item 1 above focuses on establishing a degradation rate for cis-1,2-DCE, while items 2 through 5 are aimed at identifying transformation pathways to help demonstrate the sustainability of the degradation mechanisms. These studies will be led by Clemson University, and will be performed using fresh rock core from corehole C-11.

2.7 COLLECTION AND ANALYSIS OF WATER SAMPLES

Water samples will be collected from springs and seeps (collectively referred to herein as seeps) and groundwater monitoring wells in this Phase 3 program. Each of these sample collection and analysis programs is described further below.

2.7.1 Collection and Analysis of Samples from Springs and Seeps

Analysis of samples of water from seeps downslope of the SSFL is expected to provide information regarding potential flow paths of the groundwater originating from beneath the SSFL. This work may also provide an additional line of evidence regarding the concept of strong attenuation of solutes in the Chatsworth formation.

The investigation of areas along the mountain slopes surrounding the SSFL where groundwater discharge occurs as seeps was initiated in 2002 with the identification of 28 seeps (MWH, 2003). A follow-up seep identification study was initiated in 2004 that resulted in the identification and description of a total of about 90 additional seeps as shown on Figure 3. An initial phase of sampling and analysis was completed in 2004 by MWH that provided general water quality data, and preliminary chemical and isotopic fingerprinting for many of the identified seeps.

Seeps will be further characterized in two phases. The first phase was initiated in late 2006, and involved collecting samples from approximately 50 seep locations (DTSC was present and collected split samples at many of these locations) and submitting the samples for analysis of volatile organic compounds (VOCs), perchlorate, carbon-14 (^{14}C), and general water quality parameters. The data from this study are currently being reduced, and will be used to design a second phase of sampling targeting seeps that have the highest likelihood of intercepting groundwater that may be originating from beneath the SSFL.

The second phase sampling program will focus on areas adjacent to the SSFL where the first-phase sampling results indicate that the groundwater emerging at seeps has a composition similar to groundwater from beneath the SSFL. The second phase of sampling will include a list of additional chemical and isotopic analytes that are intended to be further diagnostic of the groundwater emerging at seeps. Details of the second phase of sampling and analysis will be dependent upon the first phase results and will be submitted to DTSC in a work plan prior to initiating the work.

2.7.2 Collection and Analysis of Samples from Wells

The first phase of field studies of TCE degradation in Chatsworth formation was conducted by Amanda Pierce while a Masters student at the University of Waterloo (Pierce, 2005). The field studies showed the biological reduction of TCE to cis-1,2-DCE and the presence of dissolved gases indicative of abiotic degradation. Additional field data may be helpful in demonstrating that TCE is completely dechlorinated to non-hazardous by-products and for assessing the transformation pathway. Some of the intermediate transformation products of TCE degradation, such as vinyl chloride and other dissolved gases, require specialized sampling techniques to avoid volatilization during sample collection and to produce concentrations representative of in situ conditions. A downhole sample collection device (i.e., SNAP sampler) will be used to collect samples from below the water table in a select set of 16 monitoring wells for analysis of VOCs and other dissolved gases. The wells preliminarily identified as candidates for this program, and details of the sampling equipment and methodology are presented in Appendix F.

2.8 IDENTIFICATION AND REVIEW OF SCIENTIFIC LITERATURE ON CHEMICAL DEGRADATION

A search of the scientific literature will be undertaken to further evaluate the in-situ degradation element of the groundwater SCM. This literature search is targeted at further understanding the potential degradation pathways of chemicals other than TCE in the Chatsworth formation. This search will focus on the occurrence of and identification of mechanisms for degradation of other chemicals found in the groundwater beneath the SSFL. The information gathered may provide a basis for additional chemical-specific degradation studies at the SSFL. The literature search will be directed by the University of Waterloo, and the information gathered will be summarized in a technical memorandum.

3.0 SCHEDULE AND DELIVERABLES

A project schedule, including task names and durations and estimated start and completion dates, is presented on Figure 4. The schedule assumes that this Phase 3 SCM work plan (and any subsequent modifications and/or revisions) will be approved by DTSC for implementation by early August 2007. The estimated total duration of the Phase 3 SCM project is about 12 months, with a targeted completion in mid August 2008. Independent tasks have been scheduled concurrently to reduce the project duration.

Three of the tasks outlined in this work plan have been initiated. Physical measurements of fractured rock core were collected in late May 2006 during the Phase 2 Northeast Area field investigations. Rock core samples were collected and shipped to Clemson University in June 2006, and again in May 2007 for continued laboratory evaluations of TCE degradation. The first of two additional phases of seeps/springs sampling and analysis commenced in August 2006, and the associated data analysis is ongoing as of submittal of this work plan.

A series of deliverables is scheduled to be submitted during the Phase 3 SCM work as indicated on the project schedule (Figure 4). Where practical based on timing and subject matter, these deliverables will be combined to reduce the number of separate documents. Most of the deliverables will be brief descriptions of the work performed, and will provide the results of each of the blocks of work described in this work plan and shown on the project schedule. Results from each major task item will be reviewed and integrated with other results so that the proper interpretations of the data can be made and the remaining elements of the groundwater SCM are well supported by field data. The final deliverable will be an updated, written description of the groundwater SCM.

4.0 SUMMARY

This Phase 3 SCM work plan describes the data that will be collected to complete the confirmation of the groundwater SCM. In particular, this work plan presents an approach for obtaining field data to be used in confirming, and providing additional lines of evidence for specific elements of the groundwater site conceptual model. These data will also be used to define various boundary conditions and other parameters in the three-dimensional groundwater flow model that is under development. The field data to be collected will provide:

- Additional estimates of effective hydraulic apertures and confirmation of the number of active fractures
- Confirmation of the base of the active freshwater flow system beneath the SSFL
- Confirmation of the reduction in the permeability of the Chatsworth formation with depth due to increasing lithostatic loads
- Confirmation of the estimates of groundwater recharge
- An assessment of the composition of the groundwater discharging at seeps and springs
- Confirmation of the mechanisms that are completely dechlorinating TCE

The methods that will be used to collect these data will include: FLUTETM conductivity profiling, straddle packer testing, borehole geophysical logging, collection and analysis of rock core samples, and collection and analysis of water samples. Conductivity profiling data will be used to calculate additional hydraulic aperture values and for confirming the number of hydraulically-active fractures. The profiling will also provide data that can be used to assess a reduction in permeability with depth, and help identify the base of the active groundwater flow system. Straddle packer testing will be performed to evaluate the hydraulic conductivity and aperture of a spraying fracture. Limited straddle packer testing may also be performed to corroborate the results of the conductivity profiling and support hydraulic aperture estimates. Borehole geophysical logs will be collected to support hydraulic aperture estimates. High-resolution fluid temperature logging will be used to provide further confirmation of the number of active fractures, the permeability reduction with depth, groundwater recharge, and the base of the active flow system. Data from the collection and analysis of rock core samples will be used to confirm the expected reduction in the permeability of the Chatsworth formation with depth, provide

additional information on groundwater recharge, and for furthering the understanding of the mechanisms and rates of TCE degradation. Data produced from the collection and analysis of water samples will be used to better define groundwater recharge, evaluate the flow paths of groundwater potentially originating beneath the SSFL and emerging at the ground surface in downslope areas, and for providing further confirmation and understanding as to the mechanisms of TCE degradation. Finally, a special study will be conducted that will provide further insight on the degradation potential of other chemicals found in SSFL groundwater. A more complete summary of the proposed work is provided on Table 1. This work is projected to take about 12 months to complete. The work described herein can commence within 30 days of DTSC's approval of this work plan.

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TABLES

Table 1
Data Needs and Collection Methods
Phase 3 Groundwater Site Conceptual Model Work Plan
Santa Susana Field Laboratory

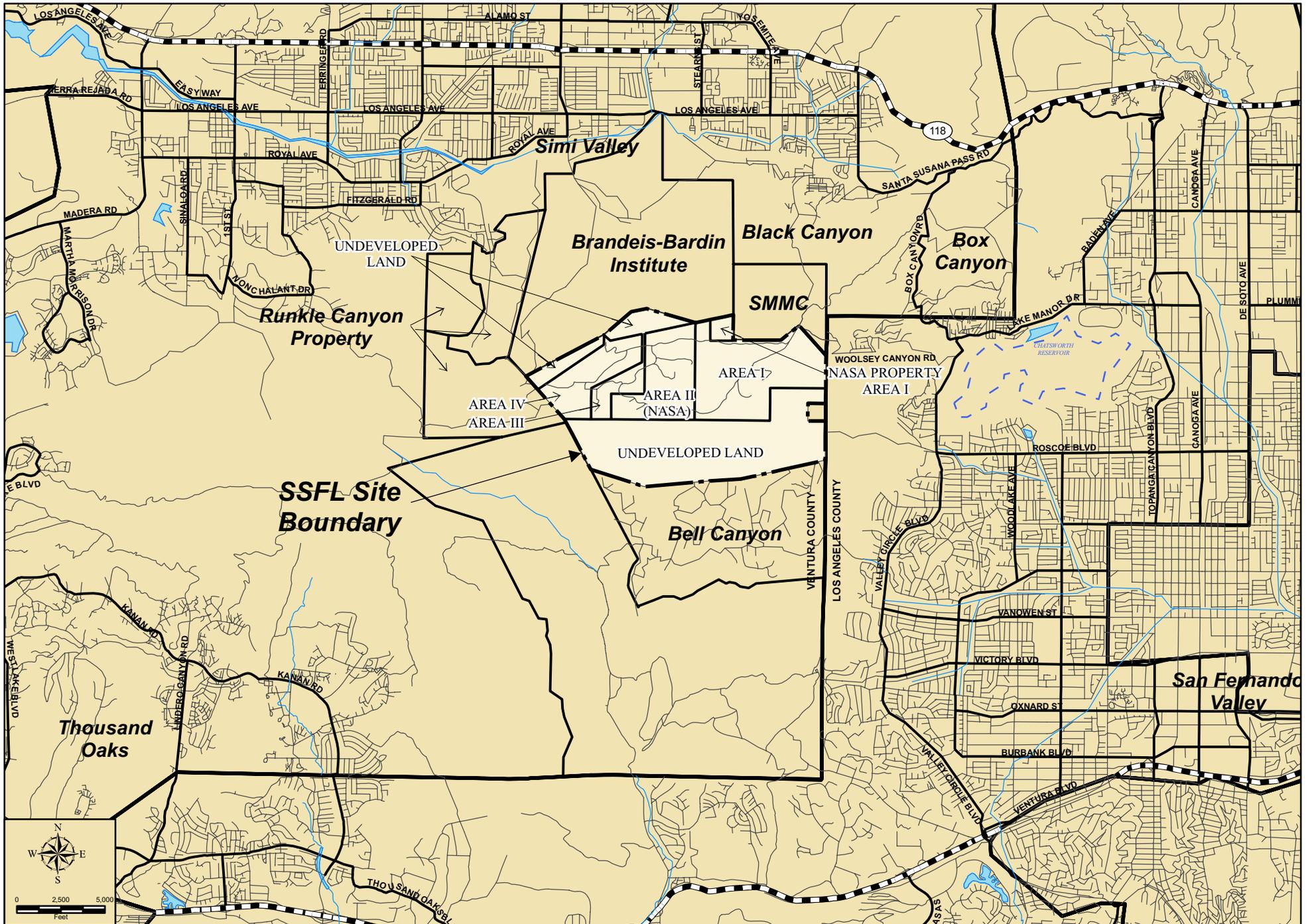
| Data Needs | | <i>FLUTE™ Hydraulic Conductivity Profiling</i> | <i>Straddle Packer Testing</i> | <i>Borehole Geophysics</i> | <i>Borehole High-resolution Fluid Temperature Logging</i> | <i>Water Sample Chemical and/or Isotopic Analyses</i> | <i>Water Sample Dissolved Gases Analyses</i> | <i>Physical or Laboratory Analysis of Rock Core</i> | <i>Search of Scientific Literature on Chemical Degradation</i> |
|---|---|--|--------------------------------|----------------------------|---|---|--|---|--|
| 1 | Hydraulic aperture estimates | √ | √ | √ | | | | | |
| 2 | Number of active fractures | √ | √ | √ | √ | | | | |
| 3 | Assessment of permeability reduction with depth | Potential | Potential | | √ | | | √ Fractures | |
| 4 | Base of active flow system | Potential | Potential | | √ | | | √ Chloride | |
| 5 | Groundwater recharge | | | | √ | √ | | √ Chloride | |
| 6 | Groundwater discharge | | | | | √ | | | |
| 7 | Degradation of TCE and other chemicals | | | | | √ | √ | √ | √ |
| Locations at SSFL Where Data Will Be Collected (See Figures 2 and 3 of Work Plan) | | | | | | | | | |
| Coreholes | C-1 | | | Completed | | | | VZ Chloride | |
| | C-2 | | Limited | √ | | | | | |
| | C-6 | √ | Contingent | 898'-1400' | √ | | | SZ and VZ Chloride | |
| | C-7 | Contingent | Contingent | Contingent | Contingent | | | | |
| | C-8 | Contingent | Contingent | Completed | Contingent | | | VZ Chloride | |
| | C-10 | Completed | | Completed | Completed | | | VZ Chloride | |
| | C-11 | | | | | | | √ | |
| | RD-31 (deepened) | | | | Completed | | | | |
| | RD-35C | Completed | | Completed | | | | | |
| RD-39Cs | Completed | | Completed | | | | | | |
| | Select on-site wells (see Appendix G) | | | | | | √ | | |
| | Offsite adjacent areas (seeps/springs) | | | | | √ | | | |

VZ - vadose zone

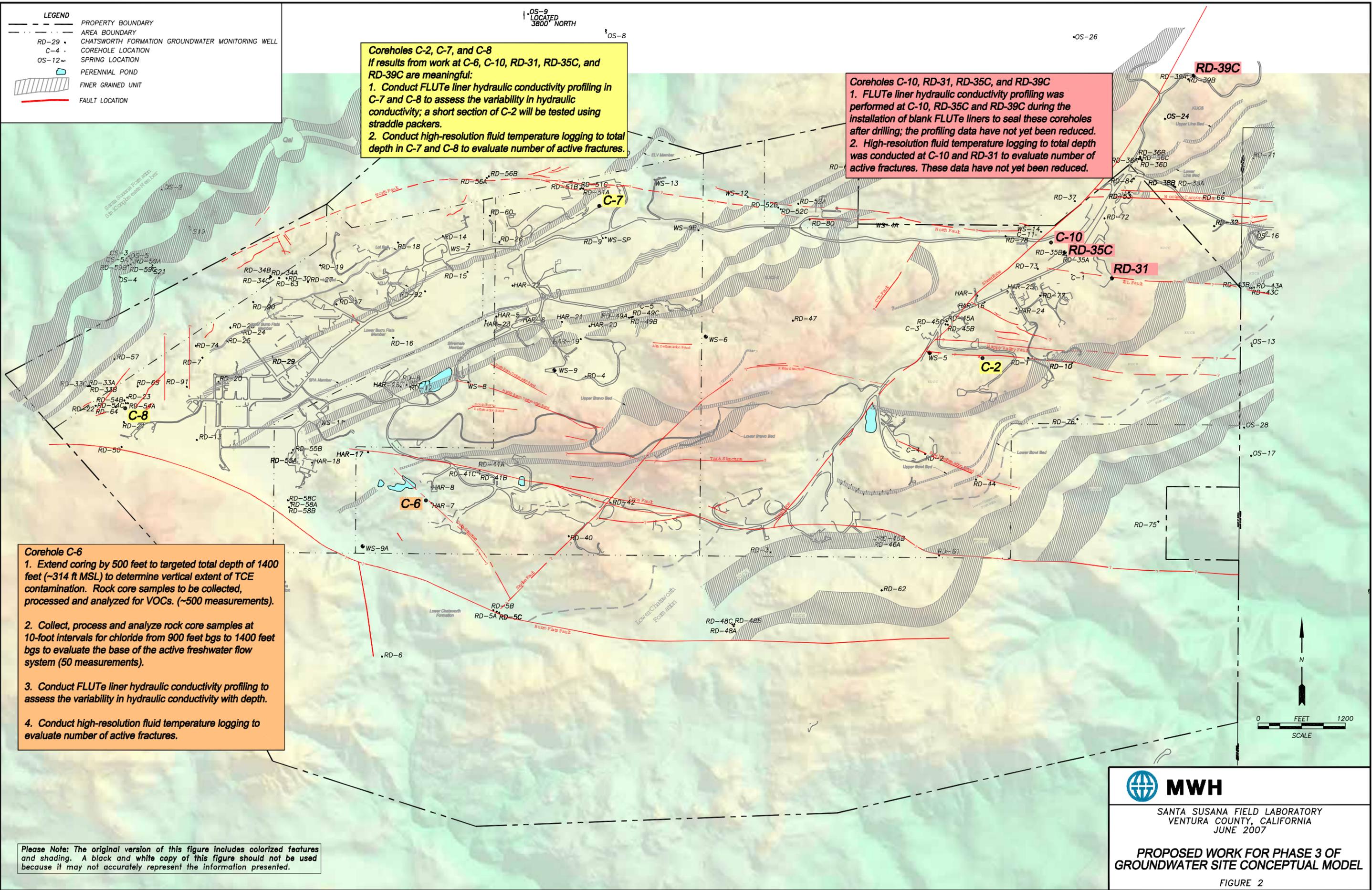
SZ - saturated zone

Check mark (√) indicates work planned at that location

FIGURES



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LEGEND

| | |
|-------|--|
| --- | PROPERTY BOUNDARY |
| - - - | AREA BOUNDARY |
| RD-29 | CHATSWORTH FORMATION GROUNDWATER MONITORING WELL |
| C-4 | COREHOLE LOCATION |
| OS-12 | SPRING LOCATION |
| ▭ | PERENNIAL POND |
| ▨ | FINER GRAINED UNIT |
| --- | FAULT LOCATION |

Coreholes C-2, C-7, and C-8
 If results from work at C-6, C-10, RD-31, RD-35C, and RD-39C are meaningful:
 1. Conduct FLUTE liner hydraulic conductivity profiling in C-7 and C-8 to assess the variability in hydraulic conductivity; a short section of C-2 will be tested using straddle packers.
 2. Conduct high-resolution fluid temperature logging to total depth in C-7 and C-8 to evaluate number of active fractures.

Coreholes C-10, RD-31, RD-35C, and RD-39C
 1. FLUTE liner hydraulic conductivity profiling was performed at C-10, RD-35C and RD-39C during the installation of blank FLUTE liners to seal these coreholes after drilling; the profiling data have not yet been reduced.
 2. High-resolution fluid temperature logging to total depth was conducted at C-10 and RD-31 to evaluate number of active fractures. These data have not yet been reduced.

Corehole C-6
 1. Extend coring by 500 feet to targeted total depth of 1400 feet (~314 ft MSL) to determine vertical extent of TCE contamination. Rock core samples to be collected, processed and analyzed for VOCs. (~500 measurements).
 2. Collect, process and analyze rock core samples at 10-foot intervals for chloride from 900 feet bgs to 1400 feet bgs to evaluate the base of the active freshwater flow system (50 measurements).
 3. Conduct FLUTE liner hydraulic conductivity profiling to assess the variability in hydraulic conductivity with depth.
 4. Conduct high-resolution fluid temperature logging to evaluate number of active fractures.

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 JUNE 2007

**PROPOSED WORK FOR PHASE 3 OF
 GROUNDWATER SITE CONCEPTUAL MODEL**

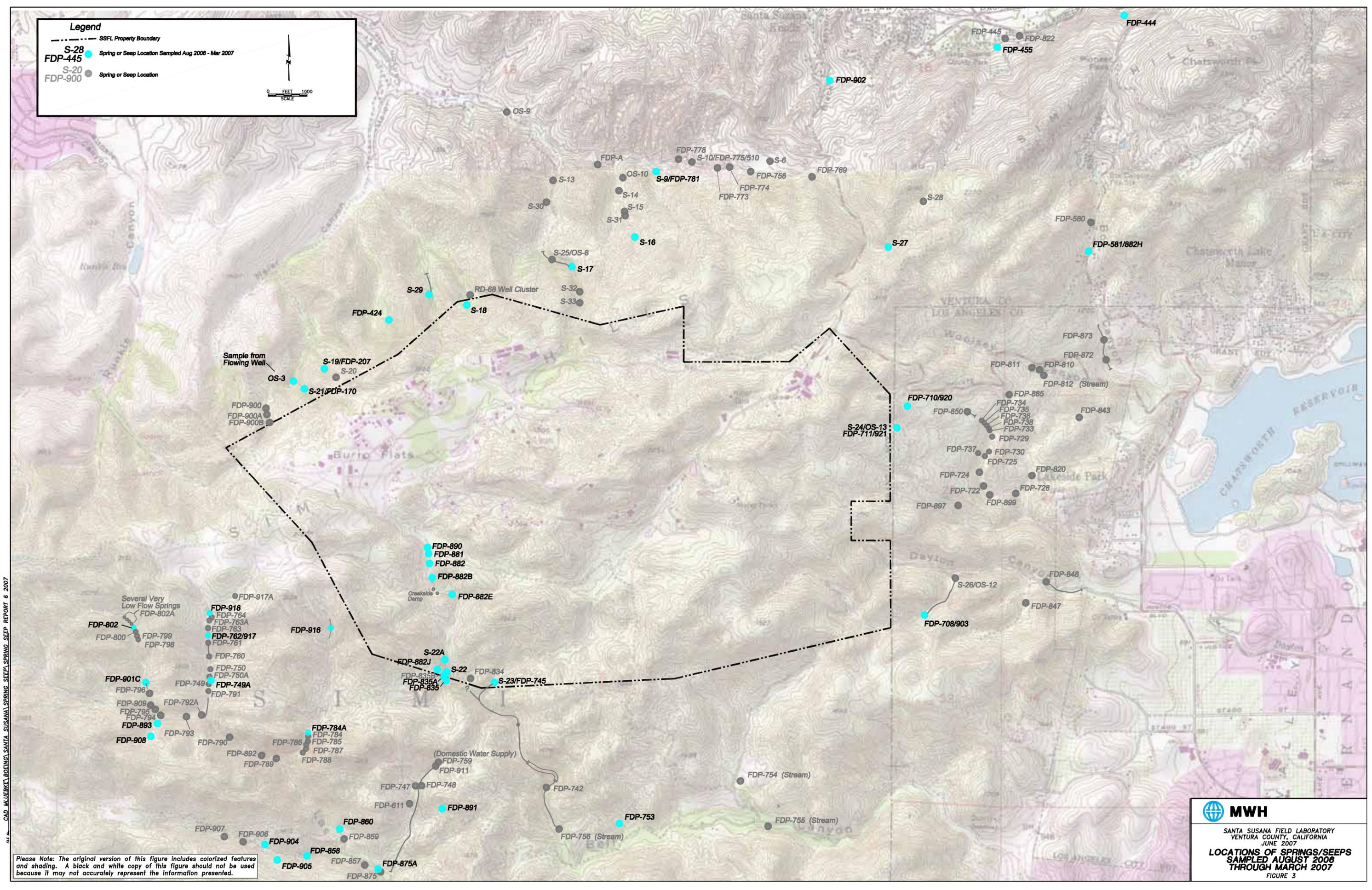
FIGURE 2

Legend

--- SSFL Property Boundary

S-28 FDP-445 Spring or Seep Location Sampled Aug 2006 - Mar 2007

S-20 FDP-900 Spring or Seep Location



FILE NO. CAD_MLUEBKE\BOEING\SANTA_SUSANA\SPRING_SEEP\SPRING_SEEP REPORT 6 2007

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**LOCATIONS OF SPRINGS/SEEPS
 SAMPLED AUGUST 2006
 THROUGH MARCH 2007**

FIGURE 3

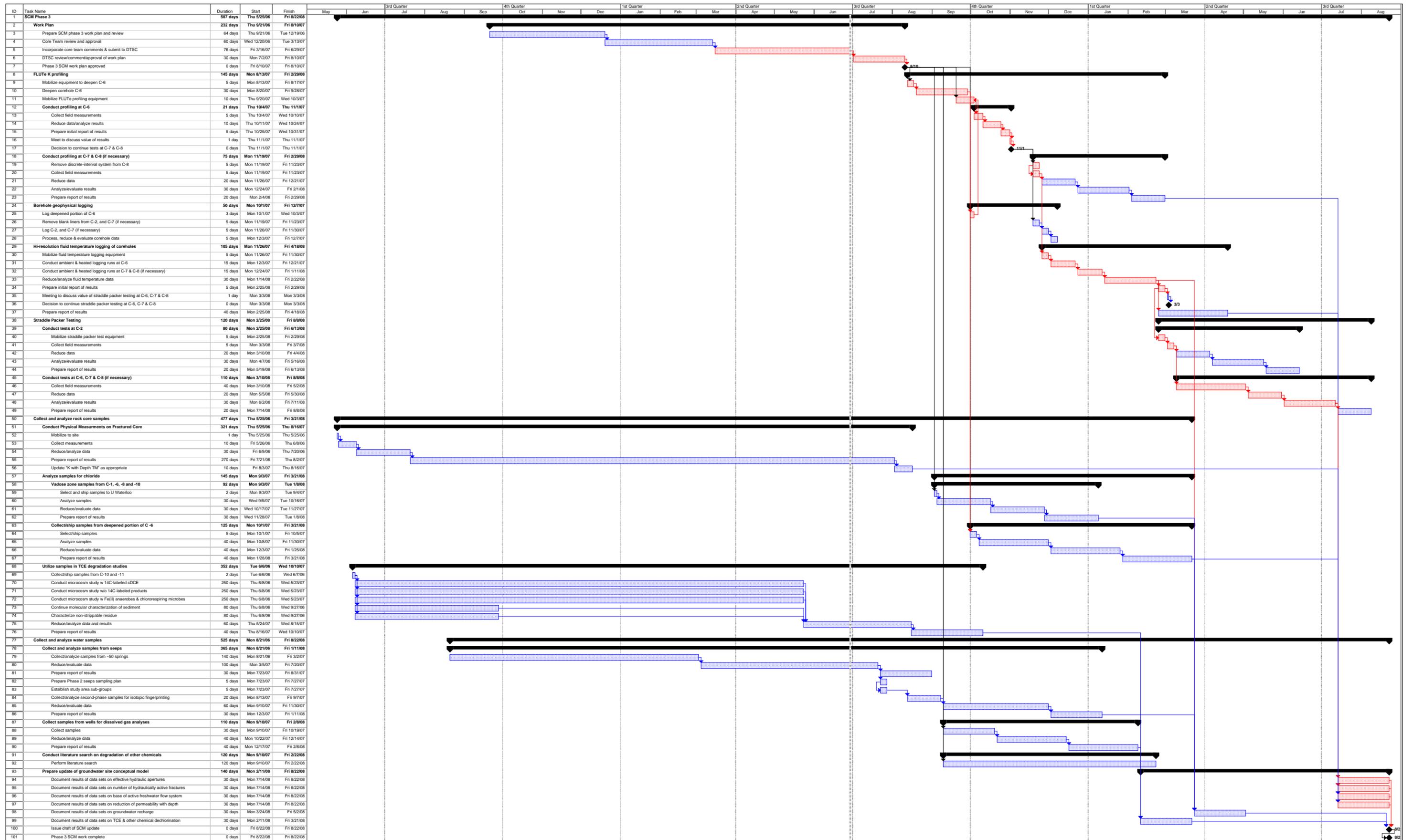


Figure 4
Project Schedule
Phase 3 Groundwater SCM



APPENDIX A

**BACKGROUND INFORMATION ON THE SSFL GROUNDWATER
CHARACTERIZATION PROGRAM**

APPENDIX A
BACKGROUND INFORMATION ON THE SSFL GROUNDWATER
CHARACTERIZATION PROGRAM

A.1 BACKGROUND INFORMATION

The Groundwater Advisory Panel (Panel) was commissioned in 1997 to develop a groundwater site conceptual model (SCM) regarding the movement of TCE in the Chatsworth formation. At the recommendation of the Panel, new methods including rock coring and crushing were used to characterize trichloroethene (TCE) in the fractured sedimentary rock of the Chatsworth formation during the late 1990's. In April, 2000 a Technical Memorandum was submitted that presented the site conceptual model (Montgomery Watson, 2000a). The SCM was based on the Panel's understanding of solute transport in fractured sedimentary rock (e.g., Chatsworth formation) and available data as of late 1999.

The groundwater site conceptual model for TCE movement in the Chatsworth formation as published in 2000 included the following three key elements:

- The fractures at the SSFL are small, systematic and interconnected.
- TCE dissolved in groundwater flowing through the small, systematic and interconnected fractures are transported into the porous sandstone matrix by molecular diffusion.
- TCE plume fronts are strongly retarded due to matrix diffusion and the presence of organic carbon, and advance at rates that are orders-of-magnitude slower than the average linear groundwater velocity.

Phase 1 site conceptual model investigations were based on a work plan¹ (Montgomery Watson, 200b) that was submitted to and approved by the California Environmental Protection Agency, Department of Toxic Substances Control (DTSC, 2000). The Phase 1 work focused on the first two elements of the SCM by:

¹ The initial methods and concepts of determining whether volatile organic compounds (VOC) mass had been transported into the Chatsworth formation sandstone matrix were developed and implemented in 1997 by members of the Groundwater Advisory Panel and proven by the installation of two coreholes drilled in source areas (RD-35B and RD-46B).

- Conducting hydraulic and borehole geophysical tests, and inspecting and analyzing rock core to assess the size, nature and interconnectedness of the fracture network. This work was completed at two areas of the site that represent the upper and lower range of Chatsworth formation permeability (the Northeast area and the Former Sodium Disposal Facility [FSDF] in the northwest portion of the Santa Susana Field Laboratory [SSFL], respectively).
- Drilling coreholes at eight source zones located throughout the SSFL to demonstrate that the solutes are transported into the porous sandstone matrix through molecular diffusion.

A Report of results from the Phase 1 investigation in the Northeast area was issued in September 2004 (MWH, 2004).

A Phase 2 Northeast Area Work Plan was submitted in October 2005 (MWH, 2005) and approved for implementation by the DTSC (DTSC, 2005) and is in progress as of the date of issuance of this work plan. The Phase 2 Northeast Area Work Plan presented a scope of work focused on both defining the nature and extent of chemicals and on the third element of the SCM, which predicts that solute transport will be strongly retarded relative to the average linear groundwater velocity. This work included installing a corehole² out near the leading edge of the groundwater plume (RD-39C), installing two coreholes (C-10 and C-11) to assess the nature and extent of source zone, and deepening an existing well (RD-31) through coring to evaluate the groundwater flow system. An additional source-zone corehole, RD-35C, was later added to the coring program. These locations are shown on Figure A-1. The three coreholes (C-10, C-11 and RD-35C) and the deepening of RD-31, along with data from two previously installed coreholes (RD-35B and C-1), provide information about the nature and extent of VOC impacts at or near a source zone. This “source zone transect” will serve as a starting point for demonstrating the retardation effect of matrix diffusion on solute plumes at the SSFL.

A Phase 2 Site Conceptual Model Work Plan (MWH, 2007) has been submitted to DTSC and is pending review and comment/approval. The Phase 2 SCM work plan focused on the third element of the site conceptual model with the objective of collecting field data that can be used to evaluate the magnitude of contaminant attenuation within a groundwater plume due to various

² Although the scope discussed here refers to corehole installation, the data yielded at these locations is from the collection and analysis of numerous rock core samples, which provide information on the nature and extent of VOC distribution in the bedrock matrix.

physical and chemical processes. Contaminant retardation is one of the key remaining elements of the groundwater site conceptual model that requires field data for validation. The average linear groundwater velocity is estimated to be on the order of hundreds to thousands of feet per year due to rapid flow through the fracture network in the bedrock. Alternately, the rate of chemical transport at or near the plume front is estimated to be on the order of a few feet per year (based on two-dimensional transport model runs), reflecting retardation factors between 100 to about 300. The northeast investigation area was identified as the best location³ at the SSFL for collecting the necessary data to validate the attenuation aspects of the groundwater SCM using a corehole transect.

The general approach to collecting the data necessary to validate the plume attenuation aspect of the SCM as described in the Phase 2 SCM Work Plan was to install a transect consisting of four coreholes across the width of a groundwater plume in the northeast area. The drilling and coring locations proposed for the four coreholes (C-12 through C-15) are shown in plan view on Figure A-2.

A.2 THREE-DIMENSIONAL GROUNDWATER FLOW MODEL

The investigation work plan submitted in 2000 (Montgomery Watson, 2000b) was developed from the SCM using the data quality objectives approach (Environmental Protection Agency, 1994) for identifying decision questions and data needs. Eight decision questions were identified during the development of the Phase 1 work plan and remain key components of the overall groundwater characterization program at the SSFL.

A three-dimensional groundwater flow model (3-D flow model) for the SSFL has been under development concurrent with the acquisition of data aimed at validating the groundwater site

³ A number of site features were considered during the transect siting process. Such features included: potential hydraulic effects on chemical transport directions associated with historical groundwater extraction; topography and access; geology, including stratigraphy and structure; and knowledge of source input locations and the occurrence and distribution of chemicals in surficial media. When these factors were considered, the northeast area was chosen as the best location at the SSFL relative to all other areas of chemical-impacted groundwater to evaluate the attenuation aspects of the SCM by drilling a transect.

conceptual model. Development of the 3-D flow model is being pursued as a means of addressing the following decision question:

“Has the three-dimensional flow of groundwater been defined such that the direction of chemical solute transport can be predicted?”

Certain concepts contained within the 3-D flow model require additional data to support their inclusion and the work needed to do so is also described in this work plan.

A.3 REFERENCES

Department of Toxic Substances Control (DTSC), 2000. Letter from Gerard Abrams to Arthur Lenox, Approval of Additional Field Investigations, Chatsworth Formation Operable Unit. September 18.

DTSC, 2005. Letter from Gerard Abrams to Dave Dassler, Approval of Northeast Area Chatsworth Formation Work Plan, Phase II, November 10.

Environmental Protection Agency (EPA), 1994. *Guidance for the Data Quality Objectives Process*, EPA QA/G-4. September.

Montgomery Watson, 2000a. *Technical Memorandum, Conceptual Site Model Movement of TCE in the Chatsworth Formation*, April.

Montgomery Watson, 2000b. *Work Plan for Additional Field Investigations*, Chatsworth Formation Operable Unit. Revision 1. October.

MWH, 2004. *Report of Results, Phase 1 of Northeast Investigation Area Groundwater Characterization*, September.

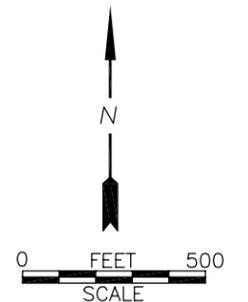
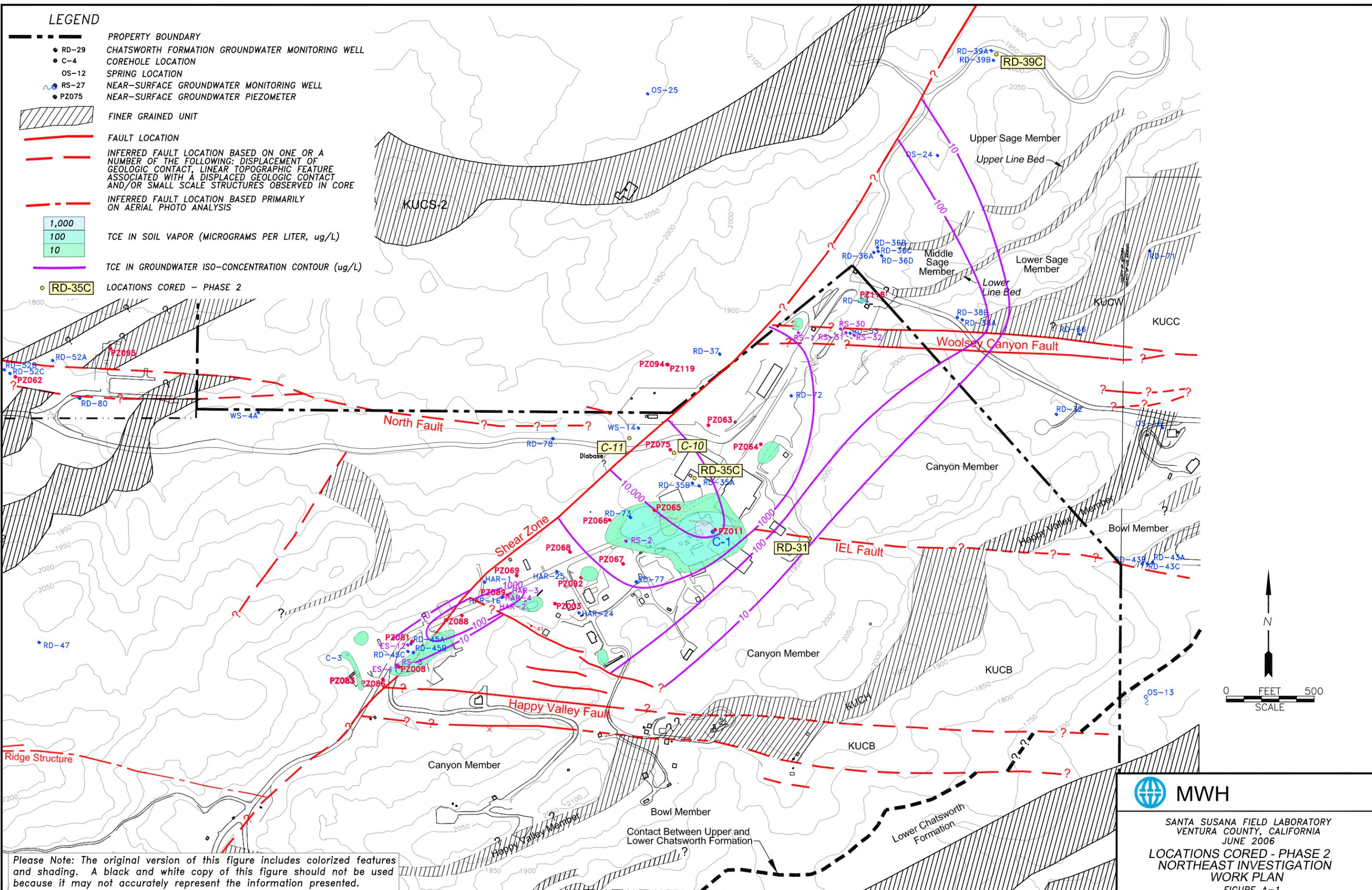
MWH, 2005. *Northeast Area Chatsworth Formation Work Plan, Phase 2*, Santa Susana Field Laboratory, Ventura County, California, October.

MWH, 2007. *Work Plan, Phase 2 Groundwater Site Conceptual Model*, Santa Susana Field Laboratory, Ventura County, California, April.

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 JOB No. ---

LEGEND

- PROPERTY BOUNDARY
- RD-29 CHATSWORTH FORMATION GROUNDWATER MONITORING WELL
- C-4 COREHOLE LOCATION
- OS-12 SPRING LOCATION
- RS-27 NEAR-SURFACE GROUNDWATER MONITORING WELL
- PZ075 NEAR-SURFACE GROUNDWATER PIEZOMETER
- ▨ FINER GRAINED UNIT
- FAULT LOCATION
- - - INFERRED FAULT LOCATION BASED ON ONE OR A NUMBER OF THE FOLLOWING: DISPLACEMENT OF GEOLOGIC CONTACT, LINEAR TOPOGRAPHIC FEATURE ASSOCIATED WITH A DISPLACED GEOLOGIC CONTACT AND/OR SMALL SCALE STRUCTURES OBSERVED IN CORE
- - - INFERRED FAULT LOCATION BASED PRIMARILY ON AERIAL PHOTO ANALYSIS
- 1,000
100
10 TCE IN SOIL VAPOR (MICROGRAMS PER LITER, ug/L)
- 10,000
1,000
100
10 TCE IN GROUNDWATER ISO-CONCENTRATION CONTOUR (ug/L)
- RD-35C LOCATIONS CORED - PHASE 2

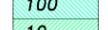
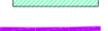
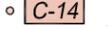


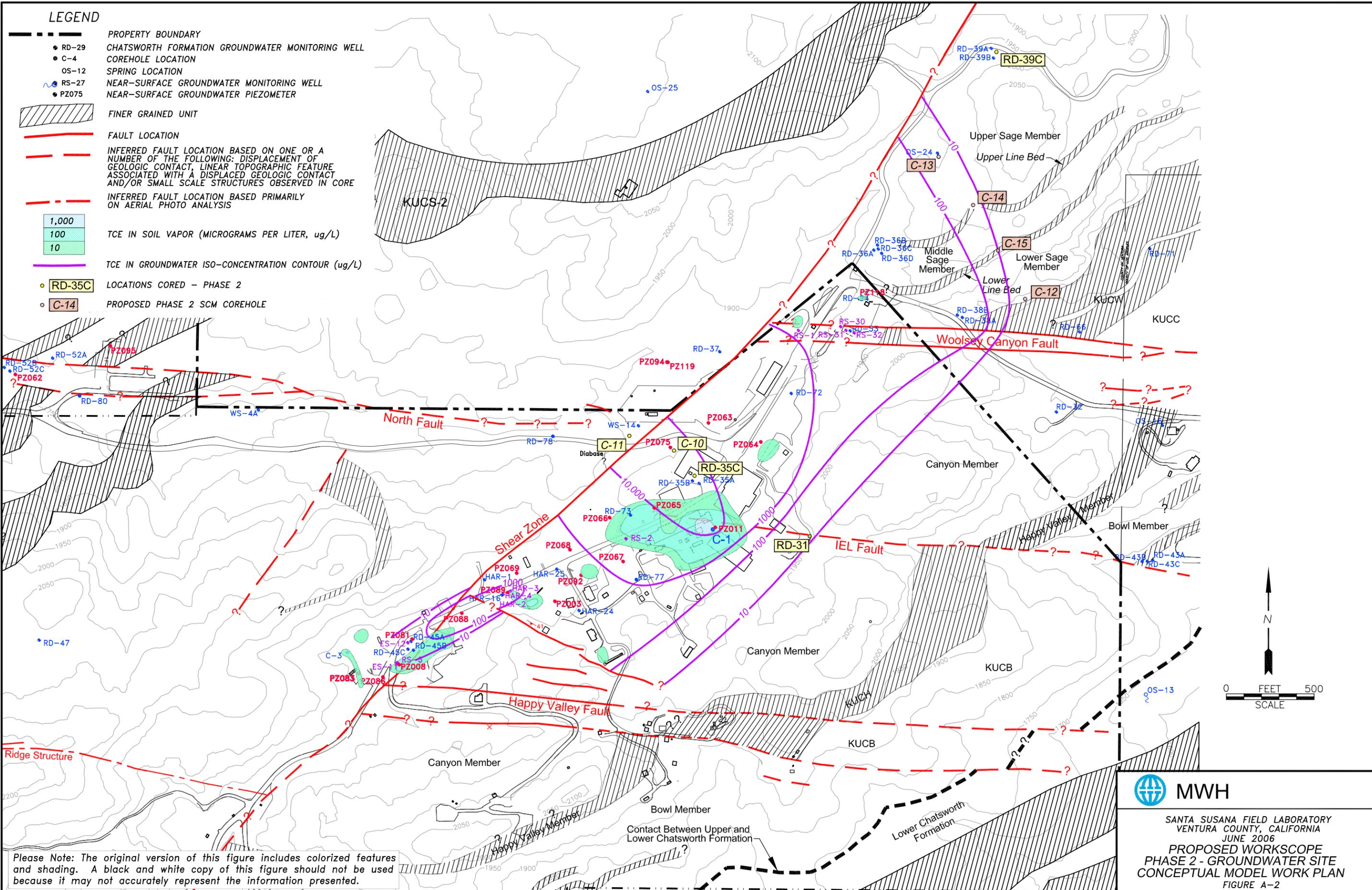
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 VENTURA COUNTY, CALIFORNIA
 JUNE 2006
LOCATIONS CORED - PHASE 2
NORTHEAST INVESTIGATION
WORK PLAN
 FIGURE A-1

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LEGEND

-  PROPERTY BOUNDARY
-  RD-29 CHATSWORTH FORMATION GROUNDWATER MONITORING WELL
-  C-4 COREHOLE LOCATION
-  OS-12 SPRING LOCATION
-  RS-27 NEAR-SURFACE GROUNDWATER MONITORING WELL
-  PZ075 NEAR-SURFACE GROUNDWATER PIEZOMETER
-  FINER GRAINED UNIT
-  FAULT LOCATION
-  INFERRED FAULT LOCATION BASED ON ONE OR A NUMBER OF THE FOLLOWING: DISPLACEMENT OF GEOLOGIC CONTACT, LINEAR TOPOGRAPHIC FEATURE ASSOCIATED WITH A DISPLACED GEOLOGIC CONTACT AND/OR SMALL SCALE STRUCTURES OBSERVED IN CORE
-  INFERRED FAULT LOCATION BASED PRIMARILY ON AERIAL PHOTO ANALYSIS
-  1,000
-  100
-  10
-  TCE IN GROUNDWATER ISO-CONCENTRATION CONTOUR (ug/L)
-  LOCATIONS CORED - PHASE 2
-  PROPOSED PHASE 2 SCM COREHOLE



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PROPOSED WORKSCOPE
PHASE 2 - GROUNDWATER SITE
CONCEPTUAL MODEL WORK PLAN
 FIGURE A-2

APPENDIX B

GROUNDWATER SITE CONCEPTUAL MODEL OVERVIEW AND FUNDAMENTAL ELEMENTS OF GROUNDWATER FLOW SYSTEM AS EMBODIED IN THE THREE-DIMENSIONAL FLOW MODEL

APPENDIX B

GROUNDWATER SITE CONCEPTUAL MODEL OVERVIEW AND FUNDAMENTAL ELEMENTS OF GROUNDWATER FLOW SYSTEM AS EMBODIED IN THE THREE-DIMENSIONAL FLOW MODEL

B.1 OVERVIEW OF UPDATED GROUNDWATER SITE CONCEPTUAL MODEL FOR CONTAMINANT TRANSPORT

Much of the data that have been collected, reduced and analyzed since the groundwater site conceptual model (SCM) was last published (Montgomery Watson, 2000) have been further evaluated and incorporated into the groundwater SCM for contaminant transport. As such, the groundwater SCM for contaminant transport now encompasses the following key elements:

1. Groundwater recharge is a small percent of the mean annual precipitation.
2. The fracture network is a systematic arrangement of bedding parallel fractures and steeply dipping joints.
3. The fracture network is well interconnected hydraulically, both horizontally and vertically.
4. The bulk hydraulic conductivity (K_b) is low to moderate.
5. Faults and shear zones have low to moderate large-scale transmissivity across and along.
6. Effective fracture apertures for groundwater flow are small to moderate.
7. The rock matrix porosity represented by interconnected pores is large and the bulk fracture porosity is extremely small.
8. Large trichloroethene (TCE) mass occurring as dissolved and sorbed phases exists in the vicinity of TCE dense non-aqueous phase liquid (DNAPL) input locations.
9. All soluble chemicals and radionuclides diffuse into and out of the porous rock matrix.
10. The chlorinated solvent contamination was initially caused by DNAPL penetration below the water table, but the DNAPL has since been converted to dissolved and sorbed mass now residing in the rock matrix and therefore contaminant migration by DNAPL flow no longer occurs.
11. Contaminant plumes are orderly and monitorable.
12. The rock matrix composition includes abundant reactive minerals and appreciable organic matter.

13. Degradation processes have caused complete dechlorination of part of the TCE mass and degradation likely influences other contaminants.
14. Much of the groundwater originating from within the Santa Susana Field Laboratory (SSFL) property discharges at springs and phreatophytes occurring on the mountain slopes.
15. The contaminant plume fronts are strongly retarded relative to the rapid groundwater velocity in the fracture network.
16. All of the contaminant plumes are being naturally attenuated due to a combination of processes.

B.2 OVERVIEW OF ELEMENTS FUNDAMENTAL TO SSFL GROUNDWATER FLOW SYSTEM

The geologic setting of the SSFL consists of a faulted sequence of sandstones with periodic interbeds of finer-grained siltstones and shales. The geologic and topographic settings complicate the interpretation of the groundwater flow system. A three-dimensional groundwater flow model is currently being developed as a tool to aid in understanding the three-dimensional flow of groundwater from the SSFL. The groundwater flow system incorporates the following fundamental elements:

1. Recharge of the groundwater at and around the SSFL is spatially variable due to factors related to slope, vegetation, topography, and the presence of varying thicknesses of alluvium, colluvium and fill. Recharge averages about 6 percent of the annual precipitation that falls at the SSFL. The average annual precipitation is about 19 inches per year.
2. Springs, seeps and phreatophyte vegetation are present on the hill slopes surrounding the SSFL and are potential outlets for groundwater originating beneath the SSFL.
3. At and just below an unconfined water table, water is initially rapidly released from storage in the interconnected fracture network in response to a negative pressure hydraulic stimulus. Once this water is removed from the fracture network, water is then slowly released from the low permeability bedrock matrix.
4. The bulk hydraulic conductivity decreases to the matrix hydraulic conductivity at some depth due to fractures closing because of increasing lithostatic loads.
5. The base of the active freshwater flow system is at sea level.

6. The hydraulic conductivity parallel to bedding is between 20 and 100 times greater than the hydraulic conductivity perpendicular to bedding.
7. When groundwater has been extracted from the SSFL, it was discharged after treatment onto the ground and flowed to unlined drainages where much of it reentered the subsurface.

B.3 REFERENCES

Montgomery Watson, 2000. *Technical Memorandum, Conceptual Site Model Movement of TCE in the Chatsworth Formation*, April.

APPENDIX C

**FLUTE™ HYDRAULIC CONDUCTIVITY PROFILING AND ASSOCIATED DATA
ANALYSIS METHODS**

FLUTE™

Flexible Liner Underground Technologies, Ltd. L.C.

For a medley of innovative designs

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Comparison of the FLUTE™ Hydraulic Conductivity Profiling results with Straddle Packer measurements

By

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Presentation at Geologic Society of America conference in Philadelphia, PA
October 25, 2006

Comparison of the FLUTE Hydraulic Conductivity Profiling results with Straddle Packer measurements

Abstract

The FLUTE technique for location and mapping of the significant flow paths in a borehole using a flexible everting liner has been reported earlier in other papers. The method allows one to map the significant flow paths in a borehole in 1-4 hrs. relatively independent of the borehole depth. The location of each flow path (e.g., fracture, or bedding plane) and the explicit measurement of the flow rate in each path in such a short time with the everting liner (10-15% of the typical time for discrete straddle packer testing of the entire hole) have obvious utility. However, the question is whether the FLUTE measurements are correct, and how do they compare to straddle packer measurements of the same hole. This paper describes the techniques that have been developed to assess the FLUTE method and to make a careful comparison of FLUTE results with the packer tests of the same borehole. The FLUTE measurements usually provide much more spatial detail than discrete packer tests and therefore the FLUTE measurements were integrated over the same vertical interval as each packer test to provide the equivalent average packer value. The differences are obvious. The next step was to use the packer conductivity profile to calculate a synthetic liner vertical velocity in the borehole. The packer data provided a substantially higher synthetic liner velocity than the FLUTE liner measured velocity. A test of the comparison was performed by integrating the FLUTE data to provide an equivalent set of packer results, and then using the integrated FLUTE results to develop a synthetic liner velocity for comparison with the actual liner velocity measured with hole depth. The comparison was nearly perfect, suggesting that there are no errors in the comparison methods used. The conclusion is that the straddle packer testing provided excessively high conductivities in the lower regions of the borehole due to bypass of the packers. There is no bypass in the liner measurement method. The everting liner measurement method seems to provide more accurate results than the packer testing for highly fractured holes. However, the straddle packer tests can measure to lower conductivities in the low flow regions of the borehole than are practical for the everting liner method. The low cost of the everting liner measurement method and the data quality should provide a significant advantage to the characterization of the flow paths in fractured rock sites for design of remediation procedures and for assessment of contaminant transport. Another advantage is that once the FLUTE measurement is finished, cross contamination is prevented by the sealing liner which is left in place.

I. Introduction

FLUTE has developed a technique for locating all significant flowing fractures in a borehole and measuring the flow rate out of each fracture or permeable interval intersected by the borehole. The measurement is performed while installing a flexible liner into the borehole. The liner is often left in place to seal the borehole once the measurement is complete. This paper describes briefly how the FLUTE measurement is performed and how the results compare to a traditional method of flow path measurement, namely the straddle packer technique. It is assumed that the reader is familiar with the performance of straddle packer measurements (Lapcevic, 1999). The

FLUTE technique is called the FLUTE Hydraulic Conductivity Profiling Method (pat. no. 6910374 B2) or more briefly, the FLUTE profiler. The comparison of the two methods is shown for a University of Waterloo investigation site at Guelph, Ontario.

II. The FLUTE Profiler method

The measurement is performed by the eversion of a FLUTE blank liner into a borehole (Fig. 1). The liner is deployed from a reel adjacent to the wellhead. The liner is driven down the hole by the pressure of the water added to the interior of the liner at the wellhead. The liner is inside-out on the reel and everts (the opposite of inverts) as the liner is fed down the hole. The everting liner drives the water from the hole like a perfectly fitting piston. The water is driven from the hole at a rate dependent upon the transmissivity of the borehole below the end of the liner, and in proportion to the driving pressure inside the liner. The driving pressure is simply the excess head inside the liner relative to the water table in the formation. As the liner descends, it sequentially seals the flow paths intersecting the borehole from the top down. It is noteworthy that the driving pressure in the borehole beneath the liner is uniform throughout the hole and there is ample time for the steady state condition to develop as the liner descends. The drawing in Fig. 2 shows the everting liner as it passes a flow path (a fracture as drawn, but it can be a permeable bed as well). The velocity of the liner at any point in the borehole depends upon the flow paths remaining below the descending liner. Therefore the liner starts with a high velocity but drops in velocity each time that a flow path is sealed.

The measurement is performed by recording the liner position with time, the tension on the liner, and the excess head driving the liner. The tension on the liner at the wellhead is controlled to be constant and the actual tension on the liner is also monitored and recorded. The excess head is also

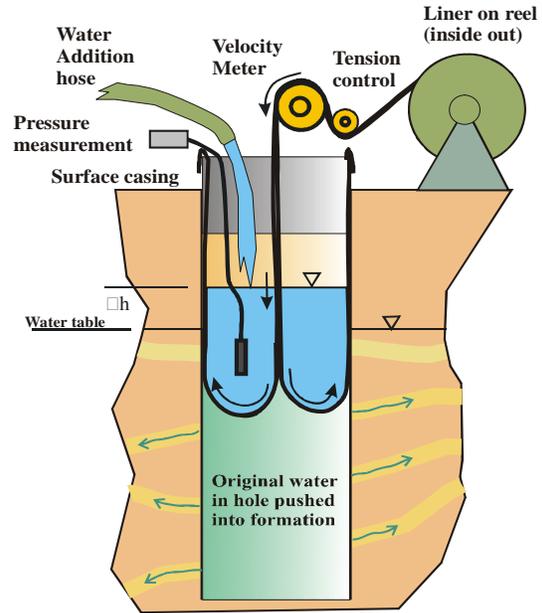
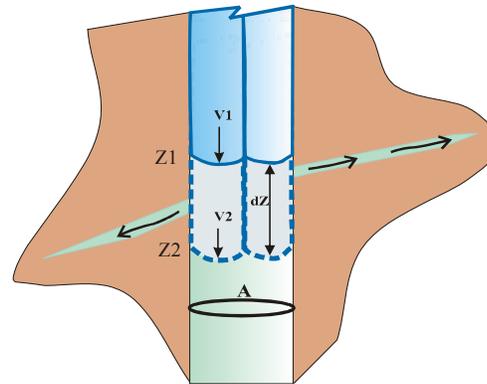


Fig. 1. Blank liner installation with measurements to identify open fractures



Flow rate into the fracture, $Q = A(V_1 - V_2)$, where $V_1 > V_2$
 Transmissivity over dZ is: $C \times dZ = \text{fctn}(A, dV, dZ, \dots)$

Fig. 2. The transmissivity over the interval dz is calculated from the liner depths and velocity change between those depths.

controlled to be relatively constant. From the recorded data, the liner velocity is calculated and divided by the driving pressure to obtain the velocity per unit driving pressure. This normalized velocity is simply called the “velocity” throughout this paper.

The typical result is the graph of monotonically decreasing velocity versus depth with the typical features shown in Fig. 3. As each significant flow path is sealed by the descending liner the change in velocity indicates the location of the flow path, and the magnitude of the velocity change is directly proportional to

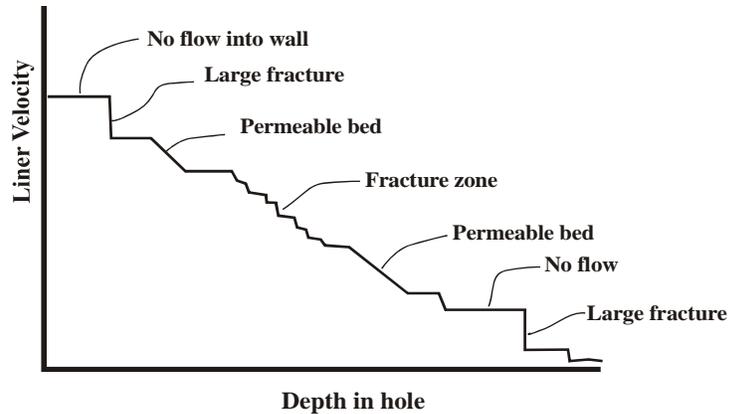


Fig. 3. Velocity profile shows the nature of the flow paths

the flow into that path before it was sealed. As shown in Fig. 2, the velocity change, dv , times the borehole cross section, A , is the flow rate into the flow path before it is sealed. The model assumes that the flow into the hole wall occurs uniformly over the interval, dz , which is traversed by the liner in moving from the depth z_i to z_{i+1} . Just as a straddle packer measurement is over an interval dz , the flow rate into that interval is used to calculate a transmissivity of the hole wall over the interval dz . The same steady state assumption is used to calculate the conductivity of that interval of the hole wall as is used for packer measurements. The liner data is recorded every two seconds, typically, so that the liner traverses an interval of the hole wall every two seconds depending upon the liner velocity. The result of the FLUTE measurement is to calculate the transmissivity/conductivity of each interval of the hole wall traversed in every time interval. This produces a very high spatial resolution measurement of the vertical borehole transmissivity. For those sections of the borehole with very little transmissivity, the liner velocity change is essentially zero.

III. The straddle packer measurements at Guelph, Ontario hole no. MW-24

The typical constant-head injection straddle packer system (Lapcevic, et al, 1999) was used to perform ~63 measurements in a 4 inch diameter by 340 ft deep hole over adjacent 5 ft intervals. The technique used a constant driving head supplied by tall tanks of several diameters and measured the flow rate into each straddled interval after achieving a nominal steady state flow rate. The measured flow rate was used to calculate the conductivity of each straddled interval. Figure 4 is a schematic of the packer measurement system used. It was developed for the Canadian Center for Inland Waters and used by the University of Waterloo at Guelph.

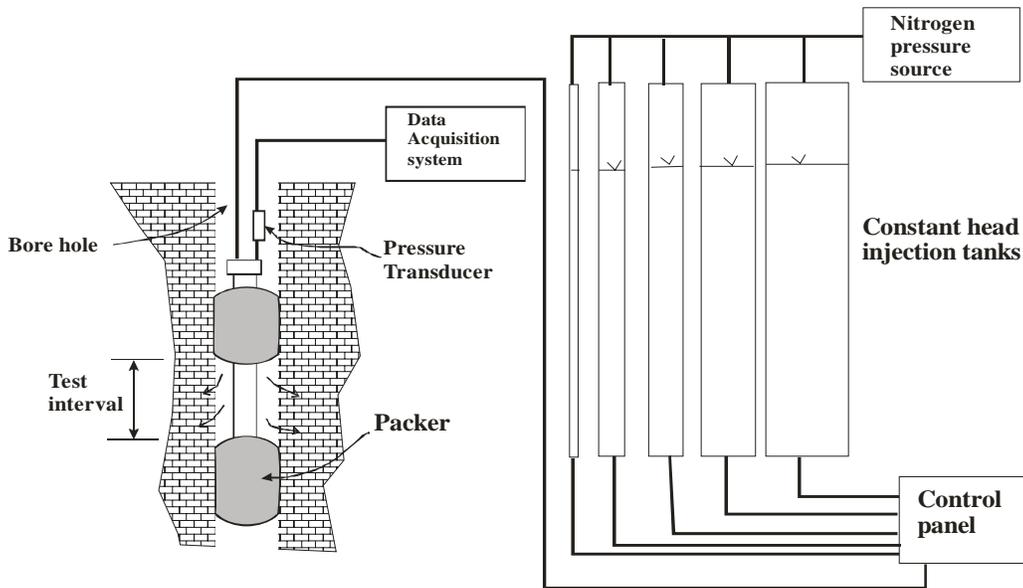


Fig. 4. Test system used at Guelph site for packer measurements

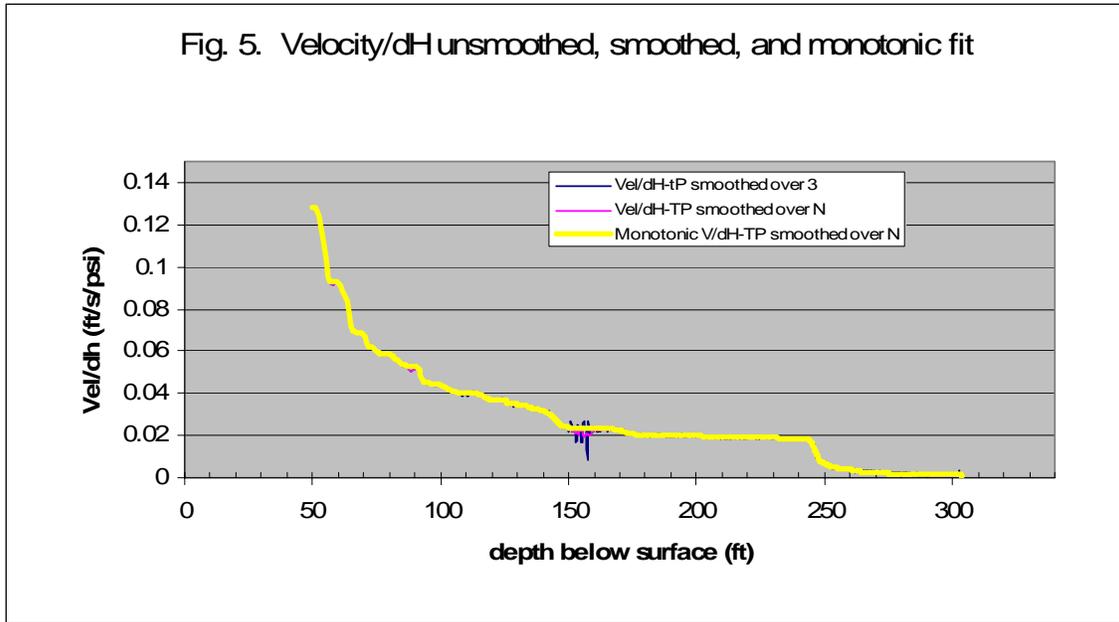
IV. The geologic setting

Three holes were profiled with the FLUTE technique, MW-24, 25, and 376-6 at the Guelph site. The total transmissivity of hole no. 24 was $5 \text{ cm}^2/\text{s}$ with an initial flow rate of 44 gal/min. The transmissivity of hole MW-25 was $9.4 \text{ cm}^2/\text{s}$ with 64 gal/min and MW-376-6 was $6.3 \text{ cm}^2/\text{s}$ with flow rate of 43 gal/min. The average conductivities of the three holes were $6\text{e-}04$, $1.5\text{e-}03$, and $7.4\text{e-}04 \text{ cm/s}$ respectively. Both MW-25 and 367-6 had high flow out of the bottom portion of the hole and therefore high liner velocities throughout most of the hole.

The geologic medium is a sequence of dolostone, limestone, and shale.

V. The comparison of the FLUTE results to packer results

The comparison of Profiler and Straddle Packers results for MW-24 is described here in detail. The straddle packer tests for each of the three wells were performed in 7-10 days by 1-2 people. MW-24 was packer tested in a total of 8 days with 3-11 intervals per day (at 10 intervals per day, it would require 6 days). The FLUTE profile of MW-24 was performed in ~2 hrs. by two people. The liner was then removed and reinstalled a second time on the same day, in the same time, with the same people, for a test of the reproducibility of the results. Most of the comparison hereafter is with the second profiling run. The results for both installations will be shown.



The FLUTE liner velocity from MW-24 is shown in Fig. 5. The raw velocity (“smoothed over 3”) is calculated over two adjacent intervals centered on the midpoint. It is plotted as the black curve. The velocity data is then smoothed over a variable number of points depending upon the liner velocity (fewer points for a high velocity and more points for a lower velocity). The resolution is better at the lower velocity in the lower portion of the hole, but the resolution based on the smoothing function ranges from 0.35 to 0.1 ft. for this data set. Figure 5 shows the raw data (black curve), the smoothed data (pink curve), and the monotonic fit to the smoothed data (yellow curve). The comparison of the black curve (raw velocity) to the pink curve (smoothed) shows very little effect of the smoothing procedure.

The monotonic fit of the data is done to ignore temporary drops in the liner velocity. Figure 6 shows the liner passing through an enlargement of the borehole. As the liner expands into the enlargement, the velocity drops due to the larger cross section of the liner driving the water from the hole. However, as the liner passes into the normal borehole, the liner cross section decreases to its area before entering the enlargement. That decrease in liner cross section as it exits the enlarged portion of hole causes a liner velocity increase.

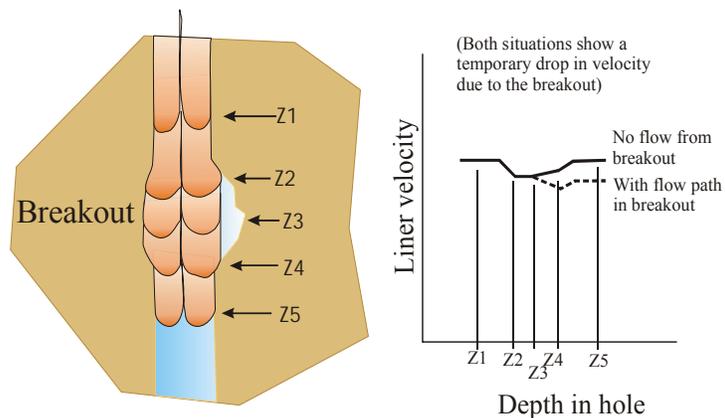


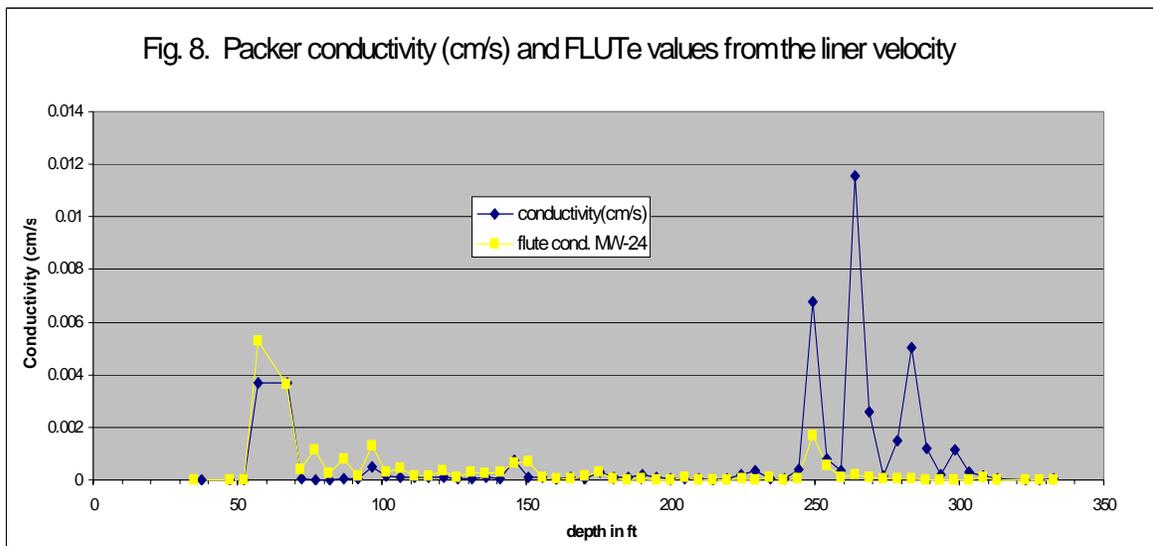
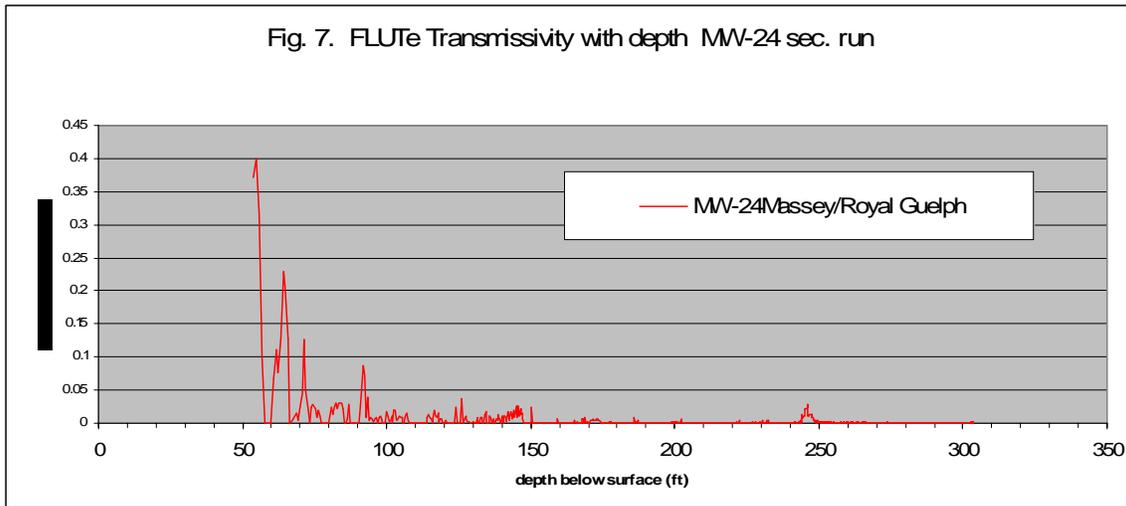
Fig. 6. Effect of liner moving thru breakout in borehole

The decrease in liner cross section as it exits the enlarged portion of hole causes a liner velocity increase. The monotonic fit therefore ignores any temporary drops in liner velocity for any reason (e.g., brief increase in liner tension coming off the reel). The yellow monotonic fit is very close to the smoothed data except at ~150 ft where the end

of the liner and associated fittings passed through the rollers of the machine and caused some brief fluctuations.

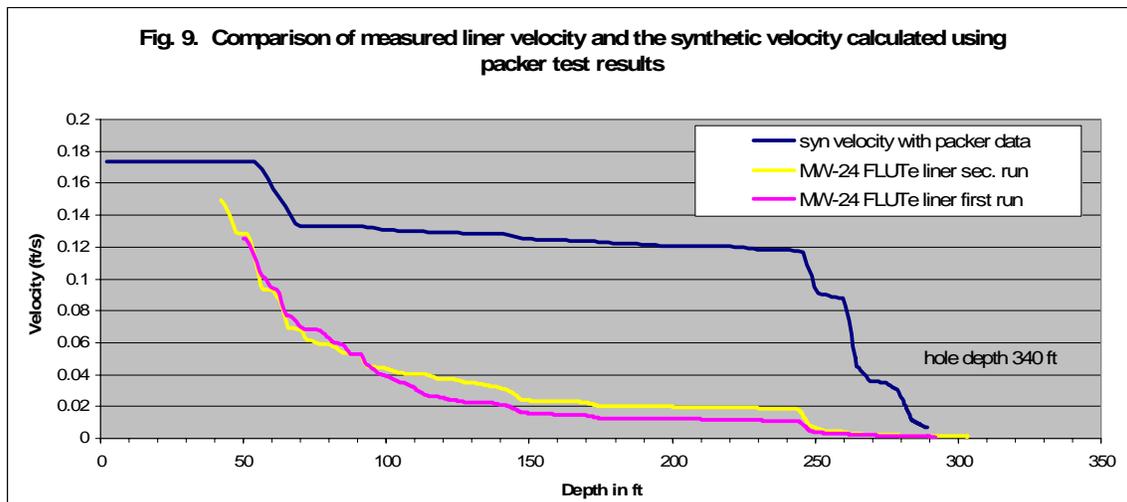
From the velocity data of Fig. 5, the transmissivity of the borehole is calculated and is shown in Fig. 7. This very detailed transmissivity result is difficult to compare to packer data measured in 5 ft intervals. The FLUTE data was therefore integrated over the same 5 ft intervals as the packer tests to obtain the conductivity for the larger averaging intervals.

Figure 8 shows the packer conductivity results and the FLUTE results for the 5 ft intervals. The agreement is excellent except for the three very large packer results below 245 ft. Which is the correct result?



VI. The synthetic velocity comparison

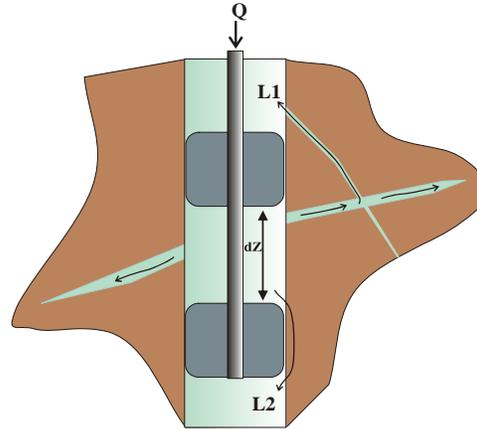
As a test of the packer result, a spreadsheet was developed which calculates the flow rate out of each packer interval for a constant driving pressure in the borehole, similar to the constant driving pressure for water flow out of the hole driven by the liner. For a discrete time interval, the flow rate out of the hole was summed for that time interval. The distance traversed by a hypothetical flexible liner is calculated by dividing the total flow in that time interval by the borehole cross section. In the next time step, that portion of the borehole flow that would be covered by the descending hypothetical liner is set to zero. The resulting flow is summed, and so on. This calculation produces the depth versus time that a hypothetical liner would descend in a hole with the conductivity profile determined by the packer measurements. This synthetic liner velocity is compared to the FLUTE liner velocity in Fig. 9. The first liner velocity of the two liner measurements is also shown. The two liner velocity curves are very near each other (the second run was slightly faster probably because of the development of the well as the first liner was withdrawn.) However the synthetic velocity developed from the packer conductivities is much higher until below 290 ft. Thereafter, the synthetic velocity and FLUTE liner velocity converge in the relatively tight lower portion of the hole.



It seems very unlikely that the two liner conductivities distributions would reproduce the packer distribution in most of the hole, but not the lower portion where the packer measurements are very high, and the liner has its best resolution. The liner velocity is a very simple displacement of the water from the hole. We believe that the packer data is probably in error due to the effect of bypass of the packer. Figure 10 is a drawing of the two possible flow paths that could add to the measured flow, Q , during a packer test. The first path, L1, is via a fracture that connects with a straddled fracture to the hole above or below the packers. The second path, L2, is via a permeable matrix that allows the packer interval to connect to the open hole above or below the packers.

These two kinds of bypass paths do not exist with the liner method. The top part of the hole is sealed by the liner and the rest is completely open. There are no bypass terms in the measured flow into the hole wall.

Only one hole volume of water is displaced by the liner. The liner measurement is continuous in time and space. There is therefore no concern about overlapping intervals or missed sections of the hole. Only flow paths that connect to distant regions are measured by the liner since the entire hole beneath the liner is at the same pressure. These generalizations are not the case for packer tests.

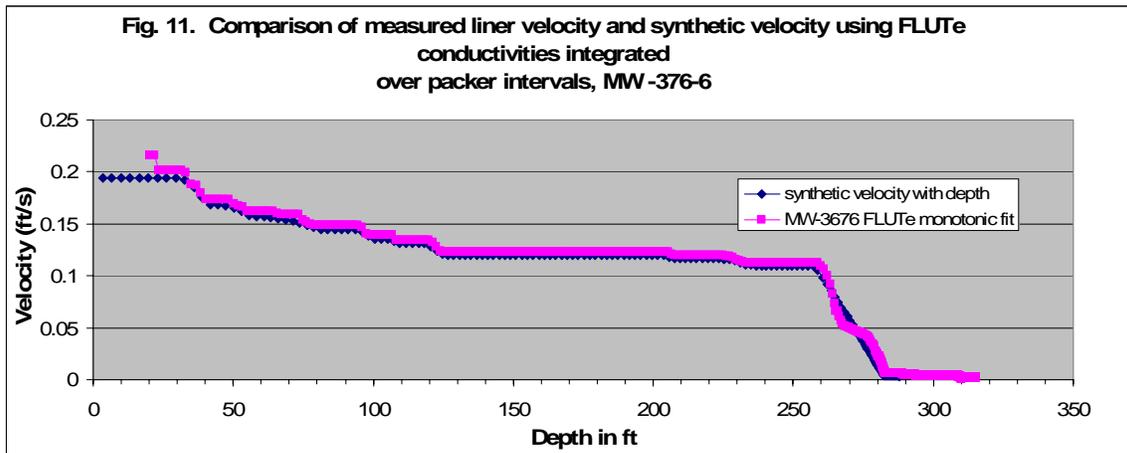


Flow rate into the fracture is $Q-L1-L2$, where $L1$ and $L2$ are flow paths past the packer.

Fig. 10. Potential flow past packer

VII. A test of the synthetic velocity and integration methods

Given the real possibility that there is an arithmetic error in either the integration of the FLUTE transmissivity profile over the packer intervals, or in the synthetic velocity calculation, the two calculations were tested by using the FLUTE packer interval conductivity values in the synthetic calculation spreadsheet to see if the synthetic calculation would reproduce the FLUTE liner velocity. Figure 11 shows the result for hole no. 367-6. The velocity curves are essentially identical with the obvious effect of loss of detail when the FLUTE data is integrated over the large packer intervals. This seems to support the general conclusion upon examination of Figs. 9 and 11 that the packer results can not produce the spatial resolution available in the FLUTE liner measurement.



It is not obvious from the geophysical data and borehole video why the packers may not have been well placed for the two high peaks at 265 and 285 ft except that region (260-320 ft) is much more coarse-grained than the rest of the hole (matrix or fracture bypass?).

The other two holes had higher transmissivity rates and showed similar zones of probable packer bypass.

VIII. Discussion and conclusions

The first concern is whether the new FLUTE method gives the correct results. We believe that the results are not only correct, but provide better spatial detail than the packer measurements in these boreholes. It seems important that the packer measurement is susceptible to bypass and therefore may produce erroneous results in regions of porous matrix or highly fractured media.

Because of the concern about bypass of the packers, pressure measurements are essential above and below the packers to possibly detect such leakage. However, the pressure measurement does not allow determination of the amount of leakage. The use of guard packers above and below the straddle packers makes pressure monitoring for leakage much more sensitive. However, such bypass is not a concern with the liner method.

The second major comparison is the time and labor required to produce the FLUTE results versus the packer results. The FLUTE liner installation took about 2 hrs. The packer tests took 7-11 days with much more equipment in the field. However, there was no need to perform the packer measurements quickly. Other similar holes have been measured in 4 days with two people. Even then, the FLUTE measurement was done in less than 10% of the time.

An advantage of the straddle packer method is that regions of very low conductivity can be measured with the straddle packer. The FLUTE liner can not resolve the difference between very low conductivity and zero flow zones. FLUTE does have a multi level sampling system called a *Water FLUTE™* which does allow the verification of very low flow zones or aquitards. Using the Profiler data, the multi level sampling intervals are easily selected.

A potential disadvantage of the liner method is that the topmost portion of the hole below the water table may not be well measured if the transition to steady state velocity has not been completed before the liner exits the casing. Abrupt changes are obvious even if imposed on the transient velocity, but a permeable zone may not be obvious until the transient has decayed away. The transient zone may be 5-50 ft long depending upon the liner initial velocity.

Finally, when the FLUTE profiling measurement is complete, the blank liner is usually left in place to seal the entire hole against cross contamination. That is not an option with straddle packers.

The synthetic velocity calculation does not introduce any new information beyond a direct comparison of packer versus liner conductivity measurements, but it does make the judgment of the data easier. In this case, the liner measurement, performed twice, is not likely to be in error by 600% in the flow rate out of the hole. A simple pumping test would be useful to confirm the liner velocity.

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Biographical Sketches –

Carl Keller has Bachelors and Masters degrees in math, physics, and engineering science from Valparaiso University and the Rensselaer Polytechnic Institute. He was employed with the U.S. Department of Energy and Department of Defense from 1966 to 1984 as an underground nuclear test containment scientist, developing a variety of models for multi-phase flow in the earth. In 1989 he developed the first everting flexible liner system for collection of pore water samples. He holds 12 patents concerning vadose zone and groundwater monitoring and other flexible liner methods. He established Flexible Liner Underground Technologies in 1996 where he is owner and chief scientist / engineer. Carl Keller is principal scientist at Flexible Liner Underground Technologies, LLC, 6 Easy St., Santa Fe, NM, 87506 (www.flut.com).

John A. Cherry has geological engineering degrees from the Universities of Saskatchewan and California, Berkeley and a Ph.D. in hydrogeology from the University of Illinois and has been a faculty member in the Department of Earth Sciences at the University of Waterloo since 1971. Since 1996, he has held the NSERC-GE Research Chair in contaminant hydrogeology. His research is focused on field studies of contaminant behavior in groundwater.

Beth L. Parker has a Bachelors degree in environmental science/ economics from Allegheny College, a Masters degree in environmental engineering from Duke University and a Ph.D. in hydrogeology from the University of Waterloo. She joined the faculty of the Earth Sciences Department at the University of Waterloo in 1996 where she is currently a Research Associate Professor. Her research involves field studies of transport, fate and remediation of chlorinated solvents in diverse hydrogeologic environments including fractured rock, clayey aquitards and sandy aquifers.

APPENDIX D

CORE SAMPLE SELECTION, TESTING AND ANALYSIS METHODS, FRACTURE CLOSURE DUE TO LITHOSTATIC LOADS

APPENDIX D

**FRACTURE CLOSURE WITH DEPTH IN SEDIMENTARY ROCKS: APPLICATION
TO THE CHATSWORTH FORMATION, SSFL
TEST METHODS**

**SUBMITTED TO
THE BOEING COMPANY**

BY

**TARIQ CHEEMA
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OCTOBER, 2006

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D.1 STUDY OBJECTIVE

The purpose of this work is to develop quantitative relationships for the decreases in fracture aperture and hydraulic conductivity with depth at the SSFL caused by the weight of the overlying rock. Although there is considerable published literature, this literature is written almost exclusively by geomechanics or petroleum engineers for purposes that do not include a hydrogeologic context. Furthermore, because fracture closure under high stress is a function of rock type, earlier work done on igneous and metamorphic rocks is of no direct use for the sandstone and shale of the Chatsworth Formation at the SSFL. This study includes conducting a comprehensive search of the scientific literature for available fracture closure models, evaluating their suitability for application to the Chatsworth formation, and developing methodologies for performing tests to collect the site-specific data required to determine the fracture closure with depth relationship using the selected model.

D.2 EVALUATION OF AVAILABLE MODELS

The models of fracture closure under normal stress that were reviewed included:

- Goodman (1974)
- Lawrence Berkeley Laboratory (Iwai, 1976; Witherspoon et al., 1980; Tsang and Witherspoon, 1981)
- Raven and Gale (1985)
- Swan (1981, 1983)
- Barton-Bandis (Bandis, 1980; Bandis et al., 1983; Barton et al., 1985; Barton and Bakhtar, 1987)

In evaluating the models and their site-specific data requirements, the following criteria were considered as recommended by Grasseli (2001):

- Size of the sample that can be evaluated
- Measurement speed
- Precision
- Repeatability
- Ease of measurement

- Ease of analyzing the data
- Suitability for use in-situ

Of all the models reviewed above, the Barton-Bandis model was determined to be the only one that is both applicable to the Chatsworth Formation, and requires only site specific data that are practical to obtain. This model requires simple index tests to be performed on intact and fractured pieces of rock core to determine the fracture closure at high normal stresses. Malama and Kulatilake (2003) consider that the Barton-Bandis model provides a better fit to the experimental data across the whole range of stress and closure values. Similarly, Kadiri (2006) found a good correlation between the in-situ hydromechanical behavior of calcareous rock mass and the predictions of the Barton-Bandis model.

D.3 SITE-SPECIFIC DATA REQUIREMENTS FOR THE BARTON-BANDIS MODEL

The Barton-Bandis model requires site-specific data that can be acquired by performing simple tests on intact and fractured pieces of rock core. These data requirements include the following:

- Compressive strength (δc)
- Joint wall compressive strength (JCS)
- Joint roughness coefficient (JRC)
- Initial mechanical fracture aperture (E_o)

D.4 TEST METHODOLOGIES

Rock core samples from coreholes C-11, RD-35C and RD-39C were selected for testing based on the core logs and additional visual inspection to provide a representative range of results for Chatsworth Formation sandstone and shale. The test methods used to measure the listed properties are described below.

D.4.1 COMPRESSIVE STRENGTH AND JOINT WALL COMPRESSIVE STRENGTH

Compressive strength (δc) and joint wall compressive strength (JCS) were obtained by performing Schmidt hammer tests. The Schmidt hammer was developed in 1948 for

non-destructive testing of concrete hardness, and later to estimate rock strength. It consists of a spring-loaded mass that is released against a plunger when the hammer is pressed onto a hard surface. The plunger impacts the surface and the mass recoils; the rebound value of the mass is measured either by a sliding pointer or electronically. Hammer rebound readings are considered consistent and reproducible.

Schmidt hammer models are available in different levels of impact energy. The Type L Schmidt hammer used in this study has an impact energy of 0.74 Nm, a relatively low impact energy that tends not to break the rock core sample being tested. The core sample is securely clamped to a steel base with a minimum weight of 20 kg. A typical Schmidt hammer and core holder assembly are shown in Figure 1.

The procedure to conduct the Schmidt hammer test is outlined in ISRM (1978). It requires the test surface of the core sample to be smooth and flat over the area covered by the plunger. This area and the rock material beneath to a depth of 6 cm must be free from cracks or any localized discontinuity of the rock mass. The hardness values obtained are affected by the orientation of the hammer. Therefore, ISRM (1978) recommends that the hammer be used in one of three positions: vertically upwards, horizontally, or vertically downwards with the axis of the hammer 5° from the desired position. When use of one of the three orientations is not feasible, the test can be conducted at the necessary angle and the results corrected to a horizontal or vertical position using the correction curves supplied by the manufacturer. The hammer orientation for the test and any corrections applied to non-vertical or non-horizontal orientations are required to be recorded and reported in the results. Ten individual tests are conducted on any one rock sample and the mean of the five highest readings are recorded as the Schmidt hardness rebound number (R or r). Test locations are normally separated by at least the diameter of the plunger. Any test that causes cracking or any other visible failure of the specimen is rejected.

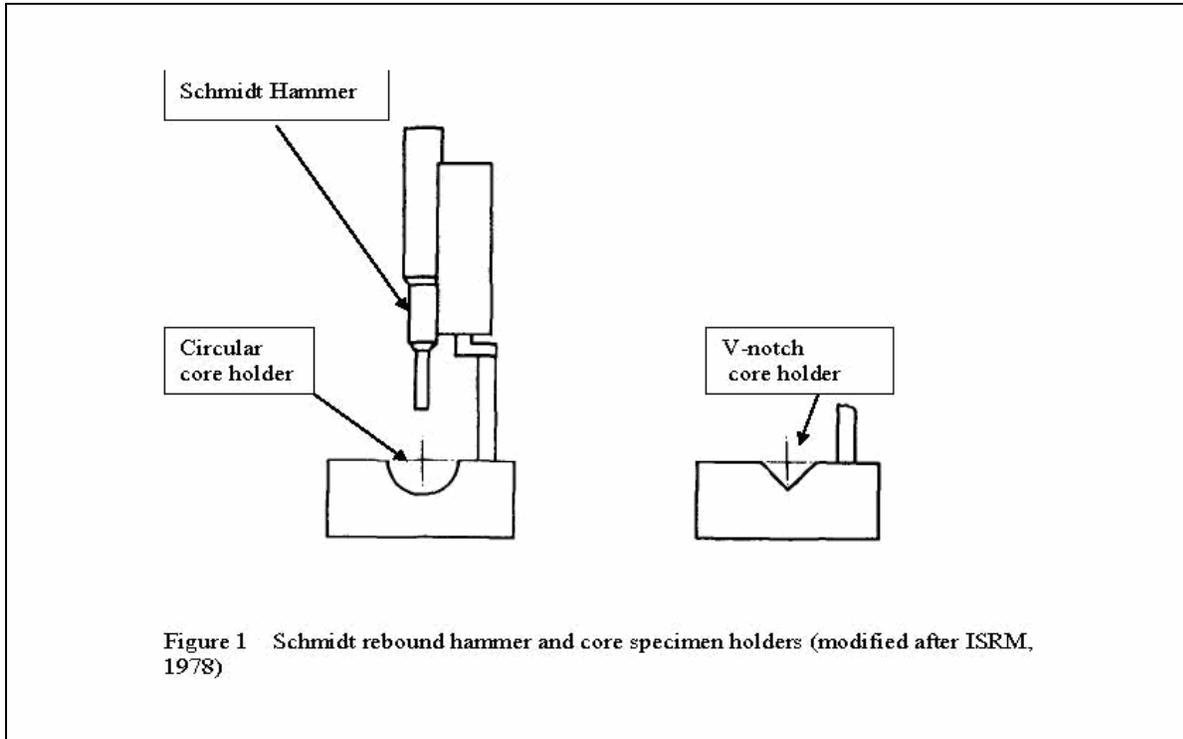
The rebound number is converted into the unconfined compressive strength (δc) by using a correlation chart (Figure 2), or the following relationship can also be used (Deer and Miller, 1966):

$$\text{Log}_{10}(\delta c) = 0.00088 \rho R + 1.01$$

Where (δc) = unconfined compressive strength

ρ = dry density of rock (kN/m³)

R = rebound number



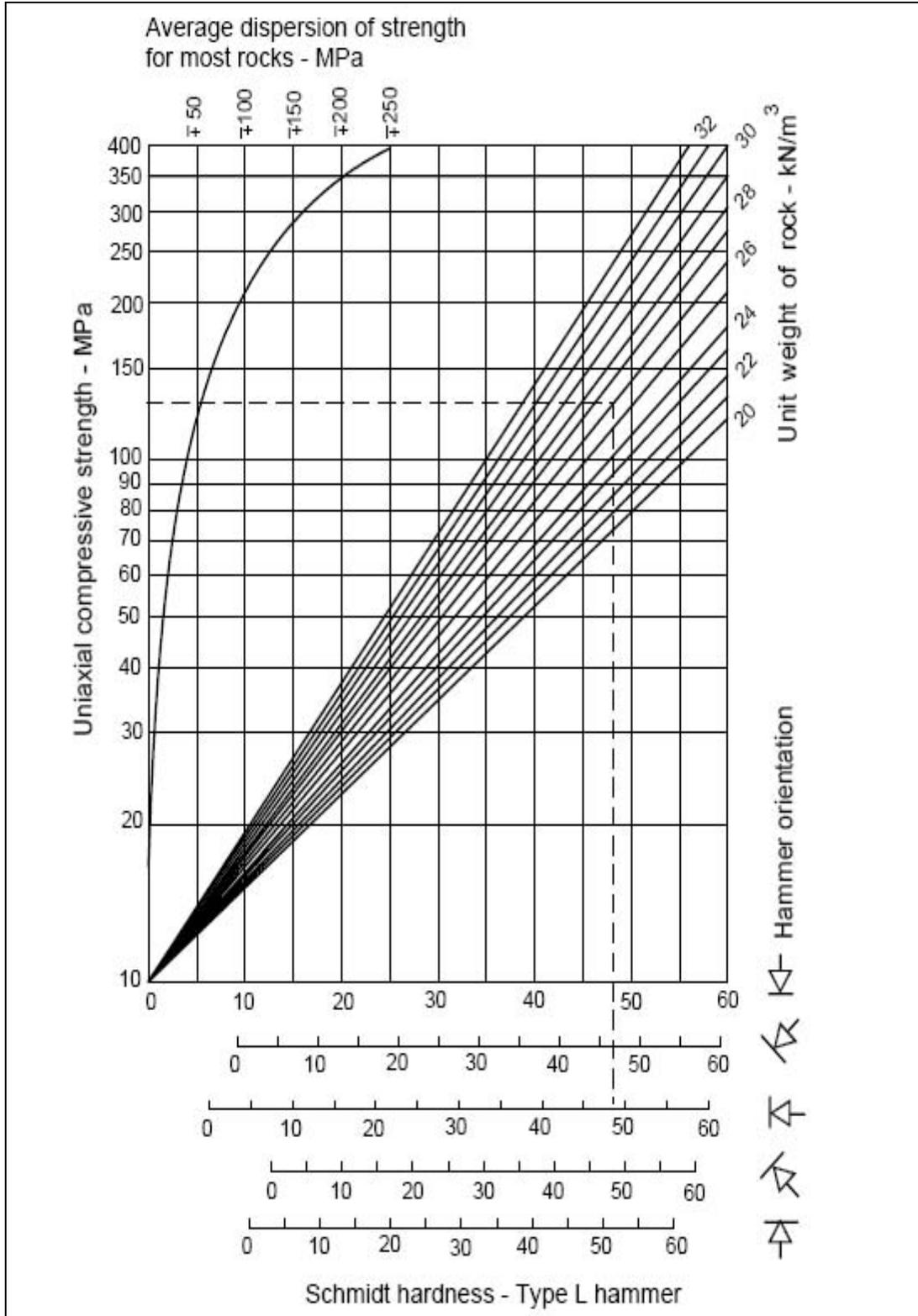


Figure 2. Correlation chart for (δc) and (R or r).

For the testing at SSFL the hammer was applied at a vertical position to the core specimen.

Where the fracture surface was tested to obtain the r value for determination of JCS, the adjacent intact core sample was tested to obtain the R value used to determine δc .

D.4.2 JOINT ROUGHNESS COEFFICIENT

JRC was measured using two test methods. The first of these, called the straight edge method, requires the profiling of a fracture surface. A standard 14.5 cm long contour gauge was used for surface profiling. A fracture core surface was placed horizontally on a table and the contour gauge was applied firmly such that all the tips of the metallic needles were properly set against the fracture surface (Figure 3A). The contour gauge was then carefully placed on a piece of paper and a pencil was pulled along the edge of the contour gauge to transfer the core surface profile to the paper (Figure 3B). The straight edge method is based on roughness amplitude-fracture length relationships obtained from an analysis of some 200 roughness profiles measured on 0.1m long fracture samples (Barton and Choubey, 1977, and Bandis 1980), and from tests on model replicas of joints (Bandis, 1980). These replicas represented fracture surfaces between 1.5 and 12 m in length. The fracture roughness amplitude and fracture length can provide estimates of JRC using Figure 4.



Figure 3A. Using a contour gauge to obtain a fracture surface profile.



Figure 3B. Transferring a fracture surface profile to paper.

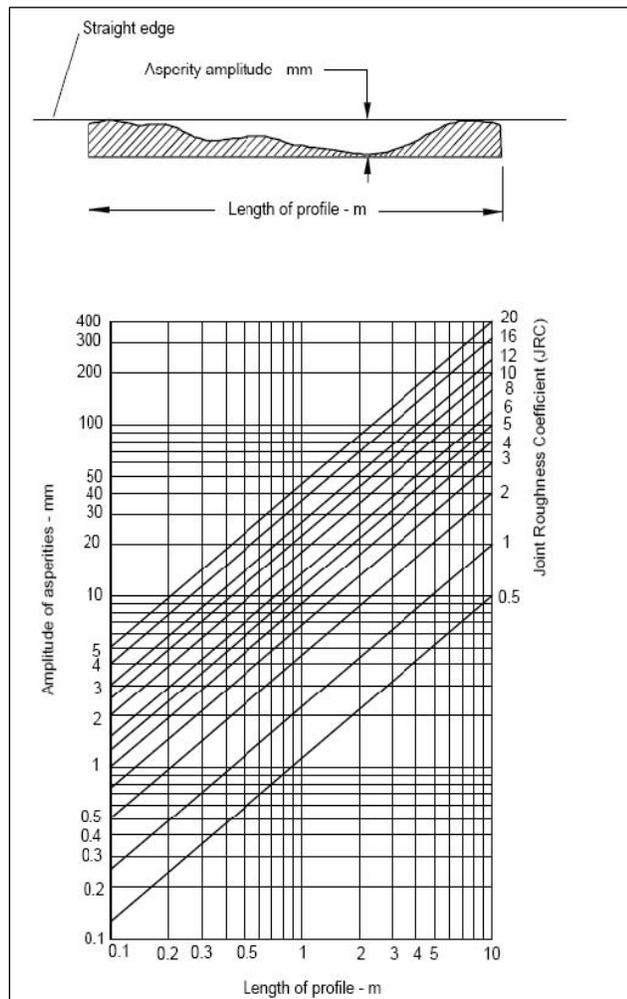


Figure 4. Straight edge method for estimating JRC (Barton, 1982).

A more reliable method for obtaining the JRC called a tilt test was also performed. The tilt test is basically a shear test under very low normal stresses and the values thus obtained match well with the basic friction angle values obtained from standard shear strength tests (Barton and Choubey, 1976). A tilt test is performed using a tilt table equipped with a clinometer to measure the angle at which a test sample begins to slide. For each test, three pieces of intact rock core were obtained in proximity to a fractured rock core sample. After removing any loose grains attached to the three intact core pieces, one piece was placed on top of the other two on the tilt table (Figure 5). The tilt wheel was then turned to slowly increase the incline angle of the tilt table until the top core piece would begin to slide across the other two pieces under its own weight. The angle at which the top core piece begins to slide is called the basic friction angle (Φ_b). This test was repeated three times for each set of core samples to obtain representative values of Φ_b .

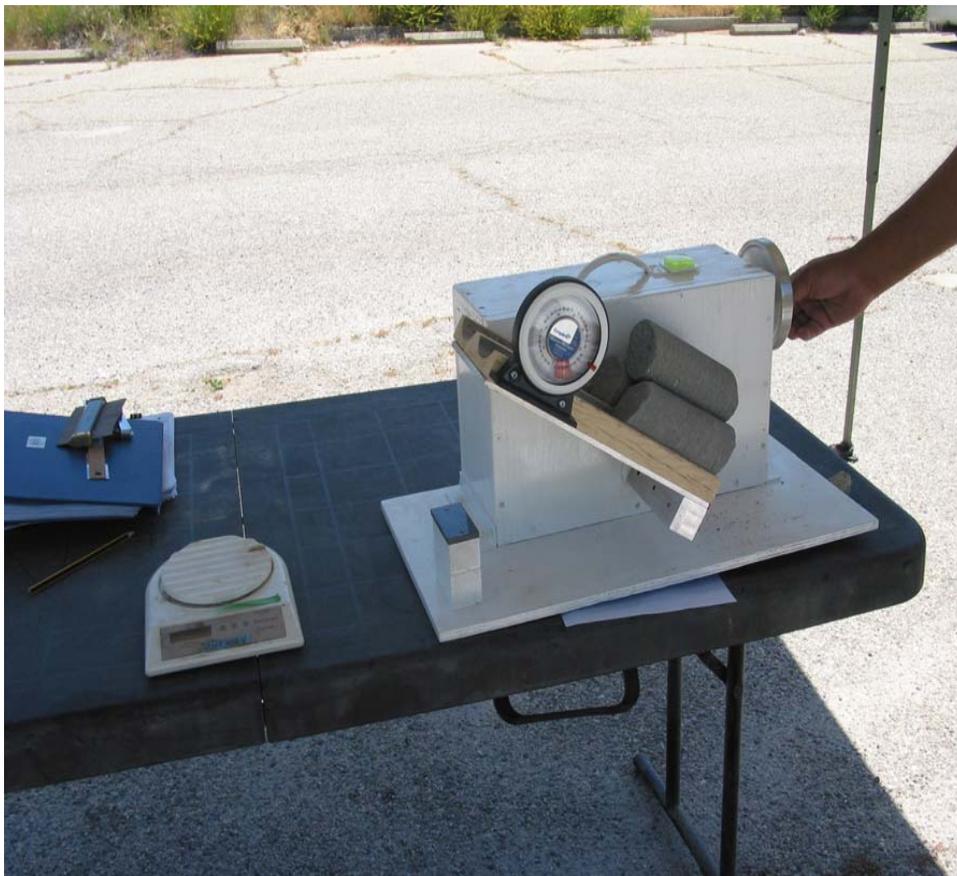


Figure 5. Determination of basic tilt angle Φ_b by a tilt test.

A similar procedure was used for determining the tilt angle (α) of the fractured surface. In this case, the fractured length of core sample was placed carefully into the tilt table and the top half

of the fractured core piece was allowed to slide over the bottom half along the fracture surface. The angle at which the top half of the fracture surface begins to slide over the bottom half is the α (Figure 6).

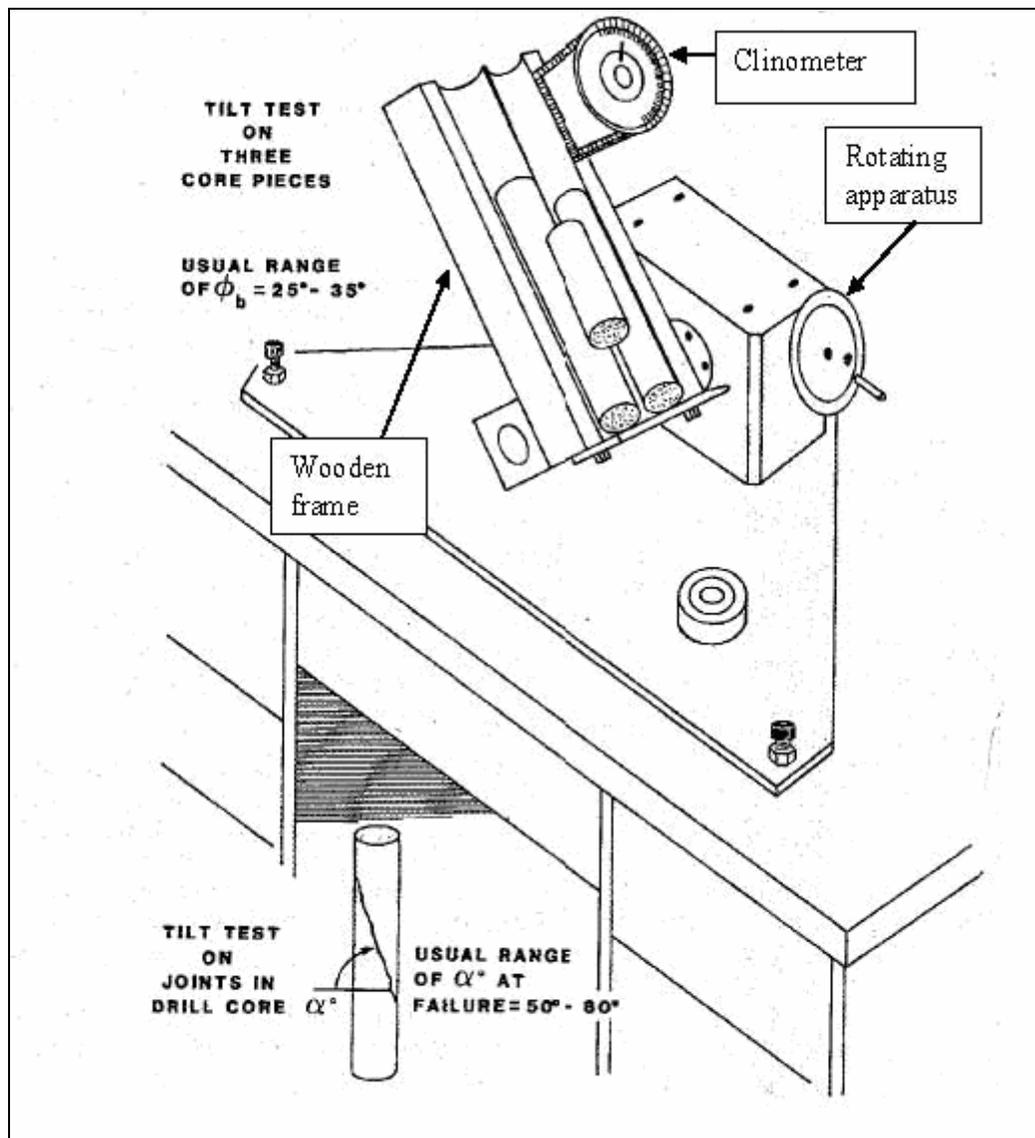


Figure 6. Tilt test apparatus showing (modified after Barton, 1981).

The top core piece in each test for Φ_b or α was also weighed, and a planimeter was used to measure the area of the fracture surface prior to tilt testing for α .

Using the measured values of Φ_b , and the Schmidt rebound numbers obtained during the δ_c and JCS testing, the residual friction angle (Φ_r) can be determined from the following empirical equation:

$$\Phi_r = (\Phi_b - 20) + 20(r / R)$$

where:

Φ_b = basic friction angle

R = Schmidt rebound number for the intact core sample

r = Schmidt rebound number for the fractured core surface

Then, the effective normal stress on the fracture surface is calculated using the following expression:

$$\delta n = w \cos^2 \alpha / A$$

where:

w = weight of the top (sliding) half of the fractured rock core sample

A = area of the fracture surface

Finally, the JRC for the fracture surface can be calculated using the following equation developed by Barton and Choubey (1977):

$$JRC = (\alpha - \Phi_r) / \log (JCS / \delta n)$$

where:

α = tilt angle

Φ_r = residual friction angle

JCS = joint compressive strength

δn = effective normal stress

D 4.3 INITIAL MECHANICAL FRACTURE APERTURE

The Barton-Bandis model requires an estimate of the initial mechanical fracture aperture that is subject to closure under normal stress. The mechanical aperture was measured on fractured rock core samples using a standard feeler gauge. The two halves of the core were held tightly together and a feeler gauge was inserted to measure the openings all along the fractured length (Figure 7). A total of 10 readings were taken for each sample and an average mechanical aperture was reported.



Figure 7. Measuring fracture aperture with a feeler gauge.

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APPENDIX E

**ANALYSIS OF ROCK CORE SAMPLES FOR CHLORIDE CONTENT
SAMPLING AND ANALYSIS PROCEDURES**

**Rock Core Sample Collection and Chloride
Analysis Methods for Coreholes C4 and C6
Santa Susana Field Laboratory**

Prepared for:

**The Boeing Company
Rocketdyne Propulsion and Power
and
National Aeronautics and Space Administration**

April 30, 2007

Field and Laboratory Methods

Rock core subsamples were collected from the archived rock core in storage at SSFL from C4 and C6 (locations shown in Figure 1) in July 2004 using a hammer and chisel, in a similar manner to the VOC sampling, and the subsamples were wrapped in foil and saran-wrap, placed in individual zip-loc bags and shipped to the University of Waterloo (UW) in coolers for extraction and analysis. In total, seventy-five samples were collected (Appendix A): twenty-two from C4 (depth interval from 9 to 50 ft bgs) including one duplicate, and fifty-three from C6 (from 406 to 898 ft bgs) including three duplicates.

On arrival at UW, the samples were individually broken into smaller pieces using a hammer and chisel, and crushed using the same hydraulic rock crusher setup used for rock core VOC sampling (Hurley et al., 2003). The crushed rock from each sample was then placed in pre-weighed 125 mL trace-clean sample jars containing about 60 mL of deionized water, adding enough crushed rock sample (~120 g) so the water level was slightly above the crushed rock level, to minimize the dilution factor while ensuring the crushed rock was fully submerged for extraction. Jars were weighed empty, with deionized water, and then with the crushed rock sample, so the mass of crushed rock and volume of deionized water were accurately known. Between samples the crushing cells were rinsed with deionized water and dried with paper towels. The duplicates (5% of the total number of samples) were collected by splitting the sample along the longitudinal axis (i.e. duplicates represent side-by-side samples from the same depth interval).

The jars containing the crushed rock samples were then shaken on an orbital shaker for 1 hour, and then allowed to sit for two weeks, shaken again, then stored for another two weeks and shaken a third time. After the four week extraction period, the samples were centrifuged for 30 minutes to separate enough water from the rock for analysis, and a 20 mL aliquot of the extract taken via pipette and placed in 20 mL plastic scintillation vials for analysis. Analyses of the extract were conducted for chloride using an ion-specific electrode (ISE) and then samples were submitted to the Chemical Engineering Analytical Lab at UW for analysis of chloride (and nitrate and sulfate) using a Dionex DX 500 Ion Chromatography (IC) System.

APPENDIX F

**GROUNDWATER SAMPLING METHODS
FOR ANALYSIS OF DISSOLVED GASES**

Standard Operating Procedure for the Snap Sampler™ Passive Groundwater Sampling Method (January 2007)

FORWARD

This standard operating procedure (SOP) was adapted from SOPs in USEPA's groundwater guidance for RCRA and Superfund project managers (U.S. Environmental Protection Agency, 2002). Portions of the applicable text are repeated here. With this forward, the authors and USEPA are acknowledged in sincerest appreciation. Edited and supplemental text is included to detail application information and procedures for use and deployment of the Snap Sampler™ passive groundwater sampling device and method.

INTRODUCTION

The goal of groundwater sampling is to collect samples that are "representative" of *in situ* groundwater conditions and to minimize changes in groundwater chemistry during sample collection and handling. Experience has shown that groundwater sample collection and handling procedures can be a source of variability in water quality concentrations due to differences in sampling personnel, sampling procedures, and equipment (U.S. Environmental Protection Agency, 1995).

The collection of "representative" water samples from wells is neither straightforward nor easily accomplished. Groundwater sample collection can be a source of variability through differences in sampling personnel and their individual sampling procedures, the equipment used, and ambient temporal variability in subsurface and environmental conditions. Many site inspections and remedial investigations require the sampling at groundwater monitoring wells within a defined criterion of data confidence or data quality, which necessitates that the personnel collecting the samples are trained and aware of proper sample collection procedures.

The purpose of this SOP is to provide a description of the Snap Sampler™ passive groundwater sampling method. The method and specialized equipment is designed to minimize the impact the sampling process on groundwater chemistry. This is accomplished through deployment and passive re-equilibration of the monitoring well to ambient

groundwater flow and/or diffusive contaminant flux within the well/aquifer system. The Snap Sampler™ method eliminates well purging prior to sample collection.

As a passive groundwater sampling device, the Snap Sampler™ is a viable alternative to well purge and low-flow sampling in qualified wells. Historical and recent research shows that many if not most well screen zones exhibit ambient flow-through under natural groundwater gradients (Gillham, 1982; Pankow, et al 1985; Robin and Gillham, 1987; Powell and Puls, 1993; Puls and Barcelona, 1996; Vroblesky, et al, 2001a; ASTM, 2002; ITRC, 2004). The screen sections of these wells are "naturally purged" without pumping. Ongoing research (Britt, 2005; Martin-Hayden and Britt, 2006; Vroblesky, et al 2006), suggests that natural ambient flow can induce mixing within wells, resulting in a flow-weighted averaging effect in the well without purging. Though not all wells are thoroughly mixed, many wells show relatively narrow ranges of vertical concentrations when vertically profiled (Vroblesky et al, 2001b; Parsons, 2003). These studies indicate flow-weighted contaminant concentration averaging within wells may be common. The Snap Sampler™ takes advantage of "naturally purged" wells by capturing natural flow-through in the open VOA vial during sampler deployment.

Wells in poor yielding formations with slow recharge during pumping have always been problematic for pumping methods. The Snap Sampler™ can be deployed in low yield wells to take advantage of the passive technology. Passive sampling of poorly yielding wells has been suggested as a better method than purging to dryness in VOC impacted wells (McAlary and Barker, 1987; Puls and Powell, 1993; Puls and Barcelona, 1996).

The Snap Sampler™ passive groundwater sampling method limits sample collection variables by sealing the sample while it is still in the well. The sample is not poured into sample bottles at the ground surface. Sampling personnel are essentially prevented from introducing error, variability, or bias during the sample collection process. Sample collection is virtually the same for any

collector because the sample is never exposed to the ambient air from the well to the laboratory.

SCOPE AND APPLICATION

This SOP should be used primarily at monitoring wells that have a screen or an open interval with a length of ten feet or less and can accept a downhole device of 1.7 inches in diameter. Longer screen interval sampling may be conducted, but vertical stratification testing is more likely to be required to identify vertical concentration gradients. Vertical stratification monitoring may be warranted if previous information about aquifer and/or well contaminant stratification is not available. The Snap Sampler™ groundwater sampling method is similar in many respects to the passive diffusion bag (PDB) sampler. Like the PDB, vertical profiling may be recommended depending on site-specific data quality objectives (DQO's) and other site requirements (Vroblecky, 2001a; ITRC, 2004).

The groundwater samples that are collected using this procedure are useable for the analyses of groundwater contaminants that may be found at Superfund and RCRA contamination sites. The analytes may be volatile, semi-volatile organic compounds, pesticides, PCBs, metals, and other inorganic compounds, including perchlorate and other emerging contaminants.

For contaminant plume monitoring, the sampler should be placed within the screened interval of the well. For consistency and comparability of results over time, the sampler should be placed in same location or depth for each subsequent sampling event.. This argues for the use of dedicated sampling devices with dedicated trigger lines whenever possible. If this is not possible, then the placement of the Snap Sampler™ should be positioned using pre-measured trigger tubing placed at the same depth during each sampling event. The Snap Sampler™ should not be placed resting on the bottom of the screened interval to avoid disturbing any sediment at the bottom of the well during deployment or when the sampler is triggered.

The Snap Sampler™ relies on natural flow-through and/or diffusion of contaminants from the aquifer to the well (Powell and Puls, 1993; ASTM, 2002). Well purging is not conducted before sampling and therefore measurement of water-quality-indicator parameters is not a prerequisite to sample collection. Water-quality indicator parameters do not need to be collected prior to sampling. If parameters are required for certain monitoring programs independent of sampling method (e.g. for monitored natural attenuation), parameters can be collected by utilizing one of the deployed Snap Sampler™ bottles or post-sampling by another method.

Samples collected for metals, semi-volatile organic compounds, pesticides, and other analytes may be impacted by sample turbidity. They also may be subject to transport by colloidal flow in the natural groundwater regime (Kearl, et al, 1992, Puls and Powell, 1992). Deployment and re-equilibrium of the Snap Sampler™ allows natural colloidal flow to be monitored within the well. This is a distinct advantage over sampling methods such as the PDB, where colloidal particles are excluded from the sample; and over purge methods where colloids may be artificially mobilized. Field filtering is not recommended for samples collected with the Snap Sampler™.

Proper well construction, development, and maintenance are essential for any groundwater sampling procedure. Prior to conducting the field work, information on the construction of the well and well development should be obtained and that information factored into the site specific sampling procedure. This SOP is not to be used where non-aqueous phase liquids (NAPL) (immiscible fluids) are present in the monitoring well.

MATERIALS AND EQUIPMENT

- Approved Field Sampling and Quality Assurance Project Plan.
- Site Health and Safety Plan with specifications for personal protective equipment and air monitoring equipment.

- Personal protective equipment in good working order as specified in the site Health and Safety Plan.
 - Air monitoring equipment in good working order as specified in the Site Health and Safety Plan.
 - Site access/permission documentation for site entry.
 - Well keys and map of well locations.
 - Tool box - All needed tools for all site equipment used.
 - Snap Samplers™ - stainless steel samplers should be used when sampling organic compounds. Acetal or other appropriate plastic sampler material may be used when sampling for metals. When sampling for metals and organics, dedicated plastic samplers are preferred.
 - Snap Sampler™ Trigger lines, – Dedicated polyethylene tubing with stainless steel trigger wire is preferred when sampling for organic compounds. Non-metallic trigger wire or stainless steel trigger wire coated with nylon or appropriate fluorocarbon may be used when sampling for metals.
 - Snap Sampler™ Well Docking Station – replacement well caps for Snap Sampler™ - deployed wells.
 - Sample bottles, sample preservation supplies, sample tags or labels, and chain-of-custody forms.
 - Well construction, field, and water quality data from the previous sampling event.
 - Field notebook, groundwater sampling logs, and calculator.
 - Polyethylene sheeting placed on ground around the well head.
 - Depth-to-water measuring device - An electronic water-level indicator or steel tape and chalk, with marked intervals of 0.01 foot. Interface probe for determination of liquid products (NAPL) presence, if needed.
 - Steel tape and weight - Used for measuring total depth of well. A lead weight should not be used.
 - Multi-parameter meter, if required. The water-quality-indicator parameters that may be monitored under common monitoring programs include pH, ORP/Eh, (ORP) dissolved oxygen (DO), turbidity, specific conductance, and temperature. Turbidity readings, if required, must be collected from a sacrificed Snap Sampler™ bottle because retrieving the sampler may agitate the well, increasing turbidity values not present in the actual samples. Calibration fluids for all instruments should be NIST-traceable and there should be enough for daily calibration throughout the sampling event.
 - Decontamination supplies - Including a reliable and documented source of distilled water and any solvents (if used). Pressure sprayers, buckets or decontamination tubes for pumps, brushes and non-phosphate soap will also be needed.
 - A suitable container for excess sample and decontamination water, as needed or required.
- Construction materials of the sampling equipment (samplers, tubing, and other equipment that comes in contact with the sample) should be limited to stainless steel, Teflon®, glass, and other inert material. This will reduce the chance that sampling materials alter the groundwater where concentrations of the site contaminants are expected to be near the detection limits. The tendency of organics to sorb into and desorb out of plastic materials makes dedicated equipment preferable where possible.
- It should be noted that sorbing materials used in the Snap Sampler™ is not usually problematic. Using this method, the sampler is deployed for one to two weeks (or more), allowing materials prone to sorption to achieve equilibrium with groundwater before the sample is collected.

DEPLOYMENT/SAMPLING PROCEDURES

The following describes the deployment and sampling procedures for the Snap Sampler™ passive groundwater sampling method. These procedures describe steps for dedicated and non-dedicated systems.

Pre-Sampling Activities

1. Well location maps, construction information, keys and sampling equipment should be assembled and transported to the site.
2. Water level monitoring and sampling must begin at the monitoring well with the least contamination, generally up-gradient or farthest from the site or suspected source. Then proceed systematically to the monitoring wells with the most contaminated ground water.
3. Check and record the condition of the monitoring well for damage or evidence of tampering. Lay out polyethylene sheeting around the well to minimize the likelihood of contamination of sampling/purging equipment from the soil.
4. Unlock well head. Record location, time, date, and appropriate information in a field logbook or on the groundwater sampling log.
5. Remove inner casing cap.
6. Monitor the headspace of the monitoring well at the rim of the casing for volatile organic compounds (VOC) with a photo-ionization detector (PID) or flame ionization detector (FID) and record in the logbook. If the existing monitoring well currently has or has a history of positive headspace readings, then the sampling must be conducted in accordance with the Health and Safety Plan.
7. Measure the depth to water (water level must be measured to nearest 0.01 feet) relative to a reference measuring point on the well casing with an electronic water level indicator or steel tape and record in logbook or groundwater sampling log. If no reference point is found, measure

relative to the top of the inner casing, then mark that reference point and note that location in the field logbook. Record information on depth to ground water in the field logbook or groundwater sampling log. Measure the depth to water a second time to confirm initial measurement; measurement should agree within 0.01 feet or re-measure.

8. Check the available well information or field check for the total depth of the monitoring well.

Deployment Activities

Selection of the deployment depth within the screen interval is dependent on site specific DQO's. If depth-specific monitoring is required, multiple samplers may be deployed at intervals appropriate for the sampling objective. If previous vertical profiling of a well has been conducted, a selected single deployment depth may be chosen based on the sampling objective. For example, previous data show the bottom three feet of a well have historically contained the highest contaminant concentration; deployment at this depth could be selected based on an objective to sample the highest known concentration within stratified wells. Alternatively, if a well is not stratified, a mid-screen deployment may be appropriate.

Sample zones within a well may be isolated using a packer or baffle device to limit in-well mixing (Britt, 2006; Vroblesky et al, 2006). These can be attached to the Snap Sampler™ trigger line or deployed separately. Installation of an upper baffle designed to isolate the unscreened well casing or well headspace is recommended. The upper baffle will limit mixing of "stagnant" casing water with screen-interval water, an/or gas exchange with the headspace air.

1. Remove the Snap Sampler bottle(s) from its package.
2. Turn the translucent (PFA) vial cap on each end of the bottle slightly to release the O-ring (the o-ring may tend to stick on the glass of the vial if the o-ring is not loosened before trying to set the sampler).

3. Insert the bottle into the upper end of the sampler as shown in Figure 1.

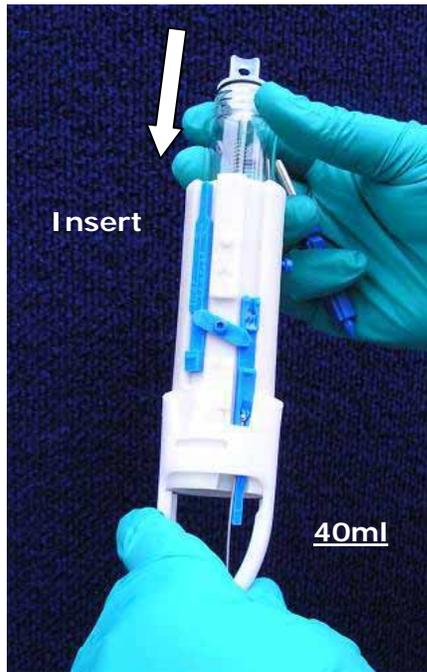


FIGURE 1

4. Place the sampler connector onto each end of the sampler; turn clockwise to align the set pins/screw; then gently tighten the set screw with the Snap Driver Tool (Figure 2).

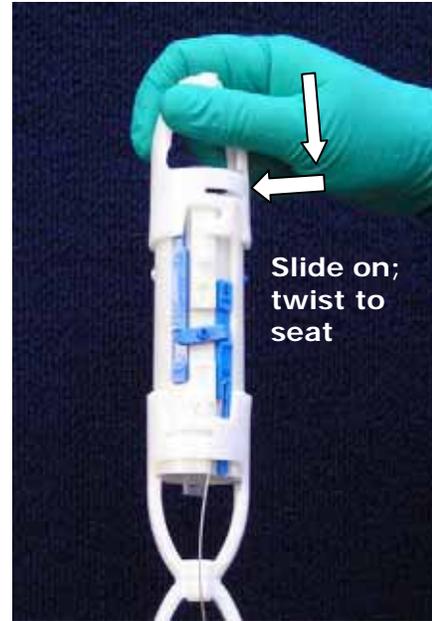


FIGURE 2

5. Pivot the vial cap (Snap Cap) into its seat with the Snap driver. Push up the retainer pin through the lower hole in the vial cap. Repeat for all Snap Caps (Figure 3). If an O-ring should dislodge from its seat during setting, remove the sample bottle and carefully replace it in the o-ring groove; repeat setting procedure.

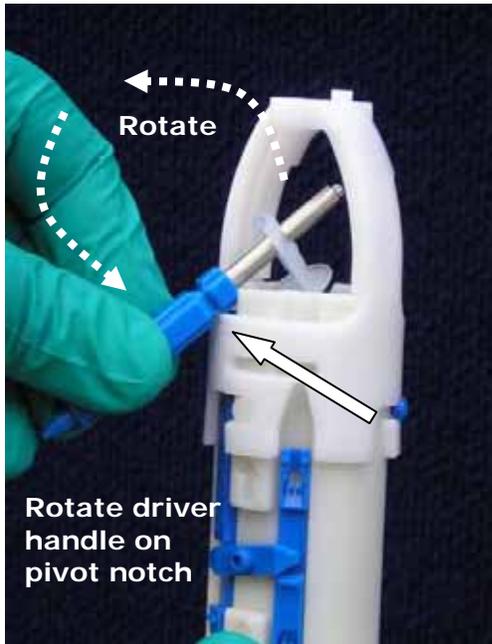


FIGURE 3

6. Feed ball-fitting end of trigger cable through lower release pin groove; click tube fitting into connector (Figure 4).

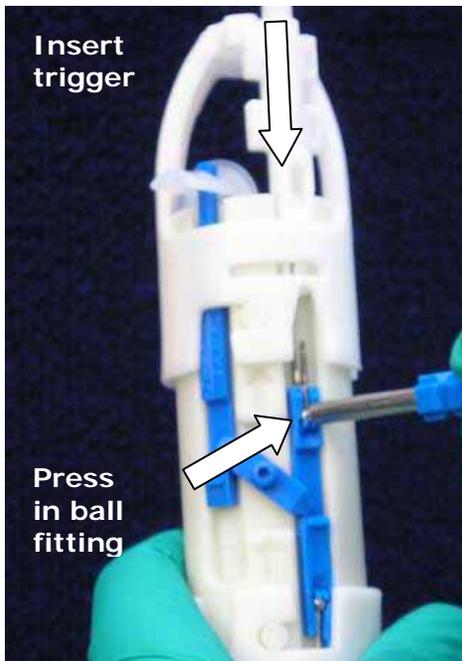


FIGURE 4

7. Press in the ball fitting to attach to lower release pin (Figure 4).



FIGURE 5

8. Deploy to selected depth with trigger cable tubing and attach to well head docking station (Figure 5).
9. Additional Snap Samplers™ can be deployed with separate trigger tubing cables or in series with a single trigger. If separate triggers are used, the ID tags should be marked at the surface for later reference.
10. The recommended deployment period is two weeks. There may be hydrogeologic conditions where a shorter deployment is possible, but two weeks would generally assure a return of the well to its steady-state condition (Vroblesky, 2001a, 2001b).
11. The Snap Sampler™ can also be deployed for more extended periods. It is suggested that quarterly or semi-annual sampling can be done with one mobilization per quarter, with one set of

samplers collected and the following quarter's samplers deployed at the same time.

Sample Collection Activities

When the deployment interval is completed, the sampler should be triggered from the well head without disturbing the sampler position. The trigger cable should be pulled with sufficient force to move the cable up the tubing. Depending on the length of the cable, closure of the samplers usually can be felt through the trigger line when the samplers trip. If more than one triggering line is present, closure should proceed from the deepest to the shallowest sampler position to limit capture of sediment re-suspended by closure of the first sampler.

After the sampler is triggered and retrieved, the upper connector should be removed by loosening the retainer screw and turning the connector.

While the vials should not leak with reasonable handling, they should not be agitated (to check for headspace) until after the screw caps are tightened. Under most circumstances there will be no air in the vials at retrieval. However, some field conditions, including deep groundwater, natural effervescence, or other causes, may allow some small air bubbles to be present in the bottle or on the spring when retrieved. This is not a concern if the air was entrained while deployed. Air adhering to the vial during deployment would be in equilibrium with the sample water upon sampler closure. Therefore it is not "headspace air" into which sample VOCs could volatilize. Deployment air could be attached to the spring or cap, and should not be larger than 1-2 mm upon retrieval. Pankow (1986) showed that small headspace air from these or other causes do not substantially impact results for most common volatiles. If air bubbles are larger than 5 mm before placing the screw cap, or water is clearly leaking from the vial, the sample may not have sealed properly and should be discarded. (A failure rate of less than 1% should be anticipated).

To seal the samples within the Snap Sampler™ bottles, the following procedures should be followed:

1. The tabs should be carefully clipped from the vial caps. Care should be taken to avoid disturbing the seal. The cap should be cut flush to the cap to ease placement of the septa screw cap (Figure 6).

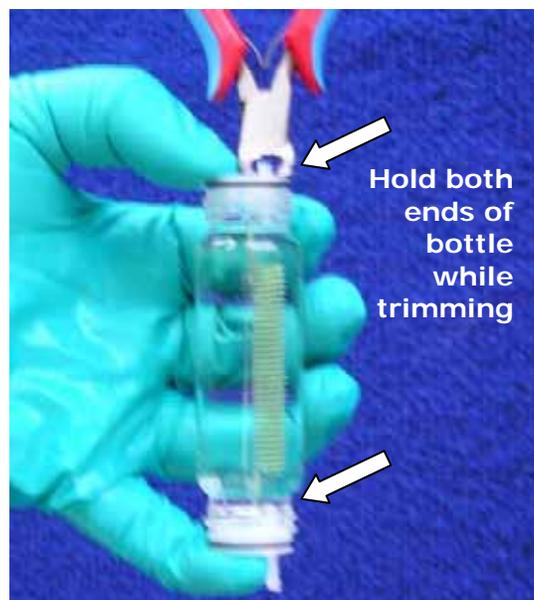


FIGURE 6

2. If no preservative is desired, or preservation will be conducted by the laboratory, firmly tighten the septa caps to seal the vial.
3. Tightening the caps compresses the o-ring and creates a PFA-to glass seal. Only PFA and glass touch the sample after the bottle is sealed with the septa caps.
4. If samples are to be field preserved, adding liquid acid preservative is relatively simple. Prepare one end of the vial as described in step #1 and gently tighten a septa cap on that end. Prepare the other end of the vial through step #1. Fill the remaining Snap Cap cavity with 1:1 HCl solution. Carefully pierce the membrane with the pointed end of the Snap Driver Tool (Figure 7). If needed, refill the cap cavity with preservative. Preservative should be added to create a meniscus covering most of the cap. Care should be taken not to introduce air into the sample

bottle. Both septa caps should be firmly tightened onto the bottle.



FIGURE 7

5. Once sample bottles are properly closed, bottles should be labeled and recorded in the sampling logs and chain-of-custody (Figure 8).



FIGURE 8

6. There are no special laboratory preparation procedures for Snap Sample bottles. The bottles can be analyzed using common 40-ml autosamplers. The spring inside the VOAs is PFA Teflon-coated and will deflect out of the way of the extraction needle during insertion.

Appendix A contains step-by-step field procedures for deployment of both 40 ml Snap Sampler VOAs and 125 ml Snap Sampler POLY bottles.

Appendix B contains step-by-step procedures for preparation of both 40 ml Snap Sampler VOAs and 125 ml Snap Sampler POLY bottles.

DECONTAMINATION PROCEDURES

The electronic water level indicator probe/steel tape, the water-quality field parameter sensors and Snap Sampler™ groundwater sampling device should be decontaminated by the following procedures:

1. The water level meter will be hand washed with phosphate-free detergent and a scrubber, then thoroughly rinsed with distilled water.
2. Water quality field parameter sensors with distilled water between sampling locations where utilized. No other decontamination procedures are necessary or recommended for these probes since they are sensitive. After the sampling event, the sensors

must be cleaned and maintained per the manufacturer's requirements.

3. The Snap Sampler™ and trigger tubing must be pressure-sprayed or bristle-brush scrubbed with soapy water, tap water, and distilled water. Depending on the condition of the Snap Sampler™, the release pin mechanism may need to be disassembled to effectively clean the pins and grooves. Disassembly can be accomplished by removing the lever screw.

FIELD QUALITY CONTROL

Quality control (QC) samples must be collected to verify that sample collection and handling procedures were performed adequately and that they have not compromised the quality of the groundwater samples. The appropriate EPA or other appropriate program guidance must be consulted in preparing the field QC sample requirements for the site-specific Quality Assurance Project Plan (QAPP).

There are five primary areas of concern for quality assurance (QA) in the collection of representative groundwater samples:

1. Obtaining a groundwater sample that is representative of the aquifer or zone of interest in the aquifer. Verification is based on the field log documenting that the field procedures were followed appropriately during sample deployment and collection.
2. Ensuring that the sampling devices are made of materials, and utilized in a manner that will not interact with or alter the analyses.
3. Ensuring that results generated by these procedures are reproducible; therefore, the sampling scheme should incorporate co-located samples (duplicates).
4. Preventing cross-contamination. Sampling should proceed from least to most contaminated wells, if known. Field equipment blanks should be incorporated

for all sampling, and decontamination of the equipment is therefore required.

5. Properly preserving, packaging, and shipping samples.

All field QC samples must be prepared the same as regular investigation samples with regard to sample volume, containers, and preservation. The chain-of custody procedures for the QC samples will be identical to the field groundwater samples. The following are QC samples that should be collected during the sampling event:

| | |
|-------------------|---------------------|
| Field duplicates | 1 per 20 samples |
| Matrix spike | 1 per 20 samples |
| Matrix spike dup. | 1 per 20 samples |
| Equipment blank | per requirements |
| Trip blank (VOCs) | 1 per sample cooler |
| Temperature blank | 1 per sample cooler |

HEALTH AND SAFETY CONSIDERATIONS

Depending on the site-specific contaminants, various protective programs must be implemented prior to sampling the first well. The site Health and Safety Plan should be reviewed with specific emphasis placed on the protection program planned for the sampling tasks. Standard safe operating practices should be followed, such as minimizing contact with potential contaminants in both the liquid and vapor phase through the use of appropriate personal protective equipment.

Depending on the type of contaminants expected or determined in previous sampling efforts, the following safe work practices should be employed:

Particulate or metals contaminants

1. Avoid skin contact with, and incidental ingestion of sample water.
2. Use protective gloves and splash protection.

Volatile organic contaminants

1. Avoid breathing constituents venting from well.
2. Pre-survey the well head space with an appropriate device as specified in the site Health and Safety Plan.
3. If monitoring results indicate elevated organic constituents, sampling activities may be conducted in elevated protective equipment (e.g. level C protection). At a minimum, skin protection will be afforded by disposable protective clothing, such as Tyvek®, appropriate gloves and face protection.

General practices should include avoiding skin contact with water from preserved sample bottles, as this water will have pH less than 2 or greater than 10. Also, when field acidifying VOA bottles, hydrochloric acid fumes may be released and should not be inhaled. Acid should not contact skin, eyes, or unprotected clothing.

POST-SAMPLING ACTIVITIES

Several activities need to be completed and documented once groundwater sampling has been completed.

These activities include, but are not limited to the following:

1. Ensuring that all field equipment has been decontaminated and returned to proper storage location. Once the individual field equipment has been decontaminated, tag it with date of cleaning, site name, and name of individual responsible.
2. Processing all sample paperwork, including copies provided to the appropriate sample handling and tracking facility.
3. Compiling all field data for site records.
4. Verifying all analytical data processed by the analytical laboratory against field sheets to ensure all data has been returned to sampler.

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Table 1
Candidate Wells: Construction Information
Snap Sampler Work Plan for SSFL
May 2, 2007

Prepared By: Amanda Pierce

Data From: Report On Annual Groundwater Monitoring, 2004, Santa Susana Field Laboratory, Ventura County, California (H&A, 2004)

| Candidate Well | Depth (fbgs) | Elevation (ft MSL) | BOREHOLE | | CASING | | Sealed Interval (feet) | Perforated Interval (feet) | Screen Length (feet) | Depth to Water (2004) ¹ (feet) | Water Column Length (feet) | Drilling Date |
|----------------|--------------|--------------------|-------------------|-----------------|--------------------------|-----------------|------------------------|----------------------------|----------------------|---|----------------------------|---------------|
| | | | Diameter (inches) | Interval (feet) | Inside Diameter (inches) | Interval (feet) | | | | | | |
| ES-17 | 28 | 1739.31 | 15 | 0-28 | 6 | 0-28 | 0-7.9 | 10.4-28 | 17.6 | 27.04 | 0.96 | 11-Nov-86 |
| HAR-07 | 100 | 1728.38 | 15 | 0-30 | 10-1/8 | 0-30 | 0-30 | | | 78.03 | 21.97 | |
| | | | 8 | 30-100 | - | - | | Open Hole | 70 | | | 20-May-87 |
| HAR-08 | 130 | 1730.75 | 15 | 0-30 | 10-1/8 | 0-30 | 0-30 | | | 53.64 | 76.36 | |
| | | | 8 | 30-130 | - | - | | Open Hole | 100 | | | 20-May-87 |
| HAR-11 | 31 | 1827.90 | 8 | 0-31 | 4 | 0-31 | 0-5 | 11.2-31 | 19.8 | 11.67 | 19.34 | 16-May-87 |
| HAR-18 | 80 | 1749.41 | 15 | 0-30 | 10-1/8 | 0-30 | 0-30 | | | 27.53 | 52.48 | |
| | | | 8 | 30-80 | - | - | | Open Hole | 50 | | | 20-May-87 |
| HAR-23 | 90 | 1805.87 | 15 | 0-30 | 10-1/8 | 0-30 | 0-30 | | | 24.71 | 65.29 | |
| | | | 8 | 30-90 | - | - | | Open Hole | 60 | | | 18-Jun-87 |
| RD-01 | 506 | 1935.89 | 15 | 0-26 | 10 1/8 | 0-26 | 0-26 | | | 207.10 | 298.91 | |
| | | | 8-5/8 | 26-506 | | | | Open Hole | 480 | | | 9-Jan-86 |
| RD-35B | 328 | 1905.65 | 24 | 0-10 | 18 | 0-11 | 0-11 | | | 125.42 | 202.58 | |
| | | | 17-1/2 | 10-162 | 12 | 0-158 | 0-162 | | | | | |
| | | | 9-7/8 | 162-328 | 4 | 0-324 | 0-292 | 303-324 | 21 | | | 18-Jan-99 |
| | | | 3 | 328-359 | - | - | 328-359 | | | | | |
| RD-41B | 390 | 1774.71 | 17-1/2 | 0-19.5 | 12-1/8 | 0-19.5 | 0-19.5 | | | 131.53 | 258.47 | |
| | | | 11-7/8 | 19.5-340 | 6-1/4 | 0-336 | 0-340 | | | | | |
| | | | 5-7/8 | 340-390 | - | - | | Open Hole | 50 | | | 19-Oct-93 |
| RD-49A | 50 | 1867.25 | 12-3/4 | 0-18.5 | 8-1/4 | 0-18.5 | 0-18.5 | | | 18.53 | 31.48 | |
| | | | 6/1/4 | 18.5-50 | - | - | | Open Hole | 31.5 | | | 8-Jun-93 |
| RD-49B | 298 | 1867.95 | 17-1/2 | 0-20 | 12-1/8 | 0-20 | 0-20 | | | 256.89 | 41.11 | |
| | | | 11-7/8 | 20-250 | 6-1/4 | 0-250 | 0-250 | | | | | |
| | | | 5-7/8 | 250-298 | - | - | | Open Hole | 48 | | | 14-Jun-93 |
| RD-55A | 106 | 1756.87 | 17-1/2 | 0-28 | 12-1/8 | 0-28 | 0-28 | | | 24.75 | 81.25 | |
| | | | 6-1/4 | 28-106 | - | - | | Open Hole | 78 | | | 19-Feb-93 |
| RD-55B | 250 | 1757.19 | 17-1/2 | 0-20 | 12-1/8 | 0-20 | 0-20 | | | 59.64 | 190.37 | |
| | | | 11 | 20-199.5 | 6-1/4 | 0-199.5 | 0-199.5 | | | | | |
| | | | 5-7/8 | 199.5-250 | - | - | | Open Hole | 50.5 | | | 19-Apr-93 |
| RD-67 | 102 | 1901.71 | 17-1/2 | 0-20 | 12 | 0-20 | 0-20 | | | 66.39 | 35.62 | |
| | | | 6-1/2 | 20-102 | - | - | | Open Hole | 82 | | | 19-Sep-97 |
| RD-72 | 182 | 1907.25 | 24 | 0-27 | 12 | 0-27 | 0-27 | | | FLUTE System | - | |
| | | | 6-1/2 | 27-182 | - | - | | Open Hole | 155 | | | 23-Dec-97 |
| RD-77 | 170 | 1918.48 | 12-3/4 | 0-46 | 8 | 0-46 | 0-46 | | | 137.07 | 32.94 | |
| | | | 4-4/5 | 46-170 | - | - | | Open Hole | 124 | | | 3-Dec-03 |

Notes: 1. Average of quarterly measurements.

Table 2
Candidate Wells: VOC and Dissolved Gas Concentrations
Snap Sampler Work Plan for SSFL
May 2, 2007

Prepared By: Amanda Pierce

Data From: Isotopic and Hydrochemical Investigation of Major Ion Origin and Trichloroethene Degradation in Fractured Sandstone (A. Pierce, 2005)

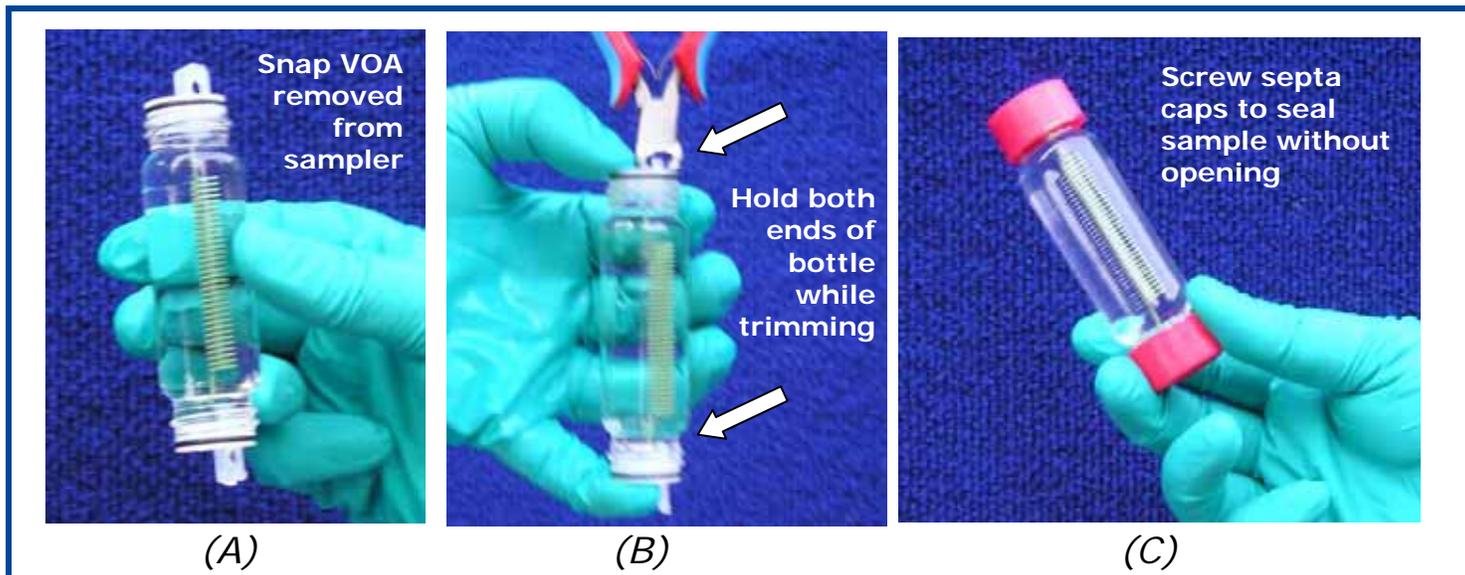
| Candidate Well | Depth (fbgs) | Screen Length (feet) | Depth to Water (2004) ¹ (feet) | Water Column Length (feet) | TCE (µg/L) | cDCE (µg/L) | tDCE (µg/L) | 1,1-DCE (µg/L) | VC (µg/L) | Methane (µg/L) | Ethene (µg/L) | Acetylene | Ethane (µg/L) | Propene (µg/L) | Propane (µg/L) | Sample Date |
|----------------|--------------|----------------------|---|----------------------------|------------|-------------|-------------|----------------|-----------|----------------|---------------|-----------|---------------|----------------|----------------|-------------|
| | | | | | | | | | | | | (µg/L) | | | | |
| ES-17 | 28 | 17.6 | 27.04 | 0.96 | 1145 | 160 | 3.4 | 14 | 6.2 | <0.5 | <0.5 | <5.0 | <0.4 | <0.6 | <0.6 | 25-Aug-03 |
| HAR-07 | 100 | 70 | 78.03 | 21.97 | 3821 | 2280 | 101 | 5.9 | 85.8 | 0.9 | 0.60 | 1.3 | 0.30 | <0.6 | <0.6 | 21-May-04 |
| HAR-08 | 130 | 100 | 53.64 | 76.36 | 245 | 14.9 | 4.3 | 3.6 | <1.3 | 0.3 | <0.5 | 2.7 | <0.4 | <0.6 | <0.6 | 21-May-04 |
| HAR-11 | 31 | 19.80 | 11.67 | 19.34 | <0.6 | <1.9 | <2.3 | <3.9 | <1.3 | 1.2 | <0.5 | 2.1 | <0.4 | <0.6 | <0.6 | 24-May-04 |
| HAR-18 | 80 | 50 | 27.53 | 52.48 | 3528 | 1912 | 107 | 86 | 74 | <0.5 | <0.5 | <0.5 | <0.4 | <0.6 | <0.6 | 26-Aug-03 |
| HAR-23 | 90 | 60 | 24.71 | 65.29 | 5.0 | 9.8 | 5.9 | <3.9 | <1.3 | 0.4 | <0.5 | 1.5 | <0.4 | <0.6 | <0.6 | 21-May-04 |
| RD-01 | 506 | 480 | 207.10 | 298.91 | 863 | 646 | 19.2 | 3.3 | 26.1 | 2.2 | 0.5 | - | 0.4 | <0.6 | <0.6 | 9-Nov-04 |
| RD-35B | 328 | 21 | 125.42 | 202.58 | 1881 | 750 | 27.5 | 104.8 | 7.5 | 144 | 2.2 | - | 0.8 | <0.6 | <0.6 | 21-May-04 |
| RD-41B | 390 | 50 | 131.53 | 258.47 | 1296 | 614 | 37 | <3.9 | 30 | 25 | 7.3 | 0.6 | <0.4 | <0.6 | <0.6 | 10-Feb-04 |
| RD-49A | 50 | 31.5 | 18.53 | 31.48 | 3387 | 1710 | 42 | 13.5 | <1.3 | 3.0 | <0.5 | - | <0.4 | <0.6 | <0.6 | 19-Feb-04 |
| RD-49B | 298 | 48 | 256.89 | 41.11 | 358 | 242 | 11 | <3.9 | 4.4 | 3.1 | <0.5 | - | <0.4 | <0.6 | <0.6 | 17-Nov-03 |
| RD-55A | 106 | 78 | 24.75 | 81.25 | 393 | 352 | 13 | <3.9 | 43 | <0.5 | <0.5 | <5.0 | <0.4 | <0.6 | <0.6 | 26-Aug-03 |
| RD-55B | 250 | 50.5 | 59.64 | 190.37 | 9.9 | <1.9 | <2.3 | <3.9 | <1.3 | 0.9 | 0.3 | 17 | 0.4 | <0.6 | <0.6 | 18-May-04 |
| RD-67 | 102 | 82 | 66.39 | 35.62 | 4 | 46.8 | 86.8 | <3.9 | <1.3 | 0.6 | <0.5 | <5.0 | <0.4 | <0.6 | <0.6 | 10-May-04 |
| RD-72 | 182 | 155 | FLUTe System | - | 130.6 | 2054 | 55.6 | 85.7 | <1.3 | 75 | 0.80 | 3.3 | <0.4 | <0.6 | <0.6 | 26-May-04 |
| RD-77 | 170 | 124 | 137.07 | 32.94 | 6563 | 194 | <2.3 | 149.6 | <1.3 | 0.3 | <0.5 | - | <0.4 | <0.6 | <0.6 | 19-May-04 |

Notes: 1. Average of quarterly measurements.

Snap Sampler Bottle Preparation

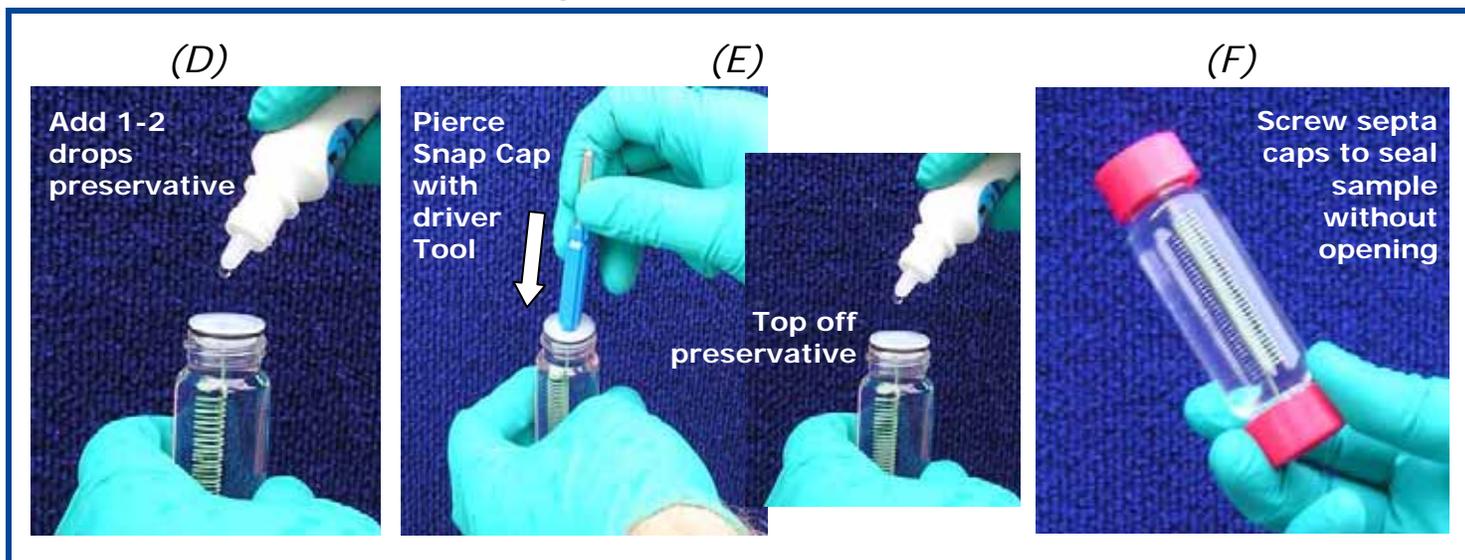
40 ml VOA

Trim Snap Caps



- A) *Snap Sampler VOA, removed from Snap Sampler.*
- B) **[UNPRESERVED]** Carefully trim Snap Caps flush. *To trim first Snap Cap, hold ends with finger and thumb while clipping--making sure not to dislodge seal. Carefully screw on first septa cap--making sure not to dislodge seal; trim second Snap Cap; screw on second septa cap, then retighten both septa caps to secure.*
- C) *Prepared, unpreserved bottle.*
- D) **[PRESERVED]** After securing one end of the Snap VOA , trim the second Snap Cap; add preservative to the cavity in the Snap Cap.
- E) **[PRESERVED]** Pierce the Snap Cap membrane with the pointed end of the Driver Tool to allow preservative to mix with the sample; top off preservative to form a meniscus, then secure the second septa cap.
- F) *Prepared, preserved bottle.*

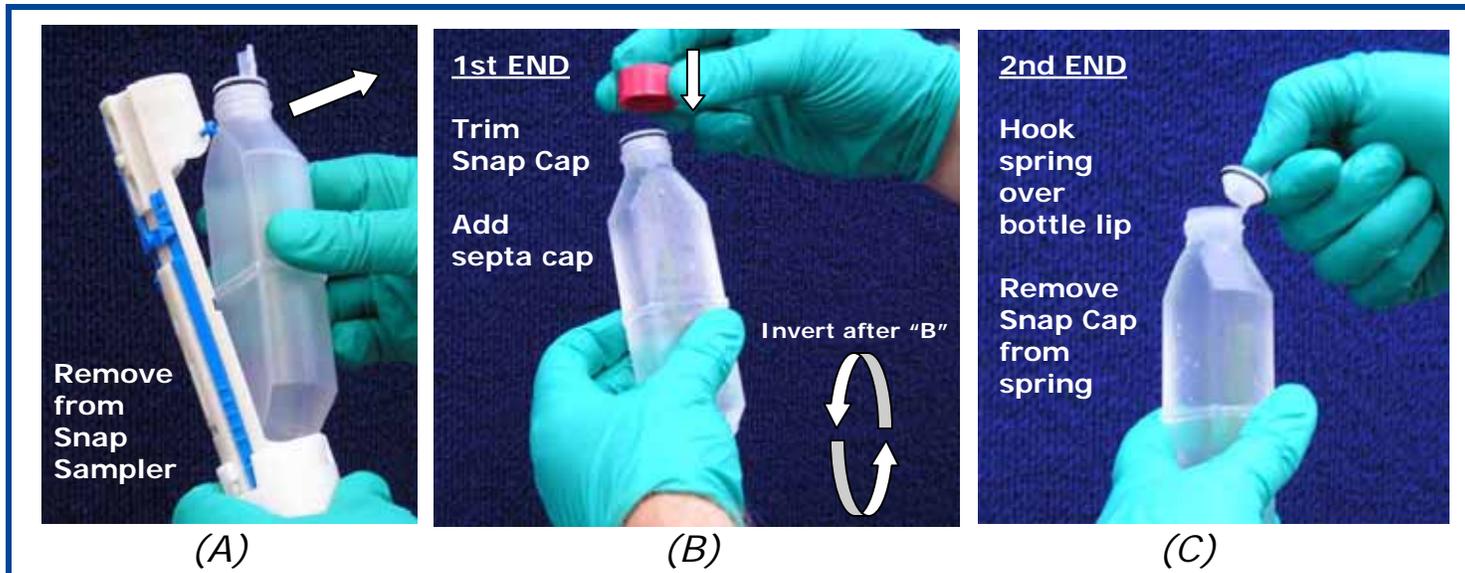
Add Preservative (as required)



Snap Sampler Bottle Preparation 125 ml Poly

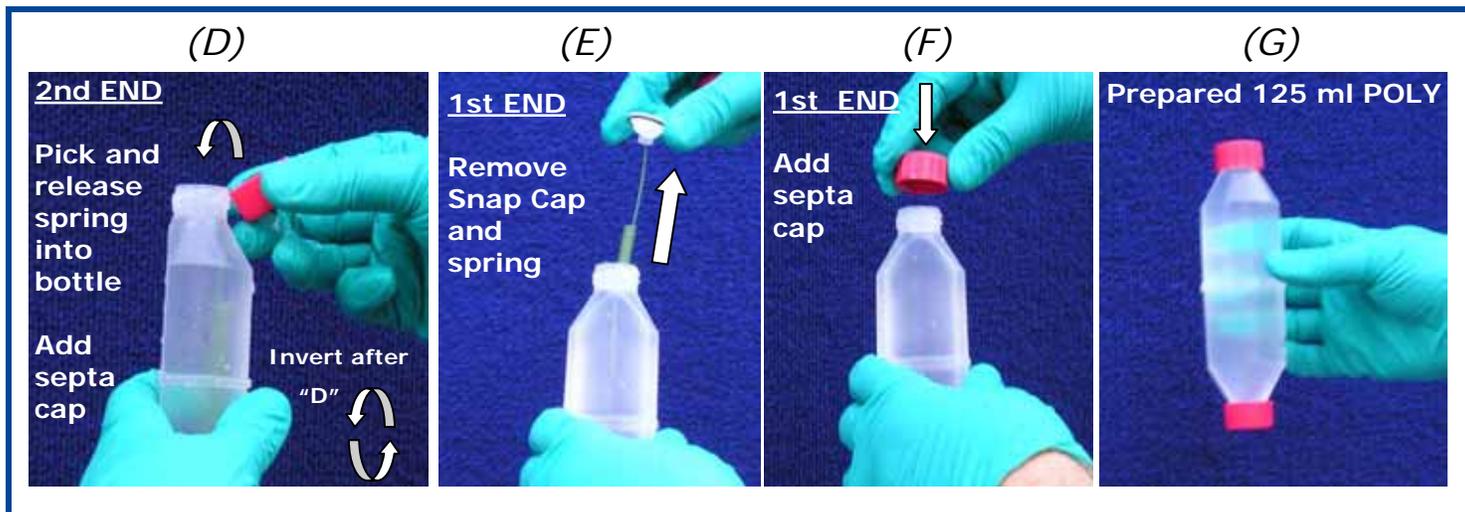
*(for analytes where air exposure after collection is not a concern,
Otherwise follow preparation procedure for 40 ml VOA on reverse)*

Trim/Remove Snap Caps



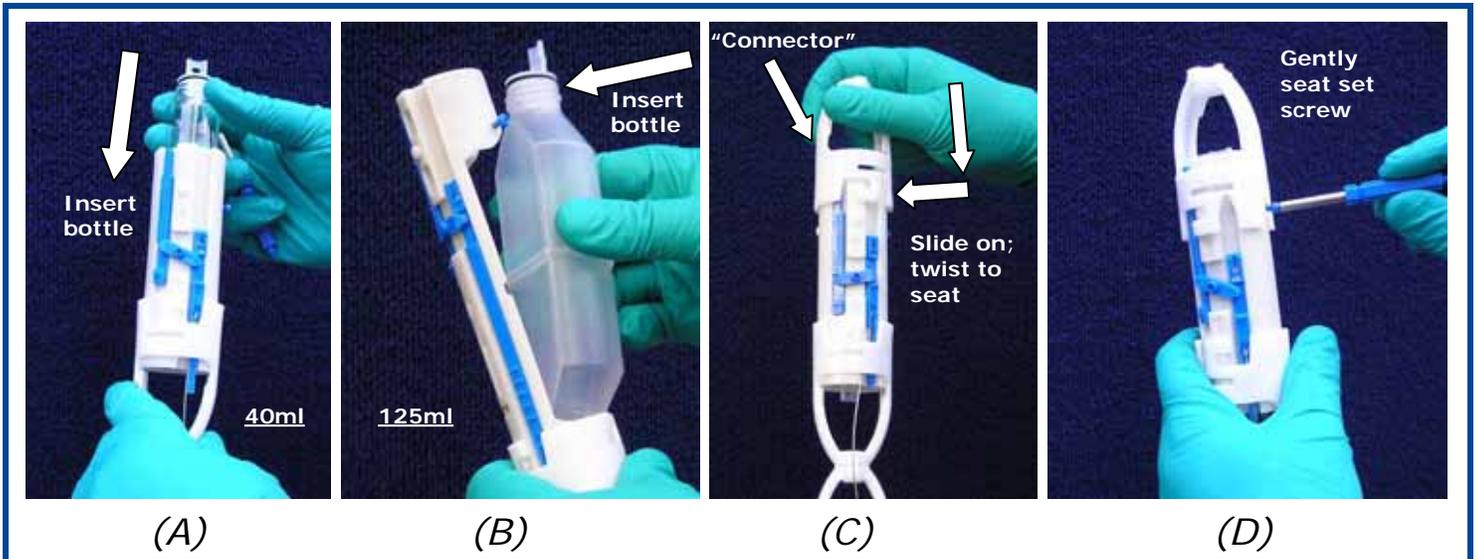
- A) Remove Snap POLY Bottle from Snap Sampler.
- B) **Trim one Snap Cap** (see step "B" on reverse); **secure septa cap lightly** (you will remove it in step "E" below).
- C) **Invert bottle and remove second Snap Cap by hooking the internal Spring over the lip of the bottle.**
- D) **Lift spring and release into the bottle using lip of septa cap; secure cap.**
- E) **Re-invert the bottle; remove septa cap; remove the Snap Cap and spring.**
- F) **Add preservative (if required), secure septa cap.**
- G) **Prepared bottle**

Remove spring



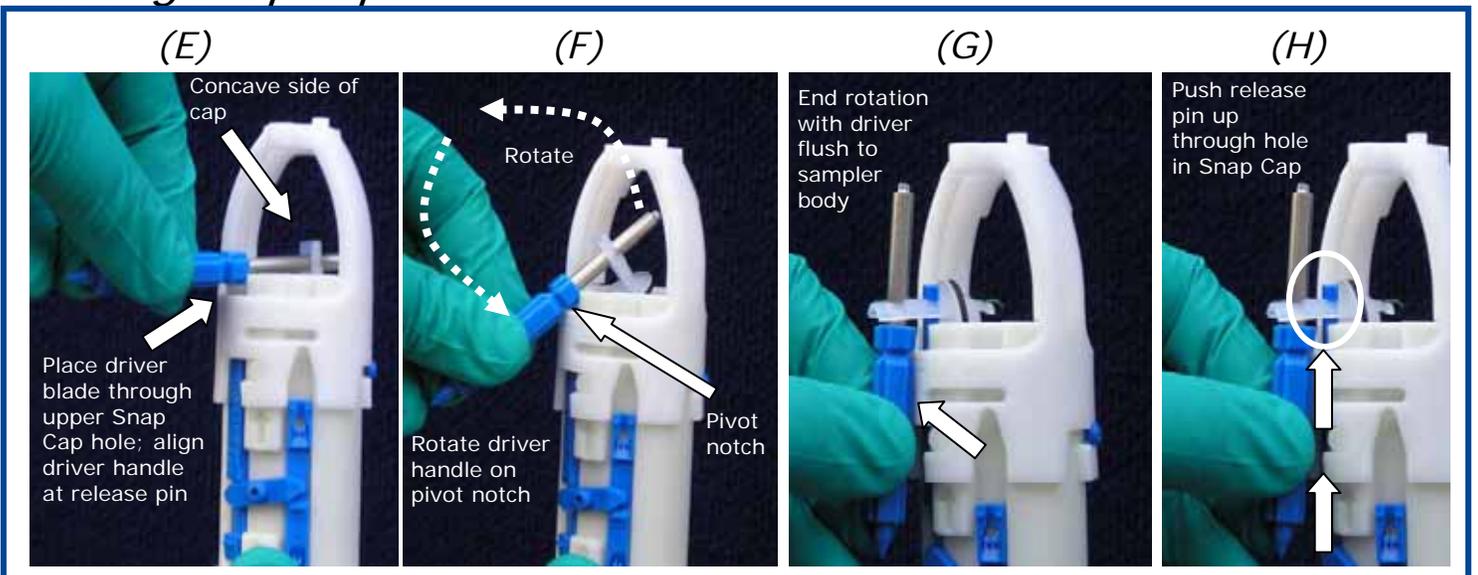
Snap Sampler Deployment (page 1 of 2)

Inserting and securing bottles



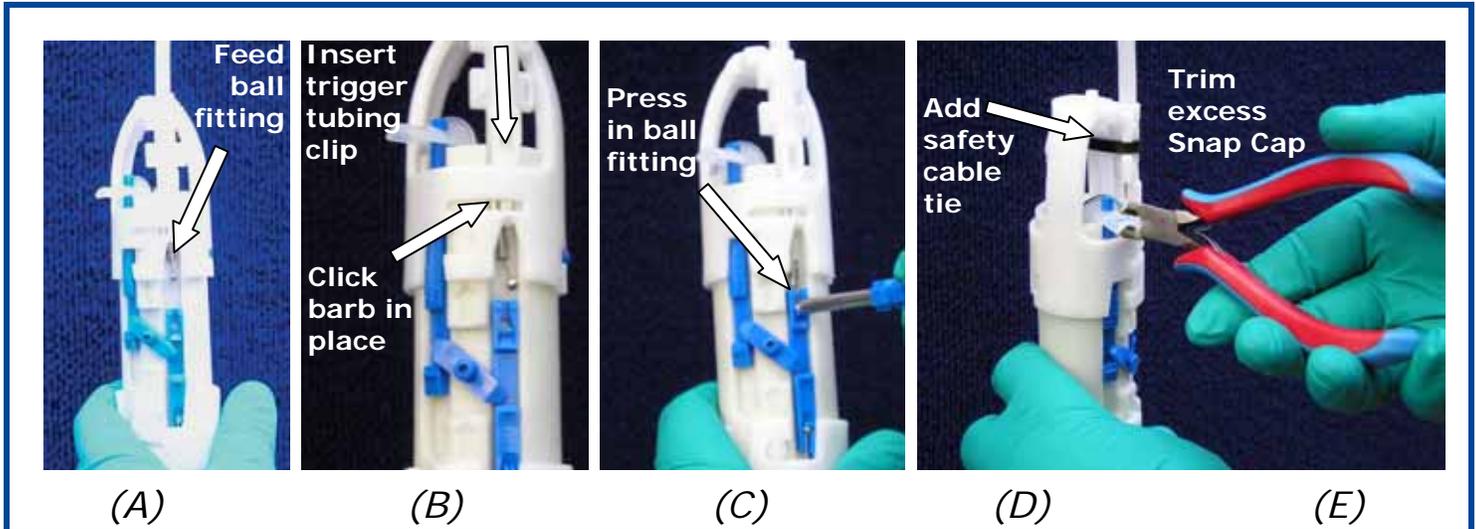
- A) Insert 40 ml VOA into top of 40 ml Snap Sampler *...or...*
- B) Insert 125 ml POLY into back side of 125 ml Snap Sampler.
- C) Slide "Connector" over sampler and twist clockwise to seat.
- D) Secure Connector and bottle with blue set screw.
- E) **Set All Bottom Snap Caps First, then Top Snap Caps.** Insert Snap Driver blade into the **upper hole** of the **concave** side of Snap Cap (insert the driver past the tip, to the **smooth part** of the driver blade shaft); **align driver handle with the release pin.**
- F) Rotate Snap driver on the pivot notch in the driver handle.
- G) Pivot on the notch in the driver handle until **driver handle is flush with sampler body** and Snap Cap is in its seat; grasp driver or use thumb to rotate driver so that fingers are kept clear of driver alignment with sampler body.
- H) Use thumb of the hand holding the Sampler to push release pin up through lower hole in the Snap Cap; repeat "E" through "H" for each Snap Cap in all Samplers.

Setting Snap Caps



Snap Sampler Deployment (page 2 of 2)

Attaching trigger



- A) Insert ball end of trigger in upper release pin groove.
- B) With **trigger barb facing out**, insert trigger until it **clicks** into position.
- C) **Press trigger line ball fitting into release pin.**
- D) Attach safety cable tie.
- E) Trim protruding Snap Caps between ribs (required for smaller diameter wells). Where more than one sampler is attached to one trigger, **connect ball-end connector cables between each sampler** (not shown).
- F) Lower Sampler to depth; seat trigger clip into ramp on Dock Ring.
- G) Close and lock well cap.
- H) To sample, **pull trigger cable while holding Dock Ring in place**; remove trigger from dock and retrieve samplers.

Well Head Dock Attachment

