

**ENHANCED IN-SITU BIOREMEDIATION
PILOT STUDY REPORT**

SILTRONIC CORPORATION

Prepared for
Siltronic Corporation
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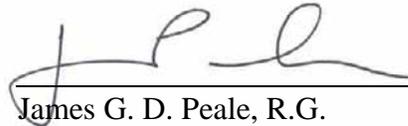
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**Enhanced *In-situ* Bioremediation Pilot Study Report
Siltronic Corporation**

The material and data in this report were prepared under the supervision and direction of the undersigned.

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ACRONYMS AND ABBREVIATIONS

ug/L	micrograms per liter
AAI	Adventus Americas, Inc.
bgs	below ground surface
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
cVOC	chlorinated volatile organic compound
DCE	Dichloroethene
DEQ	Oregon Department of Environmental Quality
DO	dissolved oxygen
EIB	enhanced in-situ bioremediation
FS	Feasibility Study
GCW	groundwater circulation well
JSCS	Joint Source Control Strategy
MFA	Maul Foster & Alongi, Inc.
MGP	manufactured gas plant
ml	Milliliter
OAR	Oregon Administrative Rules
ORP	oxidation reduction potential
PCR	polymerase chain reaction
PID	photo-ionization detector
ppm	parts per million
PRB	Permeable Reactive Barrier
RI	remedial investigation
RPSA	riverbank pilot study area
SCM	source control measure
Siltronic	Siltronic Corporation
SZPSA	source zone pilot study area
TCE	trichloroethene or trichloroethylene
the Order the Work Plan	<i>Order Requiring Remedial Investigation and Source Control Measures</i> Pilot Study Work Plan issued July 28, 2006
TOC	total organic carbon
TZW	transition zone water
USEPA	U.S. Environmental Protection Agency
UST	underground storage tank

ACRONYMS AND ABBREVIATIONS (CONT.)

VC	vinyl chloride
VFA	volatile fatty acid
VOC	volatile organic compound
ZVI	zero-valent iron

EXECUTIVE SUMMARY

On behalf of Siltronic Corporation (Siltronic), Maul Foster & Alongi, Inc. (MFA) has prepared the following report which documents the results of the pilot study of enhanced in-situ bioremediation (EIB) of trichloroethene (TCE) and its degradation products in groundwater. In short, the results indicate that EIB as tested is a viable remedy for reducing and potentially eliminating the plume of TCE and its degradation products in the upland and below the Willamette River.

This report was prepared consistent with the requirements of the *Order Requiring Remedial Investigation and Source Control Measures*, Oregon Department of Environmental Quality (DEQ) No. VC-NWR-03-16, issued to Siltronic on February 9, 2004 (the Order). The Order was issued following discovery of a groundwater plume of TCE and its degradation products at the Siltronic facility. TCE and its degradation products were found to be present in excess of Portland Harbor Joint Source Control Strategy (JSCS) screening level values (SLVs) in groundwater adjacent to the Willamette River, and in transition zone water (TZW) in the river. The nature and extent of TCE and its degradation products is further described in the *RI Report* (MFA, 2007), under review by DEQ.¹

The pilot test was proposed following completion of a technology alternatives screen and subsequent bench test of EIB alternatives, comparing a variety of commercially-available products. The EIB alternatives all utilize (at a minimum) reductive dechlorination as a primary mechanism for converting TCE and its degradation products to non-toxic ethene. The initial results of the bench test were presented previously in the Pilot Study Workplan (MFA, 2006); the extended results are included in this report. The extended results of the bench test indicated that a pilot test of a combined approach, using a hydrophilic carbon/zero-valent iron blend (EHC™) and anaerobic bacteria culture (KB-1™) had a high probability of success.

The primary criteria for measuring the effectiveness of EIB are (a) reduction of concentrations of TCE and its degradation products in groundwater to below JSCS SLVs at the riverbank, and (b) remediation of potential TCE DNAPL in the source area. Since the presence of TCE DNAPL in the source area has only been inferred from aqueous phase concentration data, remediation is defined as reducing concentrations of TCE in

¹ This report relies on the information regarding nature and extent of TCE and its degradation products presented in the RI Report, but that information is only reproduced herein as necessary.

groundwater to below the 1 percent solubility limit rule proposed in *Evaluation of the Likelihood of DNAPL at NPL Sites* (USEPA, 1993).

Supplemental data (i.e., pH, oxidation-reduction potential, concentrations of redox-sensitive species such as dissolved oxygen, methane, and sulfate, production of ethene and chloride) are critical for characterizing the geochemical conditions and confirming dechlorination. Polymerase chain reaction (PCR) data identifying the growth and distribution of KB-1 bacteria were also identified as critical.

A secondary criterion for measuring the effectiveness, identified by DEQ, is the extent to which EIB mobilizes redox-sensitive metals, such as arsenic and manganese. The extent to which EIB interacted with representative MGP-related constituents such as benzene, naphthalene, and cyanide was also identified as of secondary importance.

The pilot test data confirm that EIB meets all of the criteria. At the riverbank, concentrations of TCE and its degradation products in groundwater were reduced to below JSCS SLVs, and chlorinated volatile organic compound (cVOC) mass reduction of 99.99 percent was achieved. KB-1 bacteria were identified downgradient of the injection zone. Redox-sensitive metals were not mobilized, and free cyanide concentrations were fortuitously reduced.

In the source area, initial TCE concentrations characteristic of TCE DNAPL were reduced by 94 to 99.96 percent. Fully dechlorinated ethene was produced. The supplemental data confirmed the conversion mechanism (reductive dechlorination), and KB-1 bacteria were identified downgradient of the injection zone. Redox-sensitive metals were not mobilized, and free cyanide concentrations were fortuitously reduced.

Aquifer testing data and analytical data were used to predict the short-term (i.e., 1-3 years) performance of a full-scale remedy downgradient of the injection zones. The data indicate that the groundwater velocity at the riverbank is approximately 268 feet per year. This suggests that EIB could treat Area 1 TZW concentrations within a few years following injection at the riverbank.

Coupled with groundwater velocity data, the pilot study data suggest the following:

- 1) EIB will be successful in the source area, where concentrations of TCE are relatively high, and indicative of the presence of TCE-DNAPL.
- 2) EIB will be successful as a source control remedy, preventing migration of TCE and its degradation products in groundwater at concentrations in excess of JSCS SLVs to the Willamette River.
- 3) EIB could be implemented at the riverbank to reduce or eliminate concentrations of TCE and its degradation products in TZW.

1 INTRODUCTION

Maul Foster & Alongi, Inc. (MFA) has prepared this report summarizing the results of an enhanced *in-situ* bioremediation (EIB) pilot study that was conducted at the Siltronic Corporation (Siltronic) facility located at 7200 NW Front Avenue, Portland, Oregon. The pilot study was conducted in accordance with the Final Enhanced Bioremediation Pilot Study Work Plan (the Work Plan) (MFA, 2006a). The pilot study work plan was based on treatability study guidance from USEPA and is therefore consistent with the National Contingency Plan, as required for Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) actions. Development of the pilot study was also consistent with Oregon Administrative Rules (OAR) 340-122-0070 and related regulations OAR 340-122-0040(1), (5), and (6).

These results of the pilot study will inform the Feasibility Study (FS) with respect to the selection of a site-wide remedy or source control measure (SCM). Siltronic has recently completed a remedial investigation (RI) per the *Order Requiring Remedial Investigation and Source Control Measures* (the Order), Oregon Department of Environmental Quality (DEQ) No. VC-NWR-03-16, issued to Siltronic on February 9, 2004. Section 5.B of the Order states that Siltronic shall identify and evaluate source control measures, and that the DEQ will review and approve these measures pursuant to OAR 340-122-0070 and through consultation with the United States Environmental Protection Agency (USEPA).

This pilot study was completed within upland areas adjacent to the Portland Harbor National Priorities List (NPL, or Superfund) site. As such, it is within the jurisdiction of DEQ, consistent with the 2001 Memorandum of Understanding between DEQ, USEPA and partners, and consistent with the Joint Source Control Strategy for the Portland Harbor (JSCS) (DEQ and USEPA, 2005).

1.1 OVERVIEW OF IMPACTS

Figure 1-1 shows the site location and groundwater plume of trichloroethylene (TCE) and its degradation products (dichloroethylene [DCE] and vinyl chloride [VC]). The plume is the result of a release or releases from a former TCE management system that included

underground storage tanks (USTs). The releases are suspected to have occurred between 1980 and 1984 TCE use at the plant was discontinued in 1989.²

The source area is located on the south side of the Fab 1 building. Pre-pilot study concentrations of TCE in groundwater were as high as 592,000 micrograms per liter (ug/L) at depths ranging between 50 and 105 feet below ground surface (bgs). These concentrations were characterized as indicative of a high probability that TCE could be present as DNAPL, based on US EPA guidance (USEPA 1993). No TCE DNAPL has been found to date. Concentrations of the primary degradation product (cis-1,2-DCE) were as high as approximately 50,000 ug/L, while minimal vinyl chloride was detected (approximately 50 ug/L).

The groundwater plume extends approximately 900 feet north from the source area to an area underlying the Willamette River, terminating at the river bottom at Area 1. The plume measures approximately 350 feet in width at the riverbank. TCE and its degradation products have been observed at depths between 80 and 130 feet bgs at the riverbank.

Pre-pilot study concentrations of TCE at the riverbank ranged from approximately 848 to 2,020 ug/L, with significantly higher concentrations of cis-1,2-DCE (up to 34,000 ug/L) and vinyl chloride (up to 5,170 ug/L).

Consistent with the JSCS, the Siltronic facility is a medium-priority site, such that source control is warranted but not of immediate concern. Siltronic determined that implementation of source control, if feasible, is a reasonable course of action that provides a beneficial outcome for the environment.

1.2 TREATMENT TECHNOLOGY EVALUATION

Five treatment technologies (pump and treat, thermal remediation, groundwater circulation wells (GCW), chemical oxidation, and bioremediation) were evaluated in detail in the *Initial Source Control Technologies Evaluation* (MFA, 2006b).

The evaluation concluded that laboratory bench testing of the bioremediation technology using groundwater and soil obtained from the site was warranted. The laboratory bench-scale bioremediation test evaluated several commercially available bioremediation amendments. The following sections describe the bench test approach and results.

² The 2002 MFA *TCE Use and Management Report* provides more information regarding the TCE use history.

1.2.1 BIOREMEDIATION BENCH TEST

The bioremediation bench test compared the performance of three commercially available bioremediation amendments (electron donor materials) (EHC^{TM 3}, EOS^{® 4}, and HRC-X^{TM 5}). The test also evaluated performance of each material with and without an added microbial population (KB-1^{® 6}) that is known to completely reduce TCE to ethene in the subsurface.

The bench test consisted of adding the various amendments to columns packed with soil from the site. Groundwater from the site was spiked with TCE and manufactured gas plant (MGP) constituents (benzene and naphthalene) at concentrations comparable to site conditions.

Results from the bench test indicated that EHC provided the best performance with respect to dechlorinating TCE and its degradation products and proved more effective at higher concentrations of TCE. EHC was selected as the preferred technology for further evaluation in the pilot study with the added KB-1 microbial population. Results from the bench test are discussed in more detail below.

1.2.2 BENCH TEST RESULTS

The first phase of bench testing involved replication of downgradient conditions, with influent concentrations of TCE at about 10 ppm.

The bench test data from the first phase of bench testing indicated the following:

- All three donor materials effectively degraded TCE to the primary degradation product cis-1,2-DCE without the addition of the microbial population.
- cis-1,2-DCE was not effectively degraded to vinyl chloride by the columns without the microbial populations, with the exception of the column containing EHC.
- The columns containing EHC and EOS and the KB-1 demonstrated the best performance with respect to fully dechlorinating TCE and its degradation products as evidenced by the production of ethene.

The second phase of testing consisted of evaluating treatment of groundwater containing concentrations of TCE characteristic of the source area. Three contact periods were run

³ EHC[®] is a trademark of AAI.

⁴ EOS[®] is a registered trademark of EOS Remediation, Inc.

⁵ HRCTM is a trademark of Regensis.

⁶ KB-1 is a registered trademark of SiRem Labs.

with TCE concentrations of 240 ppm for 21 days, 870 ppm for 21 days, and 640 ppm for 42 days. The data from the second phase of testing are summarized as follows:

- The columns containing EHC (with and without the KB-1) demonstrated the best performance with respect to dechlorinating TCE and its degradation products, exhibiting the highest production of ethene in all three runs.
- At extremely high concentrations of TCE (870 ppm) EHC performed best when coupled with KB-1, converting a majority of the TCE to VC and ethene.
- The columns containing the EOS (with and without the KB-1) did not perform as well as the EHC columns, with significant accumulation of cis-1,2-DCE and lower amounts of conversion to VC and ethene.
- The columns containing the HRC-X amendments (with and without the KB-1) did not perform as well as the EOS columns, with substantially greater accumulations of cis-1,2-DCE, and little production of vinyl chloride. The HRC-X columns demonstrated a pattern of “stalled” dechlorination, where TCE is dechlorinated but the primary degradation product (DCE) is not.

The summary data from the second phase of the bench test is included in Appendix A. The bench test results indicated that the EHC and EOS products are capable of dechlorinating TCE and its degradation products at concentrations observed in WS-11-125. The results also indicate that the EHC product is capable of dechlorinating TCE and its degradation products at significantly higher concentrations characteristic of the former UST area.

The EHC product provides an additional abiotic dechlorination pathway (beta-elimination) as a result of the inclusion of ZVI. As demonstrated during the second test phase, EHC is more effective at higher concentrations of TCE. Based on the results of the bench test, a combined approach using EHC and KB-1 was selected for further evaluation in the pilot study.

1.2.3 EHC

EHC is a combination of controlled-release solid carbon (plant fiber based) and zero-valent iron (ZVI) particles that yield a material for stimulating reductive dechlorination of persistent organic solvents in groundwater and source zones. The product is shipped as a powder which is hydrated to make a slurry for injection. After the material is injected, EHC stimulates degradation via the following mechanisms:

- Initial conditioning – EHC produces strong reducing conditions that favor the low redox environment preferred by the *dehalococcoides* (DHC) bacteria. The

plant fiber (i.e., the carbon source) contained in EHC is first degraded by indigenous bacteria to release volatile fatty acids (VFAs). The VFAs supply hydrogen that is used by the DHC bacteria for dechlorination of TCE and its degradation products. During the consumption of the plant fiber, oxygen is consumed by the indigenous bacteria, reducing the redox potential within the water.

- Beta-elimination – EHC includes up to 50 percent by weight of ZVI particles. ZVI particles abiotically degrade TCE and its degradation products via the beta-elimination pathway (Figure 1-2). Unlike biodegradation, the beta-elimination pathway is not a step-wise or sequential dechlorination, and intermediate degradation products (including vinyl chloride) are not produced.
- Thermodynamic instability - The combined effect of the conditioning and beta-elimination processes can increase the reducing conditions in the groundwater to a point where TCE and its degradation products are thermodynamically unstable. Thermodynamic decomposition of TCE and its degradation products occurs in a redox range of -400 to -600 millivolts (mV). These redox conditions have been measured but often occur at time and distance scales that cannot be practically measured. As such, highly reducing conditions are also inferred by end products (Dolfing, 2006).

Initial conditioning and beta-elimination are the primary treatment processes that were observed in the pilot study. As evidenced in the bench test, the presence of the *dehalococcoides* bacteria in favorable conditions (sufficient electron acceptor and donor levels, absence of oxygen, appropriate redox conditions) can rapidly degrade TCE at concentrations exceeding those measured at the site. The beta-elimination pathway is an abiotic, physio-chemical process that occurs as soon as the ZVI particles are injected into the plume.

The standard EHC formulation is typically expected to last for 2 to 5 years (depending on site specific conditions) before reapplication is needed. An available extended release formulation releases the carbon at a rate that is about half of the standard formulation. Each of the formulations typically contain about 50 percent ZVI.

1.2.4 KB-1

Specific naturally-occurring microbial strains have been identified that are capable of dechlorinating TCE, DCE, and VC to the relatively non-toxic end-product ethene. The *Dehalococcoides* microbes perform this process only under anaerobic reducing conditions. The microbes have been isolated from soil samples so that they can be cultured commercially (similar to yogurt cultures) for application at various sites for groundwater remediation of chlorinated solvents.

The bench test data indicated that the presence of the KB-1 culture produced by SiREM had the largest influence on the degradation rates of the test columns. KB-1 is a consortium of naturally occurring microorganisms, including *Dehalococcoides*, *Geobacter*, and *Methanomethylovorans*, known to dechlorinate TCE to ethene. The conversion of vinyl chloride to ethene is generally carried out by the *Dehalococcoides* bacteria, whereas degradation of TCE to DCE may be carried out by other bacteria. From a durability standpoint, these bacteria are expected to persist indefinitely as long as subsurface conditions favor their growth.

2 PILOT STUDY PROCEDURES

The pilot study evaluated enhanced in-situ bioremediation (EIB) of TCE in two areas of the site. The following sections describe the pilot study areas and procedures for implementation, including evaluation of groundwater velocity in these areas.

2.1 TREATMENT ZONE AREAS

The pilot study was designed to evaluate the effectiveness of EIB in two areas, the Source Zone Pilot Study Area (SZPSA) and the Riverbank Pilot Study Area (RPSA).

2.1.1 SOURCE ZONE PILOT STUDY AREA (SZPSA)

The source area pilot study is intended to evaluate the remedy in the context of removing source material, consisting of high concentrations of TCE. As described in Section 4.1 of the Work Plan, the SZPSA consists of a permeable reactive barrier (PRB) in the area of highest TCE concentrations in groundwater, located between GP87 and GP89. This area is 35 feet downgradient of the former underground storage tank (UST) area on the south side of Fab 1. The design was developed in discussions between MFA and DEQ.

The length and width of the PRB are approximately 15 and 10 feet, respectively. The PRB consists of 12 injection points spaced 5 feet apart, with three rows of four injection points, as shown in Figure 2-1. The vertical extent of the injection intervals in the SZPSA was from 50 ft bgs to 106 ft bgs. Based on an average vertical spacing of 4 feet between intervals, each injection point had 14 to 15 intervals where amendments were added. Within the SZPSA the standard-release formulation EHC was injected at 1.5 percent by weight of soil within the treatment zone. KB-1 was injected at about 7 liters per injection point.

The methodology for treatment is to inject microbes and EHC (bioamendment) directly into the contaminant source materials. Injecting directly into the source should accelerate removal of the contaminant mass by degrading dissolved TCE and DCE. Removal of dissolved TCE at the source is expected to then increase the concentration gradient between the non-aqueous phase (either sorbed to soil or as non-aqueous phase liquid) and groundwater, increasing the rate of dissolution and treatment. The increased mass flux from the non-aqueous phase to the aqueous phase (where dechlorination occurs)

effectively remediates potential TCE DNAPL. By removing or reducing the high concentration source materials, less material will be transported downgradient, and eventually eliminate the need for control at the property boundary.

2.1.2 RIVERBANK PILOT STUDY AREA (RPSA)

As described in Section 4.2 of the work plan, the RPSA consists of a PRB within an area of moderate TCE concentrations, located downgradient of the northern edge of the FAB1 building.

The length and width of the PRB are about 30 and 21 feet, respectively. The PRB consists of 20 injection points spaced 7 feet apart, with four rows of five injection points, as shown in Figure 2-2. The vertical extent of the injection intervals in the RPSA was from 90 ft bgs to 130 ft bgs. Based on an average vertical spacing of 4 feet between intervals, each injection point had 10 to 11 injection intervals. Within the RPSA the standard-release formulation EHC was injected at 1 percent by weight of soil within the treatment zone. KB-1 was injected at about 3 liters per injection point.

EIB in the RPSA is intended to function as a treatment “wall” or PRB. The PRB reduces dissolved concentration of TCE, DCE, and VC to acceptable levels before the groundwater travels under the Willamette River. Based on bench test data, a 20 day treatment time for groundwater flowing through the PRB was the basis for design.

2.2 FIELD IMPLEMENTATION

The following summarizes the field work completed for the pilot tests and supplemental aquifer testing. A summary of specifications for each pilot study area is contained in Table 2-1.

2.2.1 MONITORING WELL INSTALLATION

Four monitoring wells (WS18-71, WS18-101, WS19-71 and WS19-101) in the SZPSA and three monitoring wells (WS20-112, WS21-112, and WS22-112) in the RPSA were installed by Geo-Tech Explorations, Inc. of Tualatin, Oregon (Oregon Monitoring Well Constructor License No. 10011) from May 30, 2006 through June 14, 2006 with a MINISONIC (i.e., limited access Rotosonic) drilling rig.

The wells are constructed of 2-inch polyvinyl chloride casing, stainless steel wire wrapped well screen (10 feet in the SZPSA and 15 feet in the RPSA), and a 1-foot stainless sump at the bottom. Screen intervals were determined by DEQ based on the reconnaissance groundwater sampling prior to well installation. Sand pack was installed

from approximately 2 feet above the screened interval to the bottom of the hole. Hydrated bentonite chips were installed from approximately 2.5 feet above the screen to surface.

Each well was developed using an air-lift pump. A dedicated bladder pump was installed in each well within the screen interval for low-flow sampling.

2.2.2 INJECTION OF AMENDMENTS

Amendments were injected in the downgradient RPSA from May 30, 2006 to June 28, 2006. SZPSA injections were completed from June 29, 2006 to July 17, 2006. EHC was the first amendment injected at each injection point. To ensure optimal growth conditions for microorganisms, KB-1 was injected at each boring after a minimum of 14 days had elapsed since EHC injection. Injections procedures for each media are detailed below. Injection logs are contained in Appendix B.

2.2.2.1 EHC

The procedure for injection included advancing 2-inch drill rods equipped with an injection tip to the first, or shallowest, interval of each injection point with a Geoprobe truck rig. Injection intervals began at 90 or 92 feet bgs in the RPSA and 50 or 52 feet bgs in the SZPSA. Water was added to the EHC and it was mixed in either a ChemGrout Mixer or a drum with a portable mixer. The nozzle of the pump hose was attached to the exposed end of drill rod with the intake placed in the mixed EHC drum/hopper. The injection pressure was monitored as material was delivered to the subsurface.

If any daylighting occurred at the top of the boring or if the pressure continued to increase to an unsafe level (at the discretion of the driller and/or MFA field personnel), injection was paused. Either the drill rods were kept in place and pressure was allowed to subside or the drill rods were extended to allow EHC to enter the formation. Once the required amount of EHC was injected in the interval, the nozzle was removed and the drill rods would be advanced an additional 4 feet, and the mixing and injection process was repeated until the final interval was complete (128 or 130 feet bgs in the RPSA and 104 or 106 feet bgs in the SZPSA). In each RPSA injection interval an average of 200 pounds of EHC was used. In the SZPSA, each interval received an average of 150 pounds of EHC.

After the final interval, the drill rods were raised to the depth of the initial injection interval while continuing to pump residual EHC. Typically the boring would be allowed to sit overnight to let pressure to subside. Once the pressure had subsided, the drill rods were removed and the boring was sealed with bentonite grout from approximately 40 feet bgs to the surface.

2.2.2.2 KB-1

The delivery method (using low DO water) required the following equipment: drill rig, rods with well screen, a dispenser supplied by SiREM with capacity of 500 milliliters (ml), a nitrogen tank, polyethylene tubing to the depth of the interval, peristaltic pump, quick-disconnects, and low DO water (created with sodium lactate, sodium sulfite and potable water).

Once the drill rods were advanced to the depth of the first (deepest) interval at the injection point, approximately 1-2 feet of the well screen was exposed. The tubing was inserted through the drill rods and a peristaltic pump was connected in order to collect a sample. The sample was measured for field parameters, specifically oxidation-reduction potential (ORP) and DO. If conditions were acceptable (i.e., low DO and ORP less than -75 mV), preparations were made to inject the KB-1.

The KB-1 canister was agitated prior to injecting in order to mix the microorganisms thoroughly into the solution. The canister was pressurized with nitrogen gas through a valve. Anaerobic conditions were maintained in the air-tight dispenser by purging with nitrogen gas. Then the dispenser was loaded with the appropriate volume of KB-1. The RPSA required three canisters with 300 ml delivered per interval. In the SZPSA, four canisters were used with 500 ml delivered per interval.

The peristaltic pump was set up to pump into the boring and low DO/ORP water was flushed through the line. A slug of KB-1 was delivered through the line and followed by additional low DO/ORP water. Pumping continued until a sufficient volume of low DO water was pushed through the line to ensure that the KB-1 had been delivered to the interval.

The tubing was then removed and the line was inspected for any remaining KB-1 slug. If the water in the line was clear, KB-1 delivery was confirmed. The rods were tripped out 4 feet to the next interval and the process was repeated. Once the final (shallowest) interval was completed, the drill rods were removed to 40 feet bgs and the boring was sealed with grout from approximately 40 feet bgs to the surface.

2.2.3 MONITORING

Following the completion of injections in each area, monitoring wells upgradient, downgradient and internal to the RPSA and SZPSA PRB were sampled to assess the effect of the amendments. Time 0 monitoring was initiated in the RPSA in June 2006 and in the SZPSA in July 2006 to establish initial conditions immediately following injection of the bioremediation media.

Additional sampling events were completed through May 2007, as shown on Table 2-2. Sampling and analysis was completed consistent with the RI Work Plan (MFA, 2004)

using dedicated bladder pumps and low-flow techniques. The analyses performed are listed in Table 2-3.

The source area wells were screened for the presence of DNAPL in September, but none was identified.

2.3 SLUG TESTING

As part of the RI work, MFA collected soil samples for permeability and hydraulic conductivity analysis, and conducted specific capacity testing in the source area and at the riverbank (MFA, 2007).

Additional information was warranted, so pneumatic slug tests were performed during March 2007. 12 wells were tested, including shallow wells within the plume (WS13-69, WS18-71, WS18-101, WS19-71, WS19-101, WS12-125, WS20-112, WS21-112, WS22-112), and deeper wells around the plume (WS11-161, WS12-161, and WS14-161). Wells located beyond the lateral extent or below the lower vertical extent of the plume of TCE and its degradation products were not included; nor were any wells with MGP DNAPL present.

Dedicated pumps were removed from the wells and water levels were allowed to equilibrate one week prior to slug testing. The pneumatic slug testing equipment (transducer, laptop, connections, pump or gas cylinder) was supplied by a subcontractor (Boart-Longyear of Tualatin, Oregon). The transducer was installed below the water level in the well and an air tight pressurizing apparatus was attached to the top of the well column. Before each test, the apparatus was checked to make sure that there were no leaks in the system.

The air column above the water table was pressurized, which forces groundwater out of the well screen and into the formation, to a specified pressure. For the purposes of this testing, three initial pressures were used to achieve a drop in the water column of 12-inches, 24-inches, and 36-inches. When the water level in the well had stabilized after initial pressurization, the pressure was then quickly released and the rise in head, or recovery, was recorded using the transducer. AQTESOLV software was used to analyze the recovery data for each of the three tests at each of the program wells. Results are discussed in Section 3-3.

3 RESULTS

The pilot study included eleven sampling events and generated a significant amount of data. The pilot study results from the SZPSA and RPSA are discussed in terms of the target compounds (TCE, DCE, VC, ethene, chloride), redox state indicators (DO, ORP, methane, sulfate, ferrous iron), biological cell counts, MGP contaminants of interest (benzene, naphthalene and cyanide), redox sensitive metals (manganese and arsenic), organic carbon (total organic carbon [TOC] and VFAs), and total iron. The remaining other analytes, which do not inform the evaluation of the technology, are included in data tables contained in Appendix C (laboratory reports are included in the attached CD).

The results are summarized in Tables 3-1 (SZPSA) and 3-2 (RPSA), and discussed in detail in the following sections. In general, the results confirm that EIB can successfully reduce source zone concentrations characteristic of TCE DNAPL, and can reduce downgradient concentrations to below JSCS SLVs.

3.1 ANALYTICAL SZPSA RESULTS

The SZPSA wells include well pair WS13-69 and WS13-105, located upgradient of the PRB, well pair WS19-71 and WS19-101, internal to the PRB, and well pair WS18-71 and WS18-101, downgradient of the PRB. Three wells are installed in the shallow interval (up to 71 feet bgs), and three are installed in the deep interval (up to 105 feet bgs).

In general, the results in Table 3-1 show that significant mass removal of chlorinated VOCs (TCE, DCE, and VC) was achieved, and that complete dechlorination is occurring. Reducing conditions were quickly established and maintained. In three of the four wells, TCE concentrations were reduced to orders of magnitude below the lowest threshold concentration for potential TCE DNAPL (i.e., one percent of the solubility limit). In the fourth well (downgradient of the injection zone), TCE concentrations were reduced to the lowest threshold. The TCE data confirm that EIB successfully remediates concentrations characteristic of TCE DNAPL.

Concentrations of MGP-related COIs were not affected by the installation of the PRB, with the exception of free cyanide, which was significantly reduced. Concentrations of redox-sensitive background metals (i.e., Mn and As) were generally not increased downgradient of the PRB. The exception is a very slight increase above the initial

concentration of As in WS18-101. When compared to the upgradient wells (WS13-69 and WS13-105), the increase is within the range of background concentrations.

3.1.1 TARGET COMPOUNDS

The target compounds for the pilot study include TCE, DCE, and VC. These cVOCs can be sequentially dechlorinated to ethene, and produce excess chloride (through dechlorination). The cVOCs can also be abiotically degraded (through the beta elimination process of ZVI described in Section 2.1) directly to other compounds including chloroacetylene, acetylene, ethene and ethane.⁷

3.1.1.1 TCE

In the SZPSA, TCE concentrations decreased to values lower than the TCE SLV (30 ug/L) within four months of injection (Figure 3-1). In the shallow zone PRB well (WS19-71), TCE concentration decreased from 6,500 ug/L to 15 ug/L by the fourth month after injection of the bioamendments, or a reduction of greater than 99.7 percent. Concentrations thereafter remained below 17 ug/L through the end of the study, except in the last month when the concentration increased to 142 ug/L.

In the downgradient shallow well (WS-18-71), concentrations dramatically decreased from 7,990 ug/L to 111 ug/L, greater than 98 percent.

In the deep zone, TCE concentrations within the PRB (WS19-101) decreased from 92,900 ug/L to 35 ug/L at the end of the pilot study, a reduction of greater than 99.9 percent. Concentrations were also lower than the JSCS screening level value in three sampling events starting in the fourth month of the study.

The downgradient well (WS18-101) also showed a significant decrease from 198,000 ug/L to 11,800 ug/L, an almost 95 percent reduction. The final concentration is approximately 1 percent of the aqueous solubility limit for TCE. The final concentration is at the lower end of the qualitative criteria used by EPA for predicting the presence of TCE DNAPL (USEPA, 1993), confirming that EIB will be successful for treating potential TCE DNAPL, even downgradient of an injection zone.

3.1.1.2 DCE Isomers

DCE concentrations varied in the SZPSA (Figure 3-2), and generally decreased in the PRB in the shallow zone. This discussion focuses on the results of the cis-1,2-DCE isomer, since it is the most abundant isomer (relative to 1,1-DCE and trans-1,2-DCE). In WS19-71, the DCE concentration decreased from 88,400 ug/L to 3,300 ug/L, or about 96 percent.

⁷ Groundwater samples were collected and analyzed for dichloroacetylene and chloroacetylene throughout the pilot study. These compounds were not detected in any of the samples. However, these compounds are very reactive (i.e., unstable) and the lack of detections is not significant.

The downgradient shallow well (WS 18-71) concentrations fluctuated from 50,000 ug/L to 60,000 ug/L for most of the study.

In the deep zone, cis-1,2-DCE in WS 19-101 initially increased and then fluctuated near 60,000 ug/L for most of the study.

Downgradient, at WS 18-101 cis-1,2-DCE concentrations increased from 33,600 ug/L to 239,000 ug/L, an increase of almost 700 percent.

3.1.1.3 Vinyl Chloride

Figure 3-3 shows that the concentration trend of VC generally increased within the SZPSA in both the deep and shallow zones. These increases ranged between 200 and 2,300 times the original concentration.

3.1.1.4 Ethene

Ethene was generally not detected, or only detected at very low levels prior to the pilot study. After the injection of the bioamendments in the PRB, ethene was observed in all PRB and downgradient wells within one to five months (Figure 3-4), with production reaching as high as 11 mg/L in the deep PRB well (WS19-101).

3.1.1.5 Chloride

Chloride concentrations increased in all of the PRB and downgradient wells (Figure 3-5). Chloride is produced in all steps of the degradation of TCE, DCE, and VC and increases as the compounds degrade. The increase in chloride concentration is consistent with the amount that is expected from the degradation of TCE, DCE, and VC. In the shallow downgradient well, a sharp peak was observed in the August sampling event. This is most likely an error since concentrations remained stable at lower levels during the rest of the study.

3.1.2 DISCUSSION

The results for TCE and its degradation products, sulfate, chloride, and methane were converted to molar concentrations (micro-moles per liter, or umol/L) in order to examine the processes that are occurring as TCE is dechlorinated (Figures 3-6 through 3-8). The shallow interval results are discussed first, followed by the deep results.

Concentrations of total ethylenes (TCE, DCE, VC, and ethene) in WS13-69 remained relatively stable at about 1,900 umol/L. Between 75 and 90 percent of the total molar distribution in this well was TCE, with the remainder consisting of DCE with minimal VC.

Within the PRB, the total ethylenes concentration remained fairly stable during the study (approximately 900 umol/L). Initially, the molar distribution was about 10 percent TCE (49 umol/L) and 90 percent DCE (918 umol/L), with almost no VC (0.5 umol/L) or

ethene (2 umol/L). By the end of the study, TCE and DCE were significantly reduced (to 1 umol/L and 35 umol/L, respectively), with VC representing about 70 percent (873 umol/L) of the total ethylenes, and ethene comprising 25 percent (260 umol/L). Chloride concentrations also increased, confirming that dechlorination is occurring. The shallow data clearly demonstrate remediation of source material characteristic of a TCE DNAPL zone.

In the downgradient shallow zone, the total ethylenes concentration generally remained stable at about 800 umol/L, with a sharp increase to 2,200 umol/L in the last month of the study. TCE concentrations decreased in the first 4 months (from 60 to 1 umol/L), and DCE fluctuated between 438 and 1,839 umol/L. Beginning in January, conversion to VC and ethene became more significant as levels increased to 544 and 210 umol/L, respectively. The increased production of VC and ethene corresponds to significant increase in DHC microbes observed in the well (discussed in Section 3.1.3).

In the deep interval, the trend in the conversion of the total ethylenes is similar to the trend in the shallow wells (Figures 3-9 through 3-11). Concentrations of total ethylenes in WS13-105 mostly remained below 0.3 umol/L. Most concentrations in this upgradient well were at or very near non-detect levels.

In the deep PRB well (WS 19-101), the total ethylenes concentration varied between 800 and 1,1,300 umol/L, with a peak at about 1,500 umol/L in month 6. Initially, the molar distribution was about 63 percent TCE (707 umol/L) and 36 percent DCE (407 umol/L), with almost no VC (0.4 umol/L) or ethene (4.7 umol/L). However, by the end of the study TCE was significantly reduced (to 0.3 umol/L or less than 0.02 percent of total ethylenes). DCE increased to 58 percent (543 umol/L), VC increased to 26 percent (250 umol/L) and ethene increased to 16 percent (155 umol/L). The chloride concentration increased significantly during this time, confirming that dechlorination is occurring. The deep data clearly demonstrate remediation of source material characteristic of a TCE DNAPL zone.

Downgradient in WS 18-101, total ethylenes concentrations in the deep zone generally varied between 1,300 umol/L and 2,500 umol/L. TCE decreased throughout the study (from 1,500 to 90 umol/L), DCE increased from 352 umol/L to 1,823 umol/L. Beginning in January, conversion to VC and ethene increased, ending at 128 and 68 umol/L respectively. The increased production of VC and ethene corresponds to an increase in DHC microbes observed in the well in January (Section 3.1.3)

In general, the chlorinated VOC and ethene data indicate that significant amounts of TCE and DCE were rapidly converted to vinyl chloride and subsequently ethene. The downgradient data confirm that the injection zone is functioning as a PRB, such that groundwater flowing through the PRB is dechlorinated and will continue to migrate downgradient. The data confirm that EIB will successfully reduce or eliminate high aqueous phase concentrations of source material (TCE) and its primary degradation

product (DCE) in the source area. It is reasonable to conclude that EIB will remediate TCE DNAPL by increasing the mass flux of TCE from the potential non-aqueous phase to the dissolved phase, where it is dechlorinated to DCE.

3.1.3 REDOX INDICATORS

Indicators of reducing/anaerobic conditions include dissolved oxygen (DO), redox potential (ORP), sulfate and methane. However, caution should be used in the interpretation of field measurements of redox potential, as these measurements are not always representative of or sensitive to complex non-equilibrium interactions (including relatively fast and slow reactions) in groundwater. Field measurements are good qualitative indicators, while the analytical data for redox-sensitive species provide more quantitative measurements of reducing conditions.

The redox indicators provide confirmation that conditions favorable for reductive dechlorination exist. The redox data also provide insight regarding the potential for secondary effects (such as mobilization of arsenic and manganese) that are redox-sensitive.

3.1.3.1 DO

In general, DO measurements of less than 1 mg/L suggest that anaerobic conditions may exist, and measurements of less than 0.5 mg/L are a stronger indicator. The measurement is obtained in the field directly from the well purge water before obtaining analytical samples. The DO concentrations in the SZPSA (Figure 3-12) indicate that anaerobic conditions existed prior to the injection of bioamendments for the pilot study. Anaerobic conditions were maintained throughout the study.

In all wells, the October and November DO data were rejected due to calibration errors with the DO field probe. Readings were as high as 9.5 mg/L, which exceeds the solubility limit of oxygen in water. Additionally, the November ORP data were strongly negative (less than -100 mV), which is inconsistent with high DO levels. These data indicate that field measurements of DO should be considered qualitative indicators of aerobic/anaerobic conditions.

In the shallow PRB well, a single increase in DO concentration occurred during the January sampling event, to 1.19 mg/L. In the following month, anaerobic conditions were confirmed in that well, with measurements that remained below 1 mg/L for the rest of the study.

DO increased in all SZPSA wells after March of 2007, although the concentrations were still in the anaerobic range. The cause of the increase in DO is not known, and it does not appear to be decreasing the degradation rates within the PRB.

3.1.3.2 ORP

ORP is an indicator of the redox state of the aquifer. A higher ORP value indicates a more oxidizing environment; a lower ORP value indicates a more reducing environment. Reducing environments are ideal for anaerobic dechlorination of TCE.

ORP measurements varied between positive and negative values. The majority of the results were negative, ranging from -37.7 mV to -201.8 mV, confirming that the environment is reducing (Figure 3-13). From March 2007 to May 2007, results stabilized at each well, with ORP values in the deep zone wells (WS19-101 and WS18-101) generally more negative than wells in the shallow zone (WS19-71 and WS18-71).

In all wells, the October data were rejected due to calibration errors with the ORP field probe. Readings were as high as +225 mV, which are inconsistent with reductive dechlorination and are indicative of an oxidizing environment which would be toxic to the DHC microbes. Biological samples obtained in this month show a healthy population of DHC with good conversion of TCE, DCE, and VC to ethene, confirming that the positive measurements were erroneous.

Significant errors in field measurements of ORP are common, especially under reducing conditions. Typically available ORP probes are understood to be accurate only to +/- 15 mV, suggesting that field ORP data are better understood as qualitative. Redox data are fundamentally not in equilibrium, further complicating accurate measurements in the environment (Dolfing, 2006). The presence or absence of certain redox-sensitive species, such as sulfate and methane, often provides a more accurate understanding of the reducing or oxidizing nature of the subsurface environment.

3.1.3.3 Sulfate

Sulfate concentrations typically decrease during anaerobic biodegradation as oxidized (+VI) sulfate (SO_4^{2-}) is converted to the reduced (-II) sulfide. This reaction occurs at a redox potential of -217 mV (Dolfing, 2006).

Shallow zone sulfate results in Figure 3-14 show that WS13-69 remained relatively stable from May 2006 to June 2007, ranging from 105 mg/L to 131 mg/L with a decrease noted in May 2007 to 23.1 mg/L. Concentrations at WS19-71 decreased from 149 mg/L in June 2006 to 0.5 mg/l in May 2007. Sulfate concentrations at WS18-71 remained relatively stable from June 2006 to January 2007, fluctuating between 104 mg/L and 652 mg/L, but steadily decreasing thereafter to 8.86 mg/L in May 2007.

Sulfate concentrations at WS13-105 were typically non-detect from May 2006 to May 2007, with a peak concentration in August 2006 of 1.68 mg/L. Sulfate concentrations in WS19-101 decreased from 183 mg/l in June 2006 to 0.67 mg/L in May 2007. Concentrations at WS18-101 decreased from 8.17 mg/L in June 2006 to non-detect from January 2007 to May 2007.

The removal of sulfate from the system confirms that reducing conditions as low as -217 mV are present within and downgradient of the PRB. In both PRB wells and both downgradient wells, the reduction of sulfate levels coincide with an increased conversion of DCE to VC and to ethene, indicating that cVOC degradation effectiveness increases as sulfate is removed from the system.

3.1.3.4 Methane

Generation of methane (methanogenesis) occurs as oxidized (+IV) bicarbonate is converted to the reduced (-IV) methane. This reaction occurs at a redox potential of -238 mV (Dolfing, 2006).

As shown in Figure 3-15, in the shallow PRB and shallow downgradient wells methane production was fairly stable, indicating that strongly reducing conditions are present. In the deep PRB and deep downgradient wells, methane production increases through the study, indicating that strong reducing conditions develop during the study.

The stable and increasing trends of methane production confirm that strongly reducing conditions are present and that a redox potential of less than -238 mV was achieved within the treatment zone. This redox state supports the reductive dechlorination processes that are undertaken by the KB-1 microorganisms.

3.1.3.5 Ferrous Ion

Ferrous ion is measured in the field with a colorimetric kit via visual observation. No discernable trends were detected (Figure 3-16). The presence of ferrous iron (+II) suggests that reducing conditions exist, but that they are not sufficiently low to convert ferrous iron to zero valent iron, which generally occurs at a redox condition of -440 mV.

3.1.4 BIOLOGICAL CELL COUNTS

Periodic sampling for biological analysis was performed at each of the wells in the SZPSA. Samples were analyzed for total cell counts and DHC fraction (using polymerase chain reaction (PCR) test methods. PCR testing identifies the number of copies of a DHC-specific ribosomal ribonucleic acid present in the sample. The results provide an estimate of the number of DHC present in the sample (expressed as cells per liter), as well as the fraction of the total microbial cell counts representing DHC.

KB-1 was injected into the PRB in the SZPSA at the start of the pilot test. Biological samples were collected 3, 6, 10, and 11 months following injection. In the Month 3 samples, a relatively high concentration of DHC was present in the PRB wells (10^7 to 10^8 cells/L), with lower concentrations in the downgradient wells (10^4 to 10^5 cells/L) (Figure 3-17). Background, or upgradient, DHC estimates in Month 3 were 10^4 (shallow) and 10^7 (deep).

In the Month 6 samples, the shallow PRB DHC count increased by two orders of magnitude to 10^9 cells/L, while DHC counts in the deep PRB well remained stable. In contrast, DHC in the downgradient wells (shallow and deep) increased by two to three orders of magnitude during the interval between sampling events, to 10^7 cells/L.

In the Month 10 and 11 samples, the DHC counts remained between 10^8 and 10^9 cells/L in the PRB wells. In the downgradient wells, DHC counts continued to increase to between 10^8 and 10^9 cells/L. Upgradient DHC counts decreased to 10^6 and 10^3 , in the deep and shallow wells, respectively.

The data suggest that the KB-1 may be advected downgradient of the injection zone by groundwater. An alternative explanation is that installation of the PRB rapidly improves conditions for DHC growth downgradient. The net result is the same, to the extent that bacteria capable of fully dechlorinating vinyl chloride and producing ethene are increased, by as much as four to five orders of magnitude, downgradient of the PRB.

3.1.5 MGP CHEMICALS OF INTEREST

Chemicals of interest (COIs) related to the MGP waste in the soil and groundwater include benzene, naphthalene, and cyanide. Exacerbating concentrations of these COIs in groundwater to benefit the removal of TCE would not be considered fully successful, therefore impacts to the COIs must be assessed.

Benzene concentrations remained relatively stable from May 2006 to May 2007, as shown in Figure 3-18. Concentrations at the upgradient deep well WS13-105 were consistently below PRB and downgradient wells. Concentrations at the upgradient shallow well WS13-69 were consistently above concentrations at PRB and downgradient wells. Naphthalene concentrations fluctuated within an order of magnitude of their initial concentration, in a similar pattern observed in the upgradient wells during the pilot study (Figure 3-19).

Total cyanide was relatively stable in the upgradient wells and the shallow PRB and downgradient wells, and decreased in the deep PRB and downgradient wells (Figure 3-20). Free cyanide concentrations decreased by at least an order of magnitude in both PRB wells and downgradient (Figure 3-21). The decrease in cyanide within and downgradient of the PRB is a fortuitous and significant result. Both free and total cyanides are known to react with ferrous iron to form relatively insoluble ferrocyanide complexes. The reduction and/or removal of free cyanide could simplify surface treatment alternatives for potential extraction systems under consideration.

3.1.6 REDOX SENSITIVE BACKGROUND METALS

Arsenic and manganese are redox-sensitive background metals that could be mobilized by the reducing conditions established by EHC. Manganese has been identified as an initial Chemical of Concern (iCOC) for the Portland Harbor NPL site.

3.1.6.1 Arsenic

Concentrations remained stable at WS18-101, WS13-69, and WS13-105 (Figure 3-22). Arsenic concentrations at WS19-101 varied (ranging from non-detect to 5.15 ug/L); although the concentration of arsenic at the end of the pilot study was lower than at the beginning of the pilot study. In WS19-71, concentrations decreased from 3.19 ug/L in September 2006 to 2.2 ug/L in May 2007, while at WS18-71, concentrations decreased from 3.85 ug/L in September 2006 to a level below the MRL of 1 ug/L.

The arsenic data prior to September 2006 were reported with an elevated MRL (20 ug/L), so initial data was non-detect. Beginning in September, the method was revised and the MRL was lowered to 1 ug/L. At no time were arsenic concentrations greater than background (i.e., upgradient). The data clearly indicate that installation of the PRB did not mobilize arsenic.

3.1.6.2 Manganese

As shown in Figure 3-23, manganese concentrations in WS19-101 increased from 9.48 mg/L in June 2006 to 24.1 mg/L in May 2007, with a peak of 39.9 mg/L in November 2006. Concentrations at WS19-71 increased from 12.4 mg/L in June 2006 to 22.9 mg/L in May 2007. Concentrations in WS18-71 decreased slightly, from 17 mg/L to 14.5 mg/L during the pilot study. Concentrations at the other wells remained relatively stable. These data clearly indicate that while manganese concentrations may increase within the PRB, the increases are not found immediately downgradient.

3.1.6.3 Discussion

The data confirm that neither arsenic nor manganese were mobilized downgradient of the PRB by the increasingly reducing conditions. The arsenic removal is likely due to the formation of relatively insoluble arsenopyrite (FeAsS), which is favored under reducing conditions (Craw, 2003). Manganese exhibits behavior similar to iron and easily substitutes for iron in forming sulfide minerals (Krauskopf, 1979). Formation of manganese-ferrocyanide complexes (e.g., $\text{Mn}_2[\text{Fe}^{\text{II}}(\text{CN})_6]$ and $\text{Mn}_3[\text{Fe}^{\text{III}}(\text{CN})_6]_2$) has been documented under a variety of reducing conditions (Rennert, 2005).

It is likely that the absence of increasing trends of manganese in downgradient monitoring wells is due to formation of $(\text{Fe,Mn})\text{AsS}$, manganese-ferrocyanide complexes, or a similarly insoluble mineral species, at some point between the PRB wells and the downgradient wells. Regardless of the mechanism, the data confirm that mobilization of redox-sensitive background metals downgradient of the PRB is not occurring.

3.1.7 TOC AND VFAS

The carbon based (plant fiber) component of EHC is fermented by indigenous bacteria, releasing various VFAs. Measurement of TOC and VFAs provide an indication of the amount of carbon material remaining in-situ.

3.1.7.1 Total Organic Carbon

TOC concentrations are an indicator of the PRB's ability to continue enhancing the environment for biodegradation. The organic carbon is broken down into VFAs, which are consumed by the dechlorinating bacteria. The MGP-related waste is another source of TOC in the subsurface so concentrations of TOC are not a definitive measure of remaining EHC.

TOC concentrations at the upgradient wells remained stable; WS13-105 TOC concentrations ranged from 5.62 mg/L to 6.64 mg/L and WS13-69 ranged from 13.7 mg/L to 15.9 mg/L (Figure 3-24). Concentrations at WS19-71 and WS19-101 increased from 10 mg/L and 20 mg/L, respectively, in June 2006 to 488 mg/L and 859 mg/L, respectively in May 2007. The highest concentration observed was in WS19-101, at 1,500 mg/L in November (Month 4). Concentrations at WS18-71 and WS18-101 increased from 10 mg/L and 20 mg/L, respectively, to 143 mg/L and 35.7 mg/L, respectively. The data confirm placement of the PRB materials and advection downgradient of TOC.

3.1.7.2 Volatile Fatty Acids

VFA data are contained in the data summary charts in Appendix C. Acetic acid concentrations at WS19-101 and WS19-71 increased from non-detect in June 2006 to 1710 mg/L and 763 mg/L, respectively, in May 2007. No clear trends existed for the other wells.

Lactic acid results were non-detect for all wells in June 2006 and increased to varying concentrations, only to decrease to levels of non-detect for all wells from January 2007 to May 2007. The maximum concentration observed in the SZPSA was 628 mg/L at WS19-101 in November 2006.

Concentrations of n-butanoic acid ranged from non-detect to 211 mg/L. Concentrations at WS19-101 were typically the highest result per sampling event. Since March 2007, results above MRLs were only detected at WS19-101, WS19-71 and WS18-71, listed in decreasing order of magnitude.

Concentrations of propanoic acid ranged from non-detect to 600 mg/L. Concentrations at WS19-101 were consistently the highest result per sampling event. Since March 2007, results above MRLs were only detected at WS19-101, WS19-71, WS18-71, and WS18-101, listed in decreasing order of magnitude.

Detections of pyruvic acid above (variable) MRLs occurred in July and September 2006 for WS13-69, WS13-105, WS19-71 and WS19-101. A detection above the MRL occurred in July at WS18-71. A maximum concentration was observed in September 2006 at WS19-101 of 212 mg/L.

3.1.7.3 Discussion

Given the relatively high concentrations of TOC and various VFAs, it is evident that there is sufficient carbon material remaining from the EHC injection to continue enhancing biodegradation of cVOCs. In addition, the TOC and VFAs are transported downgradient to the WS18 wells and provide an enhanced environment 15 feet downgradient of the injection point. The data confirms that electron donors can be distributed downgradient of injection points, which is an important consideration for treatment of aquifer locations under inaccessible areas.

3.1.8 TOTAL IRON

Iron concentrations were relatively stable in all SZPSA wells except for WS19-101 (Figure 3-25). Concentrations of iron in WS19-101 increased from 116 mg/L in June 2006 to 400 mg/L in May 2007, with a peak of 493 in November 2006.

Increasing total iron concentrations are expected since zero valent iron is a major component of the EHC compound. These results are different from the RPSA iron results, discussed in the following section.

3.2 ANALYTICAL RPSA RESULTS

The RPSA wells include WS21-112 upgradient of the PRB, WS22-112 within the PRB, and WS20-112 and WS11-125 downgradient of the PRB. Monitoring began in May 2006 for well WS11-125 and June 2006 for wells WS20-112, WS20-112, and WS22-112; monitoring continued through May 2007. Concentration data tables for the RPSA results are contained in Appendix C.

Within the RPSA, EIB has proven to be very effective in significantly reducing mass of cVOCs (Table 3-2). Complete dechlorination is occurring through abiotic and biological degradation pathways. Reducing conditions were established quickly and maintained throughout the study. MGP related COIs remained relatively stable, and were not adversely affected by the injection of the bioremediation amendments. Free cyanide concentrations were reduced. Concentrations of redox-sensitive background metals were not increased downgradient of the PRB.

3.2.1 TARGET COMPOUNDS

The target compounds for the pilot study in the RPSA are TCE, DCE, and VC. These cVOCs can be completely biologically degraded to ethene and chloride. The biological degradation of the compounds follows a sequential process of conversion of TCE to DCE, DCE to VC, and VC to ethene. The cVOCs can also be abiotically degraded (through the beta elimination process described in Section 1.3.2) directly to other compounds including chloroacetylene, acetylene, ethene and ethane (see note in Section 3.1.1 regarding chloroacetylenes).

3.2.1.1 TCE

TCE concentrations decreased in all wells in the RPSA (Figure 3-26). TCE concentrations decreased to values lower than the TCE SLV (30 ug/L) within the first four months of injection. In the PRB (WS22-112), TCE concentrations decreased from 584 ug/L to non-detect levels (<0.3 ug/L) within 9 months, a reduction of 99.95 percent. The TCE concentration in WS11-125, 10 feet downgradient, decreased from 158 ug/L to non-detect within 11 months. At WS20-112, 20 feet downgradient, TCE concentrations decreased to non-detect levels by the 11th month of the study.

3.2.1.2 DCE Isomers

DCE concentrations generally decreased in the RPSA. As shown in Figure 3-27, DCE concentrations decreased to levels below the cis-DCE SLV (61 ug/L) in the PRB and 20 feet downgradient by January. In the PRB, cis-DCE decreased from 3,060 ug/L to non-detect levels, or a reduction of more than 99.99 percent. Concentrations of cis-DCE in WS11-125, 10 feet downgradient, decreased from 10,500 ug/L to 1,640 ug/L, or about a 90 percent reduction.

3.2.1.3 Vinyl Chloride

VC generally decreased in all wells within the RPSA (Figure 3-28). Within the PRB, VC decreased from 474 ug/L to 2.35 ug/L, or 99.5 percent. At WS11-125, 10 feet downgradient, VC decreased by almost 92 percent, from 5,170 ug/L to 422 ug/L. VC in WS20-112 decreased from 1,610 ug/L to less than 1.42 ug/L, or 99.9 percent.

3.2.1.4 Ethene

Ethene concentrations decreased over the pilot study period (Figure 3-29) following a period of general increase. Within the PRB ethene increased from 0.247 mg/L to a peak of 0.356 mg/L in month one, before decreasing to non-detect levels (<0.117 mg/L). In WS11-125, ethene concentrations reached a peak of 2.4 mg/L in September before returning to 0.25 mg/L.

3.2.1.5 Chloride

Chloride concentrations generally increased in concentration downgradient of the PRB (Figure 3-30). The concentrations of the cVOCs were relatively low to begin with, preventing calculation of a mass balance. Within the PRB, chloride fluctuated, from 96

mg/L to 20 mg/L to 111 mg/L, and then remained relatively stable at approximately 65 mg/L.

3.2.1.6 Discussion

The total ethylene results were converted to a molar concentration and plotted on Figures 3-31 through 3-34. The comparison illustrates the degradation processes that are occurring within the riverbank PRB.

After an initial result of 52 umol/L, upgradient concentrations of total ethylenes generally remained between 10 umol/L and 25 umol/L. The distribution between TCE, DCE, VC and ethene entering the PRB is 11 percent TCE, 69 percent DCE, 18 percent VC, and 1 percent ethene.

Within the PRB, the total ethylenes concentration remained fairly constant during the first four months of the study, between 40 and 50 umol/L, with a dramatic reduction starting in the sixth month. By the end of the study total ethylene concentration dropped to less than 1 umol/L. TCE decreased to very low levels by the third month of the study, however there was not a significant commensurate resulting increase in DCE or VC concentrations, as was observed in the SZPSA. DCE, VC, and ethene concentrations dramatically decreased beginning in month 6. The decrease in ethene confirms that complete dechlorination has occurred, since there are no chlorinated species remaining to generate ethene (either by sequential dechlorination or by the beta-elimination pathway).

Chloride concentrations were variable during the first 6 months of the study, between 500 umol/L and 3,000 umol/L, and then stabilized around 2,000 umol/L at about the same time as the large reduction of total ethylenes. However, since the total concentration of the ethylenes is small relative to the chloride concentration, an observable change in chloride was not expected.

In WS11-125 (10 feet downgradient of the PRB), the total ethylenes concentration was approximately 440 umol/L prior to injecting the bioamendments, decreasing to about 150 umol/L after application of the amendments. In the second month after injection the total ethylenes concentration increased to 277 umol/L, accompanied by increases in the three remaining ethylenes (DCE, VC, and ethene). Starting in the third month there was a decreasing trend in DCE, VC, and ethene to a level of about 30 umol/L by month 7 for the rest of the study. The decrease represents a reduction of about 93 percent. There were no apparent changes to the DHC population during this timeframe but there was a significant upward trend in methane production indicating increasingly reducing conditions.

The data from WS-11-125 are not consistent with the upgradient data from within the PRB (WS-22-112) and downgradient (WS-20-112). Specifically, the degradation rates for DCE and VC are not as fast, and concentrations below the JSCS SLVs (61 ug/L for cis-DCE and 2.4 ug/L for VC) have not been achieved. MGP DNAPL is present in this

well. The MGP DNAPL contains concentrations of TCE, DCE and VC that are above the groundwater concentrations.

As discussed in the *Desorption Bench Test Report* (MFA, 2007b), TCE and its degradation products will desorb from the MGP DNAPL at a rate controlled by the concentration gradient between the non-aqueous and dissolved phases. The degradation rates for DCE and VC in WS-11-125 are likely slower because these compounds are replaced in the aqueous phase by desorption from the non-aqueous phase.

At WS20-112 (20 feet downgradient) total ethylenes concentrations were reduced by more than 99 percent, from 154 umol/L to less than 0.1 umol/L. Both downgradient wells show somewhat increased levels of concentrations of DCE and VC in a progressive pattern, indicating that there may be more of a biological influence in the downgradient degradation. However, total ethylenes drops off significantly in both wells by Month 7.

In general, the total ethylene data indicate that after an initial development period of 4 to 6 months, the PRB in the RPSA is capable of reducing downgradient concentrations of TCE, DCE, and VC to below SLVs. Lower sulfate concentrations and increasing methane production supports the conclusion that strongly reducing conditions have developed within the treatment area.

Downgradient results show that a longer period of time may be necessary to demonstrate plume elimination. This is likely due to residual cVOCs desorbing from MGP DNAPL (and soil, to a much lesser degree). The additional time required to account for sorbed contaminant mass is being evaluated and will be addressed in the Focused Feasibility Study.

3.2.2 REDOX INDICATORS

As discussed in section 3.1.2, redox indicators include DO, ORP, sulfate, and methane. The redox indicators provide qualitative and quantitative confirmation that conditions favorable to reductive dechlorination exist within and downgradient of the riverbank PRB.

3.2.2.1 DO

As shown in Figure 3-35, the DO results in the RPSA indicate that anaerobic conditions existed prior to the injection of bioamendments for the pilot study. Anaerobic conditions were maintained throughout the study, with several exceptions.

In all wells, the October data were rejected due to calibration errors with the DO field probe. Readings were as high as 9.5 mg/L, which exceeds the solubility limit of oxygen in water. Additionally the October DO readings correspond to ORP levels that are strongly negative (less than -100 mV), which is inconsistent with high DO levels.

3.2.2.2 ORP

During the pilot study ORP measurements fluctuated between varying negative values (Figure 3-36). The majority of the results indicate negative values ranging from -80 mV to -250 mV, confirming the reducing environment. As discussed in Section 3.1.3.2, field measurements of ORP are qualitative.

3.2.2.3 Sulfate

Sulfate reduction typically occurs at a redox potential of -217 mV (section 3.1.2). Sulfate concentrations in the RPSA are generally decreasing. Concentrations at WS20-112 and WS22-112 decreased to levels of non-detect between January 2007 to May 2007, as shown in Figure 3-37. Concentrations at WS11-125 decreased from 40.6 mg/L in May 2006 to 1.8 mg/L in May 2007. Concentrations in the upgradient well (WS21-112) also decreased during the pilot study, from 81.1 mg/L in June 2006 to 3.47 mg/L in May 2007.

The removal of sulfate from within the system confirms that reducing conditions as low as -217 mV are present within and downgradient of the PRB.

3.2.2.4 Methane

Generation of methane (methanogenesis) occurs at a redox potential of -238 mV (section 3.1.2). In the RPSA, Figure 3-38 shows methane concentrations are generally increasing at all downgradient and PRB wells. Concentrations at the upgradient well WS21-112 were generally stable, ranging from 4 mg/L to 14 mg/L. Concentrations at WS22-112, WS11-125, WS20-112 increased from values less than 8 mg/L in June 2006 to 42 mg/L, 70 mg/L and 81 mg/L, respectively, in May 2007. The methane production in and downgradient of the PRB confirms a redox potential of less than -238 mV.

3.2.2.5 Ferrous Ion

Ferrous ion is measured in the field with a colorimetric kit via visual observation. No discernable trends were detected in Figure 3-39. The presence of ferrous iron (+II) indicates that reducing conditions exist, but that they are not so low as to convert ferrous iron to zero valent iron (redox condition of -440 mV).

3.2.3 BIOLOGICAL CELL COUNTS

Periodic sampling for biological analysis was performed at each of the wells in the RPSA. KB-1 was injected into the PRB in the RPSA at the start of the pilot test. Biological samples were collected 3, 6, 10, and 11 months following injection. The results are displayed in Figure 3-40. In the Month 3 samples, a relatively high concentration of DHC was present in the PRB well (10^6 cells/L) and downgradient wells (10^7 to 10^9 cells/L), with lower concentrations in the upgradient well (10^0 cells/L).

In the Month 6 samples, the PRB count increased by three orders of magnitude to 10^9 cells/L. DHC counts in both downgradient wells were unchanged or decreased slightly. In the Month 10 and 11 samples the DHC counts decreased to between 10^7 cells/L and 10^8 cells/L. The decrease coincides with the removal of chlorinated VOCs. Upgradient DHC counts increased to 10^4 cells/L and 10^5 cells/L in the last two months of the study.

The data support the theory that the KB-1 may be advected downgradient of the injection zone by groundwater, based on comparison to background (upgradient). The increasing cell count in WS21-112 likely reflects growth of indigenous microbes due to an upgradient “halo” effect of improved conditions for growth. Alternatively, the data suggest an ability to migrate upgradient.

3.2.4 MGP CHEMICALS OF INTEREST

Impacts to the concentrations of the MGP COIs are important in evaluating the success of bioremediation, since exacerbating problems of co-contaminants to benefit the removal of TCE would not be considered fully successful. As shown in Figure 3-41, concentrations of benzene in the PRB (WS22-112) increased from 127 mg/L in June 2006 to 722 mg/L in July 2006, but steadily decreased to 118 mg/L in May 2007. Benzene concentrations at WS11-125 generally increased from 344 mg/L in May 2006 to 1,680 mg/L in May 2007, but this may be due to the presence of MGP DNAPL in the well screen. Concentrations have been relatively stable at WS20-112 and WS21-112.

No discernable trends were observed for naphthalene at wells WS20-112, WS21-112, and WS22-112 (Figure 3-42). Concentrations ranged from non-detect to 619 mg/L. The trend for concentrations at WS11-125 was also variable, but was consistently higher than other wells, ranging from 968 mg/L to 9,890 mg/L. The data indicate that benzene and naphthalene do not interfere with dechlorination, and PRB installation does not mobilize or adversely impact concentrations of these compounds.

Total cyanide was relatively stable in all of the RPSA wells (Figure 3-43). Figure 3-44 shows that free cyanide concentrations decreased by about 50 percent in all wells (including upgradient) during the course of the pilot study. Interestingly, the decrease in the PRB and downgradient wells was followed by a subsequent decrease in the upgradient well. These data are consistent with the SZPSA data.

3.2.5 REDOX SENSITIVE BACKGROUND METALS

Arsenic and manganese are redox-sensitive background metals that could be mobilized by the reducing conditions established by EHC. Manganese has been identified as an initial Chemical of Concern (iCOC) for the Portland Harbor NPL site.

3.2.5.1 Arsenic

Figure 3-45 shows that arsenic concentrations remained stable in the RPSA wells, with the exception of WS11-125. In that well, arsenic concentrations increased slightly, from 1.58 ug/L to 2.7 ug/L.

The arsenic data prior to September 2006 was reported using an elevated MRL (20 ug/L), so all initial data was non-detect. Beginning in September, the method was revised and the MRL was lowered to 1 ug/L. The data indicate that arsenic concentrations are not significantly increased by installation of the PRB.

3.2.5.2 Manganese

Concentrations of manganese at the PRB (WS22-112) and downgradient (WS20-112) decreased from 17.7 mg/L and 5.4 mg/L in June 2006, to 0.0999 mg/L and 0.0154 mg/L in May 2007, respectively (Figure 3-46). Concentrations upgradient (WS21-112) slightly decreased from 2.59 mg/L in June 2006 to 1.03 mg/L in May 2007. However, concentrations at WS11-125 increased from 4.49 mg/L in June 2006 to 8.98 mg/L in May 2007, with a peak of 12.8 in March 2007. The final concentration was not significantly elevated above the average background concentration (6.55 mg/L, based on the initial concentrations in all four wells).

3.2.5.3 Discussion

The data generally indicate that neither arsenic nor manganese were mobilized downgradient of the PRB by the increasingly reducing conditions. Manganese concentrations may have increased in WS11-125, but the elevated levels are not observed in the farther downgradient well (WS20-112). The data in WS11-125 are different from the other wells, which could be reflective of the difference in screen elevation. The redox data confirm that the differences in WS11-125 are not due to increased reducing conditions.

Manganese exhibits behavior similar to iron and easily substitutes for iron in forming sulfide minerals (Krauskopf, 1979). Formation of manganese-ferrocyanide complexes (e.g., $Mn_2[Fe^{II}(CN)_6]$ and $Mn_3[Fe^{III}(CN)_6]_2$) has been documented under a variety of reducing conditions (Rennert, 2005). It is likely that the decreasing trends of manganese in downgradient monitoring wells is due to formation of (Fe,Mn)AsS, manganese-ferrocyanide complexes, or a similarly insoluble manganese-enriched mineral species.

3.2.6 TOC AND VFAS

The carbon based (plant fiber) component of EHC is fermented by indigenous bacteria, releasing various VFAs. Measurement of TOC and VFAs provide an indication of the amount of carbon material remaining in-situ.

3.2.6.1 Total Organic Carbon

TOC concentrations are an indicator of the PRB's ability to continue to enhance the environment for biodegradation. TOC concentrations within the PRB and downgradient (WS20-112) have decreased over the study period. Concentrations from within the PRB decreased from 4,250 mg/L to 45 mg/L (Figure 3-47). WS20-112 concentrations decreased from 628 mg/L to 16 mg/L. In contrast, concentrations at the downgradient well WS11-increased, from 6 mg/L to 1,700 mg/l, and decreased again to 1,060 mg/L.

3.2.6.2 Volatile Fatty Acids

VFA data are contained in the data summary charts in Appendix C. Concentrations of acetic acid decreased at WS20-112, WS22-112, and WS21-112. Concentrations at WS11-125 increased from 296 mg/L in June 2006 to 1,130 mg/L in May 2007 with a peak of 2,400 mg/L in March 2007.

Concentrations of lactic acid were variable from June 2006 to January 2007, but from February 2007 to May 2007 lactic acid was not detected above the MRL for all RPSA wells.

Concentrations of n-butanoic acid at WS11-125 increased from 133 mg/L in June 2006 to 319 mg/L in May 2006 with a peak of 1,000 mg/L in March 2007. Concentrations at other wells generally decreased to levels of non-detect by May 2007.

Propanoic acid concentrations have variable trends for wells in the RPSA. Concentrations at WS11-125 generally increased from 15.2 mg/L in June 2006 to 222 mg/L in May 2007. Concentrations at WS22-112 have generally decreased from 480 mg/L in June 2006 to 9.05 mg/L in May 2007. Concentrations at WS21-112 were not detected above the MRL in February through May 2007 but in December 2006, a peak of 147 mg/L was observed. The trend at WS20-112 has been variable, ranging from 113 mg/L in January 2007 to concentrations below the MRL in April and May 2007.

Pyruvic acid was detected above the variable MRLs only at WS22-112 in March 2007. All other results were non-detect. The MRLs ranged from 5 mg/L to 100 mg/L; therefore, this detection is not significant.

3.2.6.3 Discussion

The decreasing TOC trend appeared to indicate that the carbon source in EHC was close to being exhausted. To verify this condition, soil borings were advanced in the RPSA PRB to verify soil TOC levels. Field staff verified the presence of large amounts of iron using field magnets. Samples of material that appeared to be EHC (visually and by odor) were sampled. Soil samples contained concentrations greater than 4,000 mg/kg TOC, in contrast to concentrations prior to injection of amendments at about 800 mg/kg.

The data and observations indicate that the microbes in the PRB have reached equilibrium with the carbon release rate from the EHC, such that dissolved-phase TOC is

consumed as fast as it is produced. Monitoring of biological activity would need to continue to estimate the timeframe for reapplication, if necessary.

3.2.7 TOTAL IRON

As shown in Figure 3-48, total iron concentrations at WS21-112 remained relatively stable upgradient. Downgradient iron concentrations generally decreased (WS22-112 and WS20-112), while concentrations at WS11-125 were variable. These data are consistent with the SZPSA data, and may reflect formation of relatively insoluble iron-bearing species.

3.3 SLUG TEST RESULTS AND GROUNDWATER VELOCITY ESTIMATES

The following section summarizes the results of the pneumatic slug tests completed in both pilot study areas. The results (combined with groundwater elevation data) were compared to the analytical data to estimate groundwater flow velocities. The results are generally consistent with the flow velocities discussed in the *RI Report* (MFA, 2007), which concluded that groundwater near the riverbank is flowing at approximately 0.5 feet/day, while groundwater near the source area is flowing more slowly. The following sections describe the methods used to estimate hydraulic conductivity (k) and horizontal gradients, the groundwater velocities, and the results of the calculations.

The objective of providing these data is to generally demonstrate that once treated groundwater has flowed through a riverbank PRB, it will continue to flow downgradient and reduce or eliminate TZW concentrations of TCE and its degradation products. A more detailed evaluation of groundwater flow and travel times will be included in the Focused Feasibility Study.

3.3.1 SLUG TEST RESULTS

Table 3-3 summarizes the results of the pneumatic slug testing for each pilot study area. The results are further subdivided by depth interval. In the SZPSA, the average k value for the shallower interval is 0.0546 feet/day, and 0.161 feet/day for the deep interval. These low values are consistent with the estimates provided in the *RI Report* and reflect the higher silt content of the soil in the screened intervals. However, the range of values showed a relatively high degree of variability, and in some cases (e.g., WS-19-101) no usable data was collected. The variability and inconsistent performance of the procedure likely reflects the soil conditions – sandy silt, with occasional sand layers.

Hydraulic conductivity in the RPSA was much higher, ranging from an average of 1.17 feet/day for the interval corresponding to the injection interval (90-130 feet bgs), to an average of 15.49 feet/day for the deeper interval (145-160 feet bgs). The increase with depth is consistent with field observations of increasingly coarse sand and a decrease in fines content. The data from the riverbank wells shows less intra-well variability between tests, suggesting that the performance of the procedure is more reliable in more homogeneous intervals.

3.3.2 HORIZONTAL GRADIENT ESTIMATES

Average linear velocities (ALVs, aka seepage velocities) were calculated for the *RI Report* using a site-wide gradient of 0.0035 feet/foot (i.e., based on groundwater elevations from, and distances between the source area wells and riverbank wells). The gradients were re-calculated using the new pilot study wells to provide location-specific data, which is appropriate given the significant change in lithology between the two areas.

Gradients were calculated using monthly groundwater elevation data from September 2006 through June 2007. Table 3-4 summarizes the horizontal gradient data for both areas (the full data sets are included in Table 3-5). Gradients were calculated between the upgradient monitoring wells and the PRB wells, between the PRB wells and the downgradient wells, and between the upgradient wells and the downgradient wells. The average gradients across these segments were then averaged.

In the SZPSA shallow interval, it appears that groundwater elevations in the downgradient monitoring well (WS-19-101) are higher than in the upgradient well (WS-13-69). These data suggest that groundwater flow in the shallow interval is reversed, which is inconsistent with the analytical data (discussed below) that demonstrate that groundwater flow is indeed consistent with the conceptual site model. As such, the shallow SZPSA elevation data were rejected and not included for evaluating groundwater flow velocities through the PRB.⁸

The average gradient in the SZPSA deep interval was 0.014, and the average maximum gradient was 0.044. At the riverbank, the average gradient was 0.006, and the average maximum gradient was 0.014. These average gradients are generally 2x-12x higher than the overall site gradient. The average gradients were used to estimate groundwater velocities as discussed below.

⁸ MFA is evaluating the survey data related to the measuring points of the pilot study wells for potential errors.

3.3.3 GROUNDWATER VELOCITY CALCULATIONS USING SLUG TEST-DERIVED K VALUES

The groundwater flow velocity (v) for the pilot study areas was calculated using the following equation:

$$v = \frac{k}{\theta} * i$$

where

k = hydraulic conductivity (varies, based on pneumatic slug testing results)

θ = effective porosity (assumed to be 0.3) and

i = horizontal gradient (varies between pilot study areas).

Table 3-6 summarizes the results of the velocity calculations. The maximum linear velocities ranged from 0.016 to 0.023 feet/day in the SZPSA. The results are suspect, however, because the travel time from the PRB to the downgradient wells (using these velocities) ranges from 637 to 2,234 days (clearly not the case).

At the riverbank, the calculated velocity was 0.13 feet/day (using the highest k value of 2.84 feet/day), which is similarly suspect. At this velocity, the travel time from the PRB well to the downgradient well ranges from 169 to 390 days.

The most likely source of error in the above calculation is the estimated hydraulic conductivity value. It appears that the hydraulic conductivity values derived from the pneumatic slug testing tend to underestimate true hydraulic conductivity. MFA is in the process of conducting a supplemental borehole dilution test to provide an additional estimate of hydraulic conductivity. These data will be used to develop a more detailed analysis of travel times to be presented in the FFS, as discussed above.

3.3.4 GROUNDWATER VELOCITY ESTIMATES USING ANALYTICAL DATA

An alternative method for estimating groundwater velocities is to use the analytical data from the pilot study as tracers. As such, the time delay between a change in concentration in a PRB well and a corresponding change in a downgradient monitoring well can be used to estimate the groundwater velocity. Most of the analytes are undergoing reactions as they are advected by groundwater from the PRB to the downgradient monitoring wells, so they are not “conservative” tracers, which introduces some uncertainty into the following estimates. For the purposes of this evaluation, the analytical data provide a good general understanding of groundwater flow through the PRBs.

In the SZPSA, vinyl chloride appears to be an adequate tracer for groundwater flow. This is because the material and processes generating vinyl chloride (i.e., KB-1 bacteria)

were not injected into the downgradient wells. The appearance of this degradation product in a downgradient well (at concentrations similar to the PRB) is a reasonable tracer for a front of advected vinyl chloride in groundwater.

Figure 3-49 shows a subset of the vinyl chloride concentrations in the source zone wells. The concentrations in the PRB wells increase sharply following the August and September events (deep and shallow, respectively). Similar increases are seen in the downgradient wells within approximately 83 and 49 days (deep and shallow, respectively). Based on the distance between the PRB wells and the downgradient wells and the estimated travel times from the vinyl chloride data, the estimated SZPSA groundwater velocity ranges from 0.18 (deep interval) to 0.29 (shallow interval) feet per day.

In the RPSA, the total cyanide data suffice as an adequate tracer (see Figure 3-43). For this constituent, concentration changes in downgradient well WS-20-112 appear to occur nearly simultaneously with PRB well WS-22-112. The changes between the PRB and downgradient well are not related to a change in geochemistry, as evidenced by congruent peaks from the upgradient well (WS21-112) and the other wells.⁹

The (apparently) simultaneous behavior is likely an artifact of the sampling interval (approximately 30 days); more frequent sampling could have identified a time delay that could be used for more accurate estimates. A conservatively slow estimate can be derived - if the maximum interval of 30 days is assumed, the groundwater velocity from the PRB to the downgradient point is approximately 0.73 feet/day, or 268 feet/year.

This value not only corresponds well with the estimated groundwater velocity in the SZPSA (based on the *k* data from the slug tests), but also with the estimates (based on travel times and plume lengths) provided in the *RI Report*.

3.3.5 HYDROGEOLOGIC SUMMARY

The slug test data, gradient calculations and velocity estimates were analyzed along with the analytical data. The data indicate the following:

- 1) The gradient data confirm that installation of the PRB does not result in a significant decrease in hydraulic conductivity relative to the surrounding aquifer material. This may be due to the relatively high injection pressures creating increased secondary permeability through fracturing. Presumably, the fractures are filled with EHC slurry, which does not reduce overall permeability.

⁹ Total cyanide data represent the sum of all dissolved (free) components and all complexed components.

- 2) The pneumatic slug test data provided a reasonable relative comparison of the hydraulic conductivity of the two pilot study areas, but generally underestimated conductivity based on calculated travel times. The k data for the RPSA was greater than that for the SZPSA, as expected. The pneumatic slug test data from the RPSA wells was more consistent, both on an intra-well and inter-well basis.
- 3) Analytical data from the two pilot study areas provided reasonable estimates of groundwater velocity based on travel times. The groundwater velocity at the riverbank is higher than in the source area, consistent with the pneumatic slug test data.
- 4) The estimated velocity at the riverbank is 0.73 feet/day, or approximately 270 feet/year. The estimated velocity at the riverbank is consistent with the estimates in the *RI Report* (i.e., between 0.5 and 1 feet/day). At this velocity, the estimated travel time for treated water to travel from the riverbank to the downgradient extent of the plume (i.e., approximately 550 feet) is approximately 2 years.

The hydrogeologic data indicate that full-scale implementation of EIB at the riverbank could reduce or eliminate TCE and its degradation products in the downgradient groundwater plume and Area 1 TZW as soon as 2.5 years following implementation.¹⁰

¹⁰ Allowing for 6 months of acclimation and treatment time, as demonstrated by the analytical data.

4 EVALUATION

The objective of the pilot study is to generate performance data to be used in the FS for remedy selection, and provide recommendations that could optimize potential full-scale application. Performance data include not only analytical data, but also lessons learned during implementation. The analytical data were evaluated in the context of contaminant destruction effectiveness, and estimated timeframes for establishing and maintaining in-situ chemical reductive dechlorination. The lessons learned during implementation include verification of the field methods, materials and procedures, and identifying critical or non-critical monitoring parameters. The following sections evaluate the performance data and include recommendations for optimization.

4.1 CONTAMINANT DESTRUCTION EFFECTIVENESS

The contaminant destruction effectiveness is a measure of how well EIB removes TCE and its degradation products from the aqueous phase. The measure of success varies slightly between the two pilot areas. In the SZPSA, the initial concentrations of TCE suggested the presence of a non-aqueous phase, and a potential long-term source of groundwater impacts. As such, the critical measure of effectiveness was the ability of EIB to significantly reduce source concentrations, so that potential downgradient remedies can be optimized.

In the RPSA, the critical measure of effectiveness was the ability of EIB to reduce TCE and its degradation products to concentrations below the relevant JSCS SLVs. Meeting this goal would demonstrate effective source control at the riverbank, consistent with the objective of the JSCS.

4.1.1 SZPSA

Initial reconnaissance and monitoring well data indicated that TCE concentrations were indicative of a high probability that TCE could be present as a DNAPL, using the criteria developed by USEPA (USEPA, 1993). Based upon data from WS13-69, and coupled with the results described in Gerhard et al., TCE DNAPL is not expected to be mobile, if present (Gerhard, 2007). As discussed previously, TCE DNAPL has not been detected in any of the SZPSA monitoring well sumps.

EIB was not expected to be as effective at remediating residual TCE DNAPL as other technologies (e.g., chemical oxidation, thermal destruction), since the primary mechanism is dechlorination in the aqueous phase. However, the data from the pilot study indicate that EIB is a very effective remedy for TCE DNAPL - the rate of dissolution from the non-aqueous phase is clearly less than the rate of dechlorination in the aqueous phase. The data confirm that within and downgradient of the injection zone, TCE DNAPL is being remediated by EIB.

In the shallow interval, TCE was reduced by more than 98 percent within and downgradient of the PRB. DCE concentrations were reduced by 50 to 99 percent, and VC increased by a factor of more than 1,000. The biological end product, ethene, increased significantly in the PRB and downgradient wells. The downgradient populations of DHC increased by four orders of magnitude.

In the deep portion of the injection area, TCE was reduced by 99 percent in the PRB and 94 percent in the downgradient area. DCE increased by a factor of 1.5 to 5, VC increased by a factor of 200 to 700. Production of ethene increased significantly in the PRB and downgradient wells. The downgradient populations of DHC increased by four orders of magnitude.

Often, reductive dechlorination of TCE “stalls out”, such that DCE accumulates without production of vinyl chloride or ethene. The pre-implementation and upgradient data suggest that effect was occurring – high concentrations of TCE and DCE, with little production of vinyl chloride, and little or no ethene. Along with the ethene data, the increased production of DCE (in the deep interval) and vinyl chloride (both intervals) confirms the effectiveness of EIB at increasing the rates of dechlorination and conversion to ethene.

These data confirm that EIB eliminates very high concentrations of TCE. The production of VC and ethene in the downgradient wells, coincident with a significant increase in the number of DHC microbes, confirms that the beneficial effects of the PRB are transmitted downgradient. The data confirm that EIB is very effective for reducing source area contaminants at concentrations characteristic of the presence of TCE DNAPL.

4.1.2 RPSA

EIB was very successful at the riverbank. Chlorinated ethenes were reduced by 99.9 percent within the PRB, 95 percent 10 feet downgradient of the PRB, and 99.9 percent 20 feet downgradient of the PRB. In the PRB and at the downgradient point closest to the river, TCE, cis-1,2-DCE and vinyl chloride were reduced to concentrations below the relevant JSCS SLVs (30, 61 and 2.4 ug/L, respectively). In the PRB and both downgradient wells, TCE was reduced to non-detect levels.

In monitoring well WS-11-125 (located 10 feet downgradient of the PRB), TCE was reduced to below the JSCS SLVs, but concentrations of cis-1,2-DCE and vinyl chloride were not, and remained similar to background (upgradient) levels. As discussed in the *Desorption Bench Test* letter (MFA, 2007b), it appears that these compounds are desorbing from the MGP DNAPL in that well. The “production” of DCE and vinyl chloride in the aqueous phase results in an underestimate of the true aqueous phase degradation rate.

The data confirm that EIB at the riverbank will successfully reduce TCE and its degradation products to concentrations below the JSCS SLVs.

4.2 TIMEFRAME FOR TREATMENT

A timeframe for treatment is established by reviewing downgradient residual concentrations along with estimated groundwater flow velocities over the duration of the pilot study. Concentration vs. time plots (combined with the concentration vs. distance plots) will refine treatment timeframes in the FFS. The amount of time required for dechlorinated groundwater to travel from the SZPSA to the RPSA, and similarly from the RPSA to in-river, is estimated in the following sections.

4.2.1 SZPSA

The treatment timeframe within the source zone is likely on the order of 12 to 18 months to reduce TCE concentrations to the SLV (30 ug/L). TCE in the SZPSA reached levels below the TCE SLV within 4 months after injection of the bioamendments. The 12-18 month estimate assumes that the entire source area is injected with EHC and KB-1 so that advective distribution of electron donor and microbes is not a limiting factor. The accuracy of the timeframe would require revision if TCE DNAPL were discovered at or above residual saturation, since these conditions were not encountered during the pilot study.

4.2.2 RPSA

The timeframe for treatment at the riverbank is dependant on the timeframe for the source area, in addition to the travel time between the source area and the riverbank. Assuming the source is treated, the timeframe for maintaining the riverbank treatment is shortened significantly.

As discussed in Section 3.3, effective groundwater velocity in the RPSA is estimated to be 0.73 ft/day and between 0.18 and 0.29 ft/day in the SZPSA. The distance between WS13-69 and WS11-125 is approximately 515 feet. It is unknown if the SZPSA or the RPSA effective velocity is more representative of the actual water velocity between the

two areas so a range has been calculated. If the SZPSA deep zone velocity is most representative, then groundwater could travel the distance in about 7.8 years. If the RPSA velocity is more representative, then the time of travel would be closer to 1.9 years. The actual travel time is likely to be between 1.9 and 7.8 years.

Due to retardation (sorption), the actual amount of time required for TCE and its degradation products to reach the riverbank may be somewhat longer. However, degradation continues between the source area and the riverbank. Significant mass reductions at the source area may reduce riverbank concentrations to an acceptable level (below SLVs) without requiring multiple applications in the riverbank treatment area.

4.3 DENSITY OF APPLICATION AND RESULTANT TREATMENT ZONE SIZE

The treatment zone size is evaluated by reviewing concentration data from the sampling points within and downgradient of the PRBs. Reduction of COC concentrations to the target levels downgradient of the treatment zone indicates that the application density is suitable. This information can be used to adjust the treatment zone configuration for full scale applications.

4.3.1 SZPSA

EHC was injected within the source area at an application rate of 1.5 percent (by weight) in the PRB. KB-1 was injected at about 7 liters per injection point. The PRB was defined to be between 50 and 106 ft bgs. Injections were administered on a grid with 5 ft spacing that was offset perpendicular to groundwater flow between rows. The vertical injection interval was 4 feet, with a 2 foot vertical offset between rows.

Application of EHC at 1.5 percent is adequate for achieving the mass reduction goals within the source area. VFA data indicate that the VFAs are consumed as they are produced by the end of the study. There was an initial excess of most of the VFAs, however as the study progressed consumption of the higher energy VFAs (lactic, propanoic, and pyruvic acid) was evident.

The application of additional iron is unlikely to increase the amount of abiotic degradation that is occurring in the source area. During the preliminary investigation it was noted that the soil matrix within the source area was generally smaller grained soils, silts and fine sand, with many thin layers. The fine grained materials may prevent good distribution of ZVI. Increasing the amount of ZVI component in EHC is not recommended.

The injected materials in the pilot study are shown to significantly increase TCE removal and to speed conversion to ethene. The application grid used in the SZPSA is adequate for treating areas with high concentrations of TCE. Within the treatment zone, rapid conversion of TCE to DCE, VC, and ethene is apparent. Downgradient conversion of TCE is apparent, but it occurs at a slower rate, since the process relies on advection of excess electron donor from the application zone. For full treatment within the source area, it is recommended that the injection grid be applied within the entire boundary of the accessible source area.

4.3.2 RPSA

In the RPSA EHC was injected at an application rate of 1.0 percent (by weight) between 90 and 130 ft bgs. KB-1 was applied at about 3 liters per injection point. Injection points were spaced on a 7 ft grid that was offset between rows. The vertical injection interval was 4 feet, with a 2 foot vertical offset between rows.

The analytical data suggest that abiotic degradation is significantly contributing to mass reduction in the PRB, based on the absence of sequential dechlorination. An alternative explanation is that the DHC bacteria are simultaneously dechlorinating TCE and its degradation products (unlike in the SZPSA).

Downgradient data suggest that the degradation mechanism changes outside of the PRB. Biological analysis indicates that the DHC populations downgradient of the injection zone are as high as within the PRB. Buildup of VC and ethene is apparent in WS11-125 and to a lesser extent WS20-112, suggesting contribution from the biological pathway. Electron donor material from the injection zone that is not consumed within the PRB is carried downgradient and is able to support reductive dechlorination.

TOC from the EHC carbon source persists in the subsurface after 11 months in the riverbank. Soil borings completed at the end of the pilot study confirmed that the EHC carbon was still remaining in bands in the soil. The field work also confirmed that there was good distribution of ZVI away from the injection points. It is likely that the microorganisms are consuming dissolved TOC and VFAs very rapidly, before they can appear in the monitoring well.

For full treatment of the plume at the riverbank, it is recommended that the injection grid be applied over the entire width of the plume where concentrations exceed JSCS SLVs. The EHC mixture should include the regular and long release organic carbon source to ensure the longevity of the system and reduce the number of applications that are required. The ZVI content of the injected EHC material should be reviewed in more detail during design. The application rate can be tailored depending on the concentration of the TCE and its degradation products observed in each segment of the PRB. Applying

the grid spacing used in the RPSA would ensure that similar degradation rates would be more likely to occur.

The “biological polishing” that occurs downgradient of the PRB should be included in the design consideration, since that process effectively increases the treatment zone downgradient dimension. The dual nature of the EHC material helps to ensure that concentrations of TCE and its degradation products in groundwater at the riverbank are below target levels.

4.4 IMPLEMENTATION

The implementation of the EIB technology was evaluated on the application method, application rate, installation materials, and monitoring. These factors apply directly to the reasonableness of cost in implementing the technology at the Siltronic site.

4.4.1 APPLICATION METHOD

The application method chosen for the pilot study was based on known subsurface conditions and vendor recommendations. Confirmation of the chosen method’s effectiveness is evaluated below. Adjustments made to equipment or application methods during the field application of the bioremediation amendments in the pilot study will be carried forward into the FS.

As described in Section 2.2, application of the amendments was made through direct injection methods using a GeoProbe drill rig. The injection rods were equipped with a pressure activated injection tip that prevents material from escaping when there is no pressure on the injection line. MGP-related impacts in the pilot study area were known to extend to a depth of approximately 30 feet bgs. In an effort to minimize the potential for MGP-related contaminant “dragdown”, each boring was pre-drilled by a mini-sonic with a six-inch core rod to a depth of 30 feet and then backfilled with bentonite chips. The injection rods were then pushed to the shallow injection depth, and then advanced in 4 foot intervals to the lowest depth. Injection of materials in this manner proved to be very effective.

Approximately 2 injections were completed per day in the source area for EHC, and 2.5 per day for KB-1. In the riverbank area, approximately 1.5 injections of EHC were completed per day, and 2 per day for KB-1.

Implementation issues and the approaches used to resolve them included

- **Pre-Drilling:** Isolation of the injection rods from the potential shallow soil MGP contaminants using large diameter (4 inch) GeoProbe outer casing was unsuccessful. Installation of the large diameter rod was extremely difficult and

time consuming. It was also found that the lack of support for the 30 feet of injection rod in the outer casing subjected the rod to additional stress, and resulted in the loss of drilling rod in the subsurface. An auger rig proved to be ineffective for pre-drilling the holes as a means of isolating the injection rods. The abundance of riprap in the subsurface prevented adequate progress with of the auger flights. A minisonic drill rig with a 6 inch core barrel was determined to be successful at pre-drilling each of the injection holes to 30 feet bgs. The boring was backfilled with bentonite chips and hydrated prior to injection. It was found that the bentonite chips provided enough support to the injection rods to reduce the amount of stress and breakage of the rods. However, the presence of MGP-related impacts throughout the fill, silt, and underlying AWBZ (and deeper than the injection zone) suggests that pre-drilling the holes provides little environmental benefit, and substantially increases implementation costs and safety risks. Pre-drilling is not recommended for full-scale implementation.

- **Injection Pump:** EHC is injected in slurry form after it is mixed with water. A ChemGrout pump was recommended by AAI, which is equipped with a mixing hopper and a positive displacement pump. The pressure necessary for injection was found to be much higher than the capability of the pump. A Bean Pump was able to generate sufficient pressure to overcome hydrostatic pressure and to displace the soil. Mixing of the slurry was carried out in a steel drum with a pneumatic mixer and the ChemGrout pump was returned.
- **Injection of EHC Backpressure:** Due to backpressure, if an injection rod was not immediately capped following completion of an injection interval, EHC would escape through the opening. To avoid EHC and/or grout backflow from the drill rods, a cap was maintained whenever possible. Following completion of an injection point rods were withdrawn to about 40-45 ft bgs and capped to allow the pressure in the hole to subside, usually overnight. Once pressure had dissipated, the injection point was sealed. When extremely high pressure (>1000 pounds per square inch as indicated by a gauge) was observed, it often indicated a refusal of EHC delivery, either due to a tight formation or an injection tip that was not properly extended. Solutions to this problem included advancing the rod slightly past the injection interval until EHC was accepted or, if necessary, pulling the drill rods to ensure the injection tip was properly functioning.
- **Daylighting:** Daylighting of EHC along the outside of the injection rods would occasionally occur within the injection point or a nearby injection point or well. This was minimized by sealing each injection point as soon as possible after injection and ensuring that the current injection point and recently completed injection point were separated by a large distance.
- **Drum hazards:** Slurry waste and decontamination water was drummed and disposed of according to Siltronic's direction. A reaction caused by wet EHC

caused a build-up of pressure within the drums and resulted in deformed drums and one instance of a drum lid being blown off. This issue was resolved by using drum lids with a pressure release opening and venting prior to removing.

- **EHC Supply:** Two shipments of EHC were sent to the site, one for the RPSA and one for the SZPSA. Upon original counts, a sufficient supply of EHC was shipped, but when EHC injections in the RPSA were nearing completion, 12 bags had to be borrowed from the SZPSA shipment. Careful planning during field installation of EHC should occur to minimize the occurrence of wasted material. In addition careful inspection of the delivered materials should verify that the desired quantity has been delivered. Additional EHC material can be ordered initially or near the completion of the field work to replace any missing or wasted materials. In addition, the supply should be kept dry to prevent any reaction from occurring prior to injection.
- **Drilling issues:** When injecting, drilling rods were lost due to soil conditions or improper drill rod connections. Deep drilling (below 40 feet bgs) with a Geoprobe rig may be difficult and loss of drilling rods is more likely to occur. Careful inspection by the drillers when connecting rods assisted in reducing the problem. When the problem occurred, rods were attempted to be recovered by over-drilling with an auger rig. If rods were lost, the injection point was stepped over and re-attempted.
- **Low DO Water:** As part of the injection method for KB-1, low DO chase water was required to deliver the microbes to the injection tip. Maintaining low DO conditions in the water tank was difficult since the tank could not be completely sealed, so in addition to the regular addition of sodium lactate, SiREM recommended regular doses of sodium sulfite to scour oxygen from the water. This solution was very effective.
- **Equipment maintenance:** With a long-term field operation, equipment failure is likely. Care must be given to the pump in order to ensure proper maintenance. Pressure gauges needed to be replaced several times during operations and hydraulic lines leaked and need to be repaired.

4.4.2 APPLICATION RATE

The pilot study application rate for the source area and the downgradient area will be evaluated with regard to the treatment efficiency (remaining TCE concentration) versus the application rate and destruction efficiency from the bench test. Information regarding the ability to deliver the required amount of material to the PRB in each injection interval for the source area and downgradient area is also used to ensure that the application rate for the EHC that is selected in the FS is reasonable.

4.4.2.1 SZPSA

The EHC application rate in the SZPSA of 1.5 percent by weight of soil was adequate to support enhanced degradation of the high concentrations of TCE. Concentration reductions for TCE, and subsequent conversion to DCE, VC, and ethene were significant. Additional ZVI in the EHC formulation is not necessary because soils in this area are typically fine grained and hinder the distribution of the microscale ZVI particles away from the injection point.

Groundwater samples indicate that there is sufficient TOC and VFAs (with the exception of lactic, propanoic, and pyruvic acid) present in the PRB and downgradient to continue to support biological degradation. The addition of the longer release carbon donor in the EHC may be considered, but the slower release rate of electron donor may slow down the overall TCE degradation rate.

Given the rapid establishment of the DHC microbes in the subsurface, the application rate of 7 liters of KB-1 per injection hole appears to be appropriate for this area. Strong bacterial colonies were established quickly within the PRB. Distribution of DHC downgradient of the injection zone was also observed, suggesting that inaccessible areas may be addressed in a more passive method by treating adjacent to it.

4.4.2.2 RPSA

The EHC application rate in the RPSA of 1 percent by weight of soil in the PRB was adequate to treat incoming concentrations of cVOCs in the riverbank area. A significant contributing mechanism in the PRB is abiotic degradation by ZVI. Soil boring data obtained after the completion of the pilot study provided evidence of very good distribution of ZVI particles away from the injection point and into the soil matrix. Increasing the percentage of ZVI in the EHC mixture could increase the capacity to reduce chlorinated ethenes prior to discharge.

Biological counts provide evidence that there are significant amounts of DHC in the PRB and downgradient. These data confirm biological degradation downgradient of the PRB. Low dissolved concentrations of TOC and VFAs suggest that the electron donor may be quickly consumed, depleting the organic carbon source. The addition of long release carbon donor material to the EHC mixture could help to provide a more stable and long term source of electron donor to sustain the biological polishing of water leaving the treatment zone.

DHC counts increased downgradient during the course of the study, to levels higher than in the PRB. This indicates that conditions may be preferable downgradient. Applying KB-1 inoculums at 3 liters per injection hole across the application zone appears to have been sufficient to develop a healthy community within the PRB, and has lead to a strong community of microbes downgradient.

Organisms within the KB-1 culture may be responsible for an increased carbon release rate of the EHC material. Since the injection of KB-1 carried a large concentration of microbes directly into a carbon rich environment, it is possible that certain species of the culture degraded the plant fibers at a higher rate than intended. Consideration should be given to injecting the microbes in a downgradient portion of the treatment zone to facilitate the downgradient movement of the biologically active zone and reduce the carbon consumption rate from the EHC substrate.

4.4.3 MONITORING

The monitoring data collected during the pilot study provided insight for the selection of monitoring parameters in the full-scale implementation. Parameters that exhibit little or no impact due to the treatment technology may be considered for deletion in the full-scale phase.

- Monitoring of cVOCs (TCE, DCE, and VC), ethene, and chloride is necessary to verify that the technology is functional and achieving treatment goals.
- Monitoring of redox conditions (ORP, DO, sulfate, methane, and ferrous iron) is recommended to verify that suitable conditions exist to support reductive dechlorination.
- Monitoring of the source area TOC/VFA is recommended to monitor removal/conversion rates and electron donor consumption. These data are critical for optimizing the design requirements for re-application.
- Monitoring of benzene and naphthalene indicated that there were negligible changes in MGP dissolved constituents and would not be necessary, however they are part of the standard 8260 analysis that is required for cVOC analysis.
- Periodic biological monitoring is recommended to monitor fluctuations in community size in response to degradation effectiveness.
- The pilot study data demonstrated that concentrations of arsenic, manganese, and cyanide were not increased and in some cases were significantly reduced. Continued monitoring of these parameters is not necessary.

5 CONCLUSION

The primary criteria for measuring the effectiveness of EIB are (a) reduction of concentrations of TCE and its degradation products in groundwater to below JSCS SLVs at the riverbank, and (b) remediation of potential TCE DNAPL in the source area. Since the presence of TCE DNAPL in the source area has only been inferred from aqueous phase concentration data, remediation is defined as reducing concentrations of TCE in groundwater to below the 1 percent solubility limit rule proposed in *Evaluation of the Likelihood of DNAPL at NPL Sites* (USEPA, 1993).

Supplemental data (i.e., pH, oxidation-reduction potential, concentrations of redox-sensitive species such as dissolved oxygen, methane, and sulfate, production of ethene and chloride) are critical for characterizing the geochemical conditions and confirming dechlorination. Polymerase chain reaction (PCR) data identifying the growth and distribution of KB-1 bacteria were also identified as critical.

A secondary criterion for measuring the effectiveness, identified by DEQ, is the extent to which EIB mobilizes redox-sensitive metals, such as arsenic and manganese. The extent to which EIB interacted with representative MGP-related constituents such as benzene, naphthalene, and cyanide was also identified as of secondary importance.

The pilot test data confirm that EIB meets all of the criteria. At the riverbank, concentrations of TCE and its degradation products in groundwater were reduced to below JSCS SLVs, and chlorinated volatile organic compound (cVOC) mass reduction of 99.99 percent was achieved. KB-1 bacteria were identified downgradient of the injection zone. Redox-sensitive metals were not mobilized, and free cyanide concentrations were fortuitously reduced.

In the source area, initial TCE concentrations characteristic of TCE DNAPL were reduced by approximately 94 to 99.96 percent. Fully dechlorinated ethene was produced. The supplemental data confirmed the conversion mechanism (reductive dechlorination), and KB-1 bacteria were identified downgradient of the injection zone. Redox-sensitive metals were not mobilized, and free cyanide concentrations were fortuitously reduced.

Aquifer testing data and analytical data were used to predict the short-term (i.e., 1-3 years) performance of a full-scale remedy downgradient of the injection zones. The data indicate that the groundwater velocity at the riverbank is approximately 268 feet per year.

This suggests that EIB could treat Area 1 TZW concentrations within a few years following injection at the riverbank.

Coupled with groundwater velocity data, the pilot study data suggest the following:

- 1) EIB will be successful in the source area, where concentrations of TCE are relatively high, and indicative of the presence of TCE-DNAPL.
- 2) EIB will be successful as a source control remedy, preventing migration of TCE and its degradation products in groundwater at concentrations in excess of JSCS SLVs to the Willamette River.
- 3) EIB could be implemented at the riverbank to reduce or eliminate concentrations of TCE and its degradation products in TZW.

LIMITATIONS

The services described in this report were performed consistent with generally accepted professional consulting principles and practices. No other warranty, express or implied, is made. These services were performed consistent with our agreement with our client. This report is solely for the use and information of our client unless otherwise noted. Any reliance on this report by a third party is at such party's sole risk.

Opinions and recommendations contained in this report apply to conditions existing when services were performed and are intended only for the client, purposes, locations, time frames, and project parameters indicated. We are not responsible for the impacts of any changes in environmental standards, practices, or regulations subsequent to performance of services. We do not warrant the accuracy of information supplied by others, nor the use of segregated portions of this report.

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TABLES

**Table 2-1
PRB Specifications
Siltronic Corporation
Portland, Oregon**

Description	SZPSA		RPSA		Unit
	Per Draft Work Plan	Per Field Modified Plan	Per Draft Work Plan	Per Field Modified Plan	
BAZ Length (Perpendicular)	15				Feet
BAZ Width (Parallel)	10				Feet
BAZ Thickness (Vertical)	55	55	40	40	Feet
Top of BAZ	50	50	90	90	Feet bgs
Bottom of BAZ	105	106	130	130	Feet bgs
Injection Points	12	12	20	20	Each
Vertical Interval	4	4	4	4	Feet
Injection Spacing	5	5	7	7	Feet
EHC					
Slurry Solids Content	30	20	30	25	Percent
Percent EHC by Soil Mass	1.5	1.5	1	1	Percent
Amount per Interval	--	150	--	200	Pounds
Mass per Injection Point	2271	2100-2300	2094.4	2,000-2,200	Pounds
Total EHC	27,250	26,800	41,888	42,000	Pounds
KB-1					
Amount per Interval	500	500	300	300	milliliters
Amount per Injection Point	--	7.0-7.5	3.0	3.0-3.3	Liters
Total KB-1	84.0	88.0	60	63.4	Liters

Note:
bgs = below ground surface

**Table 2-2
Pilot Study Monitoring Schedule
Siltronic Corporation
Portland, Oregon**

Month	SZPSA			RPSA		
	Time	Chemical Analysis	Biological Analysis	Time	Chemical Analysis	Biological Analysis
May-06	-	WS13-105 and WS-13-69 (Quarterly)	-	-	WS11-125 (Quarterly)	-
Jun-06	-	WS18-71, WS18-101, WS19-71, WS19-101 (Baseline)	-	Time 0	All RPSA wells	-
Jul-06	Time 0	All SZPSA wells	-	Time 1	All RPSA wells	-
Aug-06	Time 1	All SZPSA wells	-	Time 2	All RPSA wells	-
Sep-06	Time 2	All SZPSA wells	-	Time 3	All RPSA wells	WS11-125, WS21-112, WS22-112
Oct-06	Time 3	All SZPSA wells	All SZPSA wells	Time 4	All RPSA wells	WS20-112
Nov-06	Time 4	All SZPSA wells	-	-	Quarterly (WS21-112)	-
Dec-06	-	-	-	Time 6	All RPSA wells	All RPSA wells
Jan-07	Time 6	All SZPSA wells	All SZPSA wells	Time 7	All RPSA wells	-
Feb-07	Time 7	All SZPSA wells	-	Time 8	All RPSA wells	-
Mar-07	Time 8	All SZPSA wells	-	Time 9	All RPSA wells	-
Apr-07	Time 9	All SZPSA wells	All SZPSA wells	Time 10	All RPSA wells	All RPSA wells
May-07	Time 10	All SZPSA wells	All SZPSA wells	Time 11	All RPSA wells	All RPSA wells

Notes:

SZPSA: Source Zone Pilot Study Area

RPSA: Riverbank Pilot Study Area

SZPSA wells: WS13-69, WS13-105, WS18-71, WS18-101, WS19-71, WS19-101

RPSA wells: WS11-125, WS20-112, WS21-112, WS22-112

**Table 2-3
Groundwater Monitoring Parameters
Siltronic Corporation
Portland, Oregon**

Parameter	RPSA			SZPSA		
	WS-21-112 (Upgradient)	WS-22-112 (Internal)	WS-20-112 WS-11-125 (Downgradient)	WS-13-69 WS-13-105 (Upgradient)	WS-19-71 WS-19-101 (Internal)	WS-18-71 WS-18-101 (Downgradient)
Temperature	X	X	X	X	X	X
Conductivity	X	X	X	X	X	X
Dissolved Oxygen	X	X	X	X	X	X
Oxidation/Reduction Potential	X	X	X	X	X	X
Volatile Organic Compounds	X	X	X	X	X	X
Polycyclic Aromatic Hydrocarbons	X	X	X	X	X	X
Total Organic Carbon	X	X	X	X	X	X
Volatile Fatty Acids	X	X	X	X	X	X
Fixed Gases	X	X	X	X	X	X
Alkalinity	X	X	X	X	X	X
Sulfate	X	X	X	X	X	X
Chloride	X	X	X	X	X	X
Total Metals*	X	X	X	X	X	X
Dissolved Metals*	X	X	X	X	X	X

Note:

*Metals include total and dissolved aluminum, antimony, arsenic, cadmium, chromium, copper, cyanide (free and total only), iron, lead, manganese, mercury, nickel, selenium, silver, and zinc.

**Table 3-1
SZPSA Results Summary
Siltronic Corporation
Portland, Oregon**

Parameter (unit)	WS-13-105		WS-13-69		WS-19-101		WS-19-71		WS-18-101		WS-18-71	
<i>Location</i>	Upgradient				Permeable Reactive Barrier				Downgradient			
<i>Date</i>	07/19/06	05/23/07	07/19/06	05/23/07	06/27/06	05/23/07	06/27/06	05/23/07	06/28/06	05/22/07	06/27/06	05/22/07
<i>Sampling Event</i>	Month 0	Final Sampling	Month 0	Final Sampling	Pre- Injection	Final Sampling	Pre- Injection	Final Sampling	Pre- Injection	Final Sampling	Pre- Injection	Final Sampling
TCE (ug/L)	3.49	1.93	178,000	191,000	92,900	35.3	611	142	103,000	11,800	2,960	111
1,1-DCE (ug/L)	ND	ND	133	150	58.3	90.9	168	9.11	176	299	166	51.4
cis-1,2-DCE (ug/L)	8.52	7.15	36,000	51,400	114,000	52,400	61,300	3,300	55,400	176,000	83,700	180,000
trans-1,2-DCE (ug/L)	ND	ND	148	122	861	203	459	121	590	959	563	162
VC (ug/L)	ND	1.27	28.4	378	23.1	15,600	67.5	54,600	57.2	7,980	24.9	8,680
Ethene (mg/L)	ND	ND	ND	ND	ND	4.35	ND	7.3	0.126	1.9	ND	5.9
ORP (mV)	-144.1	-110.8	-141.6	-114	-119.6	-107.1	-134.9	-86.3	-143.6	-96.5	-131.6	-66.6
Methane (mg/L)	30	57	24.6	29	13.7	59	5.55	11	41.3	33	7.05	7
Benzene (ug/L)	ND	ND	1,140	1,160	78.5	33.5	753	566	125	72.8	574	345
Naphthalene (ug/L)	ND	ND	1,510	1,180	91.6	148	181	212	211	61.8	73.2	29.3
Cyanide (mg/L)	ND	ND	0.51	0.53	0.11	0.032	0.64	0.72	0.036	0.02	0.75	0.99
Cyanide, Free (mg/L)	ND	ND	0.52	0.12	0.092	ND	0.65	0.041	0.03	ND	0.88	0.2
Arsenic (ug/L)	ND	8.4	ND	8.9	ND	1.5	ND	2.2	ND	5.3	ND	ND
Manganese (mg/L)	2.83	2.72	10.9	10.7	12.2	24.1	13.3	22.9	7.22	7.75	17.2	14.5

Notes:

- DCE: dichloroethylene
- mg/L: milligram per liter
- mV: millivolts
- ND: Not detected above the MRL.
- ORP: oxidation reduction potential
- TCE: trichloroethylene
- ug/L: microgram per liter

Table 3-2
RPSA Results Summary
Siltronic Corporation
Portland, Oregon

Parameter (unit)	WS-21-112		WS-22-112		WS-11-125		WS-20-112	
Location	Upgradient		Permeable Reactive Barrier		Downgradient		Farthest Downgradient	
Date	06/28/06	05/22/07	06/28/06	05/22/07	06/28/06	05/22/07	06/28/06	05/21/07
Sampling Event	Month 0	Month 11	Month 0	Month 11	Month 0	Month 11	Month 0	Month 11
TCE (ug/L)	572	113	584	ND	22.9	ND	1,100	ND
1,1-DCE (ug/L)	4.13	4.84	6.95	ND	9.81	0.82	19.7	ND
cis-1,2-DCE (ug/L)	2,960	1,520	3,060	ND	10,500	1,640	10,000	ND
trans-1,2-DCE (ug/L)	49.6	11.5	7.21	ND	47.5	2.58	47	ND
VC (ug/L)	548	395	474	2.35	2,490	422	1,610	1.42
Ethene (mg/L)	0.21	ND	0.247	ND	0.439	0.25	0.452	ND
ORP (mV)	-123.2	-86.1	-114.5	-186.7	-159.7	-167.5	-178.6	-266.1
Methane (mg/L)	7.79	12.7	2.62	42	3.12	70	4.73	81
Benzene (ug/L)	1,120	846	157	118	1,340	1,680	132	252
Naphthalene (ug/L)	548	440	3.38	ND	5,100	9,280	1.99	ND
Cyanide (mg/L)	0.76	0.48	0.46	0.49	0.48	0.42	0.47	0.34
Cyanide, Free (mg/L)	0.73*	0.21	0.32*	0.24	0.4*	0.062	0.44*	0.19
Arsenic (ug/L)	ND	1.3	ND	ND	ND	2.7	ND	ND
Manganese (mg/L)	2.59	1.03	17.7	0.10	4.49	8.98	5.54	0.015

Notes:

*: Month 1 data.

DCE: dichloroethylene

mg/L: milligram per liter

mV: millivolts

ND: Not detected above the MRL.

ORP: oxidation reduction potential

TCE: trichloroethylene

ug/L: microgram per liter

Table 3-3
Hydraulic Conductivity Derived from Pneumatic Slug Testing
Siltronic Corporation
Portland, Oregon

Location	Hydraulic Conductivity (K) (ft/day)			Average K (ft/day) per well	Average K (ft/day) per depth interval ^d
	12-inch Test	24-inch Test	36-inch Test		
Source Area					
WS13-69 ^a	10.90 ^a	7.27 ^a	10.90 ^a	9.69	0.546
WS13-69 ^b	0.51	0.20	0.72	0.48	
WS18-71	0.56	0.53	0.55	0.55	
WS19-71	1.20	0.38	0.26	0.61	
WS18-101	0.25	0.13	0.10	0.16	0.161
WS19-101 ^c	0.000000283 ^c	0.000000283 ^c	1.37 ^c	--	
Riverbank Area					
WS12-125	1.21	1.11	1.07	1.13	1.17
WS20-112	0.17	0.21	0.21	0.19	
WS21-112	2.77	2.84	2.84	2.82	
WS22-112	0.95	0.23	0.42	0.54	
WS11-161	2.84	2.80	2.84	2.83	15.49
WS12-161	0.35	0.38	0.38	0.37	
WS14-161	37.9	44.2	47.7	43.27	
Notes:					
^a = Represents early recovery data.					
^b = Represents late recovery data.					
^c = Results skewed due to waterlevel oscillation amplitude during recovery.					
^d = Average does not include early data from WS13-69.					
Pneumatic slug testing at location WS-13-105 was unsuccessful					
ft: feet					
K: Hydraulic Conductivity					

Table 3-4
Hydraulic Gradients Based on Groundwater Elevations
(feet/foot)
Siltronic Corporation
Portland, Oregon

Location		SZPSA		RPSA
		Shallow Zone	Deep Zone	
<i>Total Measurements</i>		10	10	9
Count of Positive Gradients	Upgradient to PRB	4	8	8
	PRB to Downgradient	3	7	1
	Upgradient to Downgradient	1	9	5
<hr/>				
Maximum Gradient	Upgradient to PRB	0.017	0.013	0.028
	PRB to Downgradient	0.013	0.105	0.002
	Upgradient to Downgradient	0.001	0.013	0.012
	Average Maximum Gradient	0.010	0.044	0.014
<hr/>				
Average Gradient	Upgradient to PRB	0.006	0.007	0.011
	PRB to Downgradient	0.005	0.028	0.002
	Upgradient to Downgradient	0.001	0.007	0.005
	Average Gradient	0.004	0.014	0.006

**Table 3-5
Supporting Elevation and Gradient Data
Siltronic Corporation
Portland, Oregon**

<i>RPSA Elevation and Gradient Data</i>							
Well ID	Date	TOC Elevation	Depth to Water	Elevation (ft-MSL)	Upgradient to PRB (WS-21 to WS-22, 44 ft)	PRB to Downgradient (WS- 22 to WS 20, 22 ft)	Upgradient to Downgradient (WS-21 to WS-20, 66 ft)
WS-21-112	Sep-06	33.63	29.01	4.62	0.007		
WS-22-112	Sep-06	32.51	28.21	4.3		-0.021	
WS-20-112	Sep-06	31.49	26.73	4.76			-0.002
WS-21-112	Nov-06	33.63	24.86	8.77	0.028		
WS-22-112	Nov-06	32.51	24.95	7.56		-0.031	
WS-20-112	Nov-06	31.49	23.25	8.24			0.008
WS-21-112	Dec-06	33.63	24.86	8.77	0.0002		
WS-22-112	Dec-06	32.51	23.75	8.76		-0.021	
WS-20-112	Dec-06	31.49	22.26	9.23			-0.007
WS-21-112	Jan-07	33.63	25.67	7.96	0.021		
WS-22-112	Jan-07	32.51	25.47	7.04		-0.034	
WS-20-112	Jan-07	31.49	23.7	7.79			0.003
WS-21-112	Feb-07	33.63	25.21	8.42	0.004		
WS-22-112	Feb-07	32.51	24.27	8.24		0.002	
WS-20-112	Feb-07	31.49	23.29	8.2			0.003
WS-21-112	Mar-07	33.63	24.64	8.99	-0.0002		
WS-22-112	Mar-07	32.51	23.51	9		-0.005	
WS-20-112	Mar-07	31.49	22.39	9.1			-0.002
WS-21-112	Apr-07	33.63	25.11	8.52	0.005		
WS-22-112	Apr-07	32.51	24.21	8.3		-0.004	
WS-20-112	Apr-07	31.49	23.11	8.38			0.002
WS-21-112	May-07	33.63	24.14	9.49	0.010		
WS-22-112	May-07	32.51	23.45	9.06		-0.010	
WS-20-112	May-07	31.49	22.2	9.29			0.003
WS-21-112	Jun-07	33.63	25.08	8.55	0.012		
WS-22-112	Jun-07	32.51	24.5	8.01		-0.033	
WS-20-112	Jun-07	31.49	22.76	8.73			-0.003
Count of (+)					8	1	5
Average					0.011	0.002	0.004
Maximum					0.028	0.002	0.003

**Table 3-5
Supporting Elevation and Gradient Data
Siltronic Corporation
Portland, Oregon**

SZPSA Elevation and Gradient Data - Shallow Interval							
Well ID	Date	TOC Elevation	Depth to Water	Elevation (ft-MSL)	Upgradient to PRB (WS-13 to WS-19, 43.1 ft)	PRB to Downgradient (WS- 19 to WS 18, 14.2 ft)	Upgradient to Downgradient (WS-13 to WS-18, 57.3 ft)
WS-13-69	Sep-06	33.32	28.36	4.96	-0.005		
WS-19-71	Sep-06	33.71	28.53	5.18		-0.005	
WS-18-71	Sep-06	33.92	28.67	5.25			-0.005
WS-13-69	Oct-06	33.32	28.18	5.14	0.006		
WS-19-71	Oct-06	33.71	28.82	4.89		-0.048	
WS-18-71	Oct-06	33.92	28.36	5.56			-0.007
WS-13-69	Nov-06	33.32	23.58	9.74	-0.007		
WS-19-71	Nov-06	33.71	23.69	10.02		0.001	
WS-18-71	Nov-06	33.92	23.91	10.01			-0.005
WS-13-69	Dec-06	33.32	23.04	10.28	-0.002		
WS-19-71	Dec-06	33.71	23.33	10.38		0.013	
WS-18-71	Dec-06	33.92	23.72	10.2			0.001
WS-13-69	Jan-07	33.32	24.88	8.44	0.002		
WS-19-71	Jan-07	33.71	25.34	8.37		-0.065	
WS-18-71	Jan-07	33.92	24.64	9.28			-0.015
WS-13-69	Feb-07	33.32	24.35	8.97	0.017		
WS-19-71	Feb-07	33.71	25.47	8.24		-0.056	
WS-18-71	Feb-07	33.92	24.89	9.03			-0.001
WS-13-69	Mar-07	33.32	23.84	9.48	-0.004		
WS-19-71	Mar-07	33.71	24.05	9.66		-0.017	
WS-18-71	Mar-07	33.92	24.02	9.9			-0.007
WS-13-69	Apr-07	33.32	23.73	9.59	-0.003		
WS-19-71	Apr-07	33.71	24	9.71		0.002	
WS-18-71	Apr-07	33.92	24.24	9.68			-0.002
WS-13-69	May-07	33.32	23.69	9.63	-0.005		
WS-19-71	May-07	33.71	23.87	9.84		-0.029	
WS-18-71	May-07	33.92	23.68	10.24			-0.011
WS-13-69	Jun-07	33.32	23.99	9.33	0.0002		
WS-19-71	Jun-07	33.71	24.39	9.32		-0.022	
WS-18-71	Jun-07	33.92	24.29	9.63			-0.005
				Count of (+)	4	3	1
				Average	0.0062	0.005	0.001
				Maximum	0.0170	0.013	0.001

Table 3-5
Supporting Elevation and Gradient Data
Siltronic Corporation
Portland, Oregon

<i>SZPSA Elevation and Gradient Data - Deep Interval</i>							
Well ID	Date	TOC Elevation	Depth to Water	Elevation (ft-MSL)	Upgradient to PRB (WS-13 to WS-19, 45.6 ft)	PRB to Downgradient (WS- 19 to WS 18, 14.8 ft)	Upgradient to Downgradient (WS-13 to WS-18, 60.4 ft)
WS-13-105	Sep-06	33.3	28.31	4.99	0.013		
WS-19-101	Sep-06	33.78	29.38	4.4		-0.020	
WS-18-101	Sep-06	33.95	29.26	4.69			0.005
WS-13-105	Oct-06	33.3	28.2	5.1	0.001		
WS-19-101	Oct-06	33.78	28.72	5.06		0.028	
WS-18-101	Oct-06	33.95	29.3	4.65			0.007
WS-13-105	Nov-06	33.3	23.96	9.34	-0.0004		
WS-19-101	Nov-06	33.78	24.42	9.36		-0.001	
WS-18-101	Nov-06	33.95	24.58	9.37			0.000
WS-13-105	Dec-06	33.3	23.16	10.14	-0.019		
WS-19-101	Dec-06	33.78	22.76	11.02		0.105	
WS-18-101	Dec-06	33.95	24.48	9.47			0.011
WS-13-105	Jan-07	33.3	24.93	8.37	0.008		
WS-19-101	Jan-07	33.78	25.76	8.02		0.003	
WS-18-101	Jan-07	33.95	25.97	7.98			0.006
WS-13-105	Feb-07	33.3	24.15	9.15	0.012		
WS-19-101	Feb-07	33.78	25.19	8.59		0.016	
WS-18-101	Feb-07	33.95	25.59	8.36			0.013
WS-13-105	Mar-07	33.3	23.71	9.59	0.004		
WS-19-101	Mar-07	33.78	24.38	9.4		0.001	
WS-18-101	Mar-07	33.95	24.57	9.38			0.003
WS-13-105	Apr-07	33.3	23.91	9.39	0.013		
WS-19-101	Apr-07	33.78	24.97	8.81		-0.011	
WS-18-101	Apr-07	33.95	24.98	8.97			0.007
WS-13-105	May-07	33.3	23.35	9.95	0.006		
WS-19-101	May-07	33.78	24.1	9.68		0.011	
WS-18-101	May-07	33.95	24.43	9.52			0.007
WS-13-105	Jun-07	33.3	23.84	9.46	0.005		
WS-19-101	Jun-07	33.78	24.55	9.23		0.030	
WS-18-101	Jun-07	33.95	25.17	8.78			0.011
Count of (+)					8	7	9
Average					0.008	0.028	0.007
Maximum					0.013	0.105	0.013

Note:

Elevations in feet relative to mean sea level

Table 3-6
Groundwater Velocity Calculations
Siltronic Corporation
Portland, Oregon

	SZPSA		RPSA
	Shallow	Deep	
<i>Velocity Based on Slug Test and Elevation Data</i>			
Hydraulic Conductivity (ft/day)	0.45	0.16	2.84
Average Gradient (ft/ft)	0.004	0.014	0.006
Average Velocity (ft/day)	0.006	0.007	0.056
Maximum Gradient	0.010	0.044	0.014
Maximum Velocity (ft/day) ⁽¹⁾	0.016	0.023	0.131
PRB-->Downgradient Well Distance (ft)	14.2	14.8	22
Travel time (days) using average gradient	2234	2004	390
Travel time (days) using maximum gradient	915	637	169
<i>Velocity Based on Analytical Data</i>			
Actual Travel Time (days)	49	83	30
Velocity (ft/day)	0.29	0.18	0.73
Velocity (ft/year)	106	65	268
<i>Travel Time Estimates (years)</i>			
SZPSA --> Riverbank (515 ft)	4.9	7.9	
Riverbank --> Extent of LOF (560 ft)			2.1

Note:

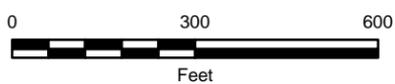
(1) Assuming effective porosity of 0.3

FIGURES



Legend

- Navigation Line
- Area 1
- Area 2
- Pilot Study Areas
- Siltronic Property Boundary
- Locality of Facility (Based on Estimated Maximum Lateral Extent of TCE Related Groundwater Impacts)



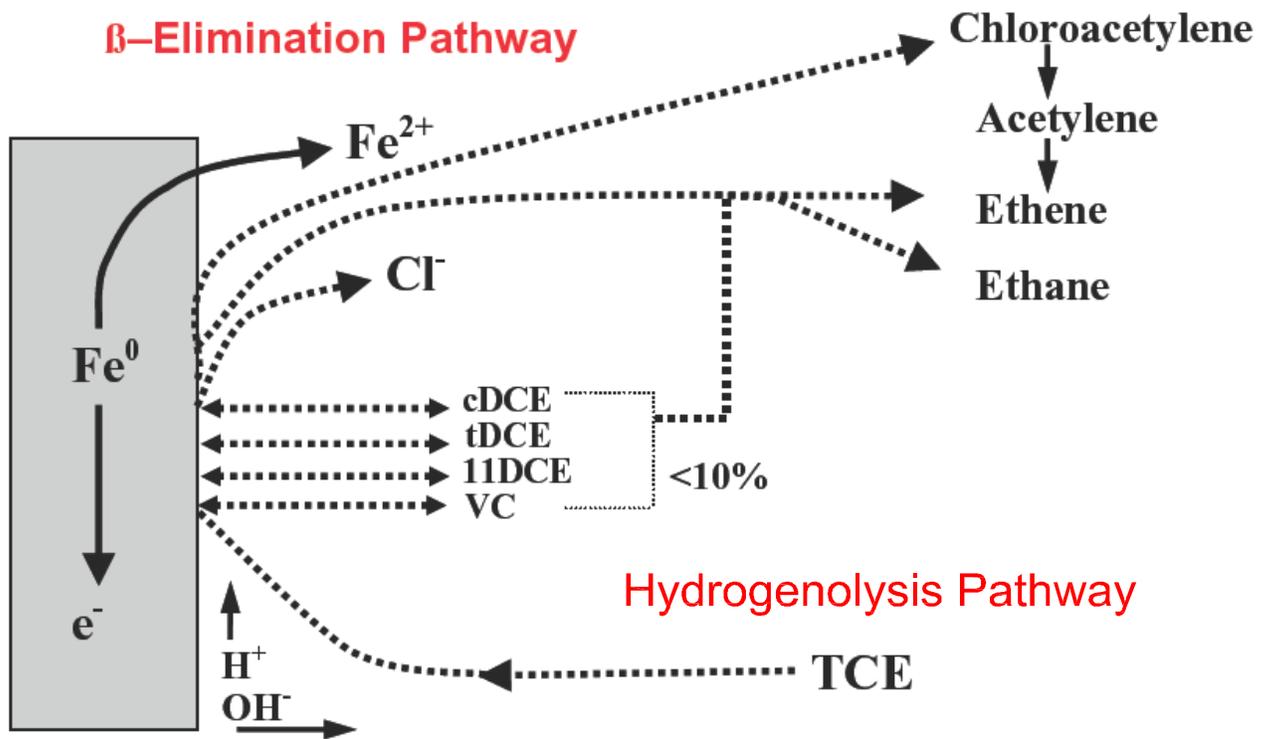
**Figure 1-1
Site Location and Plume**

Siltronic Corporation
Portland, Oregon



*Source: Aerial Photograph (2006) obtained from Metro Regional Land Information System (RLIS)

**Abiotic Beta Elimination
 Pathway for TCE**



G:\8128.01 Siltronic Corporation\10_Pilot Study Final Report\Fig1-2_Abiotic Beta Elimination.dwg, Layout1, 7/23/2007 1:55:52 PM, jfisher

Figure 2-1
Source Zone Pilot
Study Area
 Siltronic Corporation
 Portland, OR

Legend

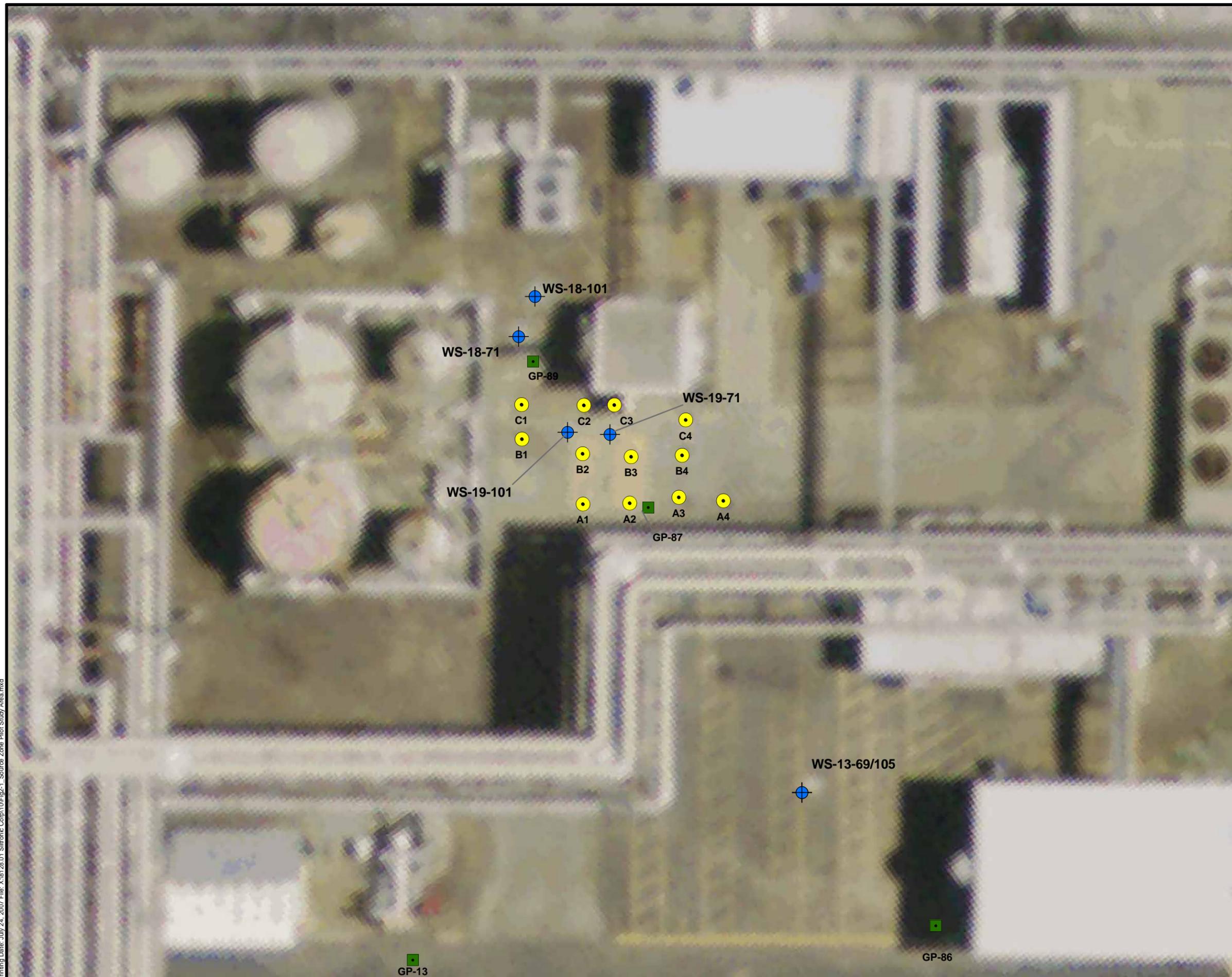
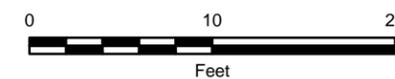
-  Injection Points
-  Geoprobes
-  Monitoring Wells

Notes:
 1. Source: Aerial Photograph (2006) obtained from Metro Data Resource Center
 2. Survey completed by Minister-Glaeser Surveying Inc. on 09-08-06.

Horizontal Datum:
 NAD 83/91, Oregon State Plane Coordinate System, North Zone, International Feet

Vertical Datum:
 NGVD 29/47

Bench Mark:
 Port of Portland Brass Cap "A-39"
 Located at Port of Portland
 Terminal 4, Berth 410
 Elevation = 34.50 NGVD29/47 Datum



Printing Date: July 24, 2007 File: X:\8128.01_Siltronic_Corp\10\Fig2-1_Source_Zone_Pilot_Study_Area.mxd

Figure 2-2 Riverbank Pilot Study Area

Siltronic Corporation
Portland, OR

Legend

-  Injection Points
-  Monitoring Wells
-  Geoprobes

Notes:

1. Source: Aerial Photograph (2006) obtained from Metro Data Resource Center
2. Survey complete by Minister-Glaeser Surveying Inc. on 09-08-06.

Horizontal Datum:
NAD 83/91, Oregon State Plane Coordinate System, North Zone, International Feet

Vertical Datum:
NGVD 29/47

Bench Mark:
Port of Portland Brass Cap "A-39"
Located at Port of Portland
Terminal 4, Berth 410
Elevation = 34.50' NGVD29/47 Datum

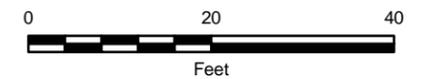


Figure 3-1
SZPSA TCE Concentration (ug/L)
Siltronic Corporation
Portland, Oregon

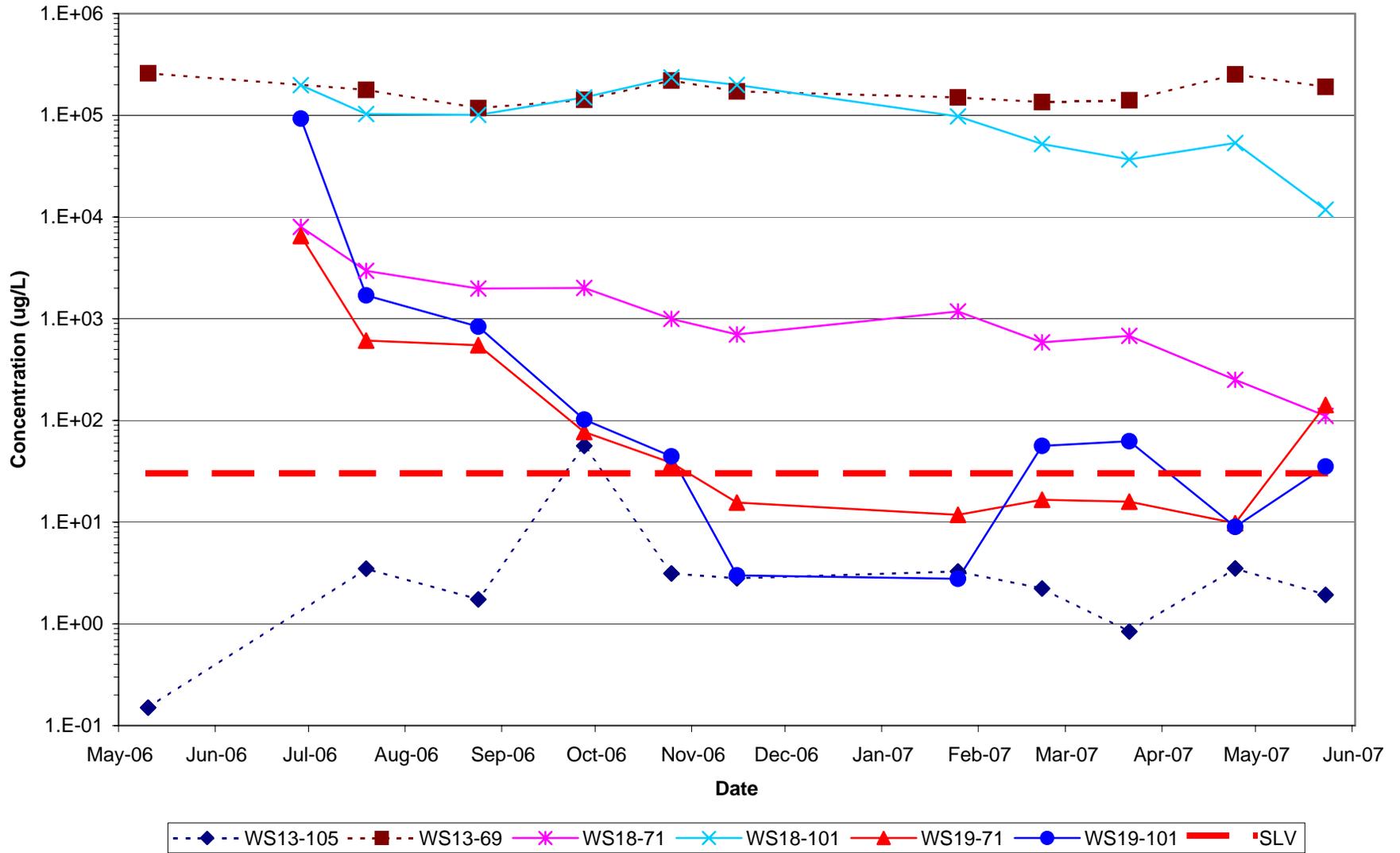


Figure 3-2
SZPSA Total DCE Concentration (ug/L)
Siltronic Corporation
Portland, Oregon

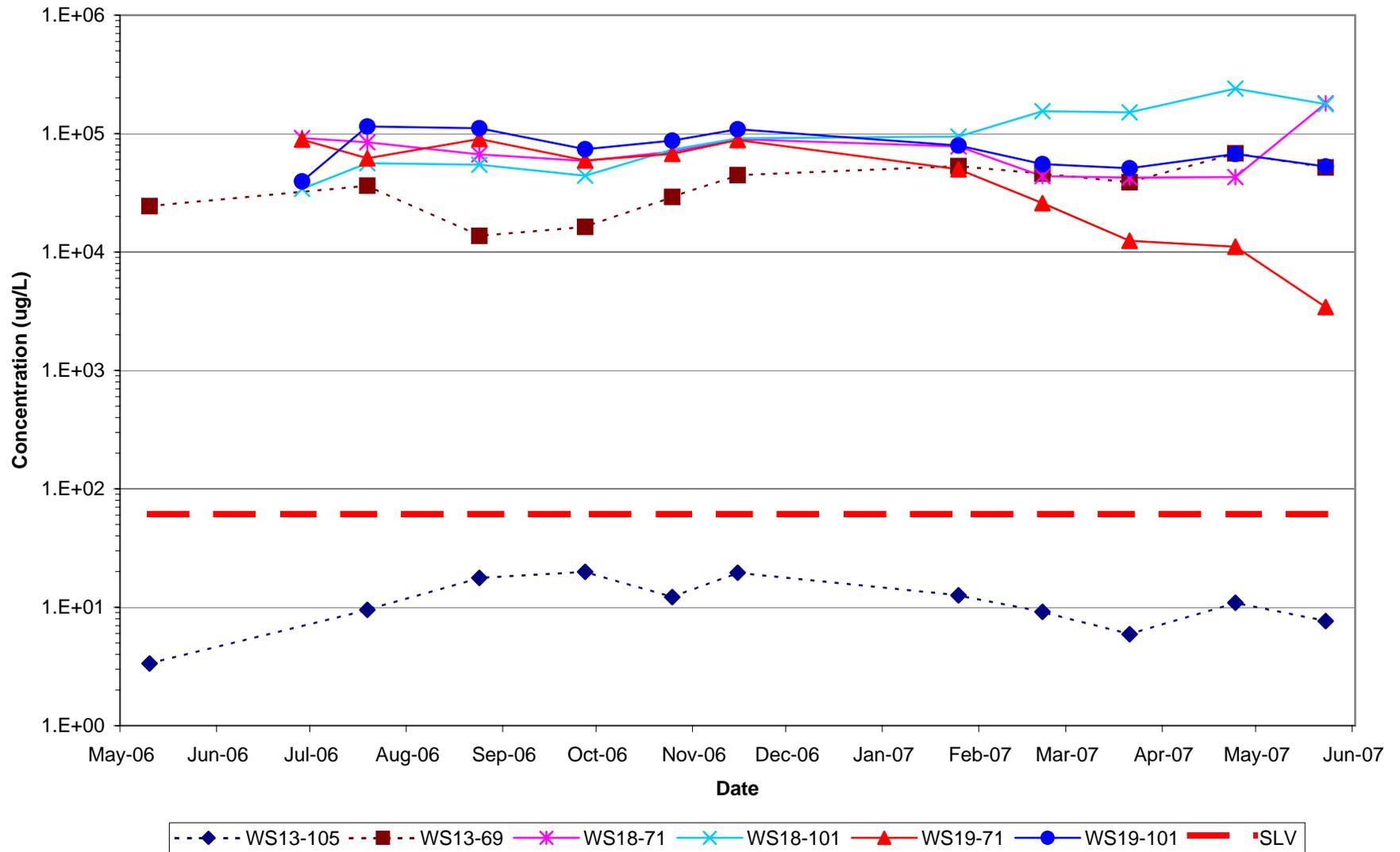


Figure 3-3
SZPSA Vinyl Chloride Concentration (ug/L)
Siltronic Corporation
Portland, Oregon

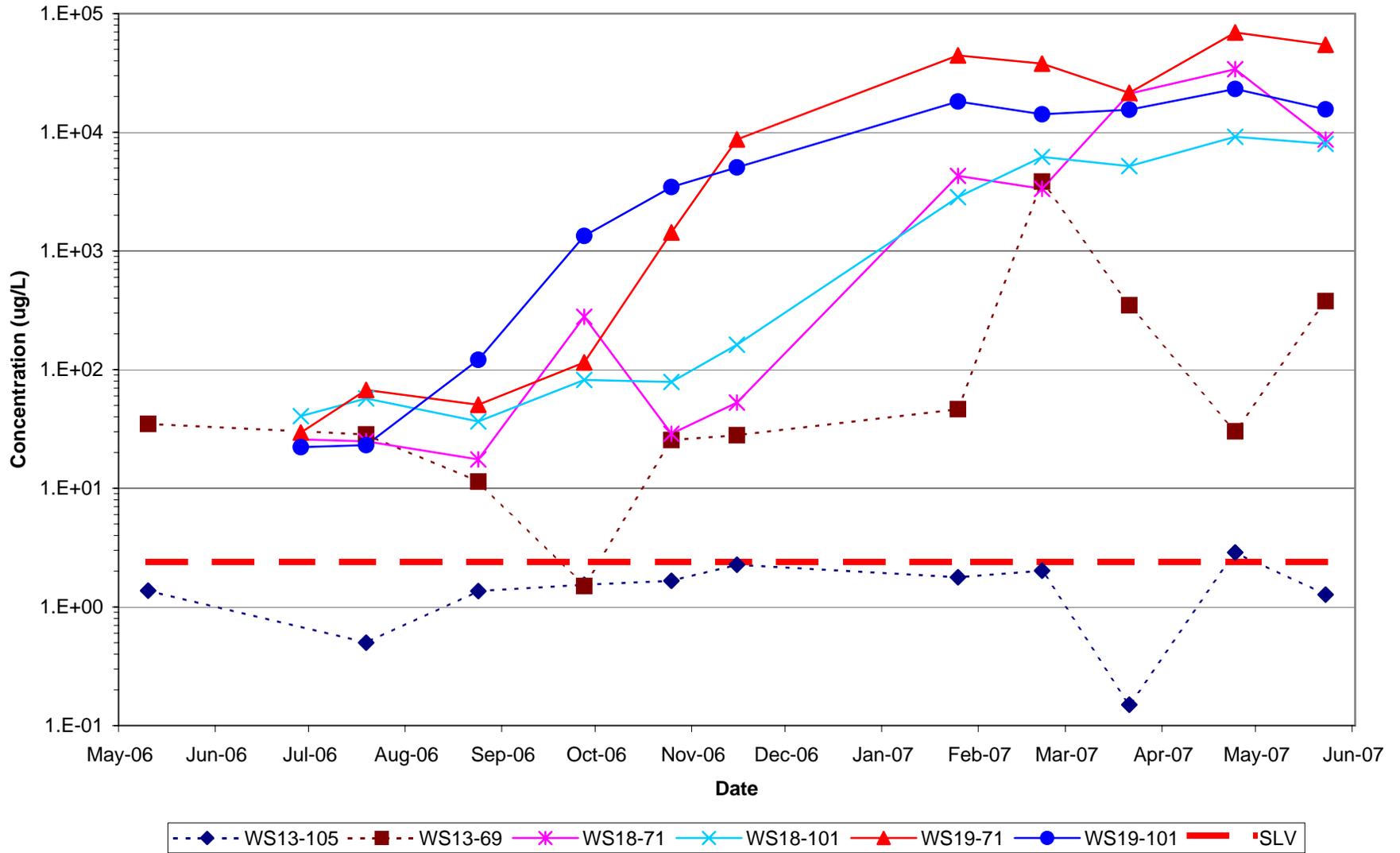


Figure 3-4
SZPSA Ethene Concentration (mg/L)
Siltronic Corporation
Portland, Oregon

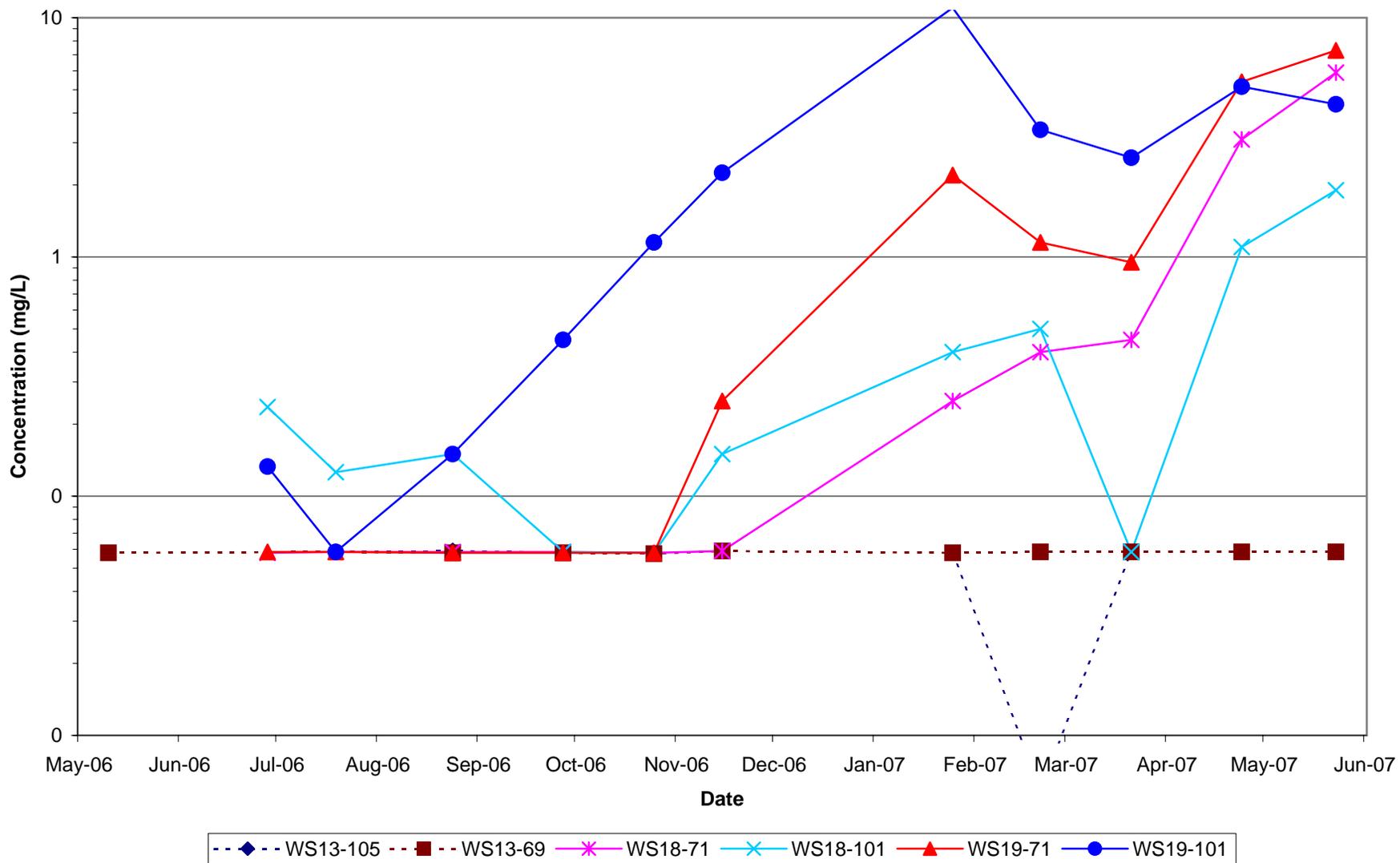


Figure 3-5
SZPSA Chloride Concentration (mg/L)
Siltronic Corporation
Portland, Oregon

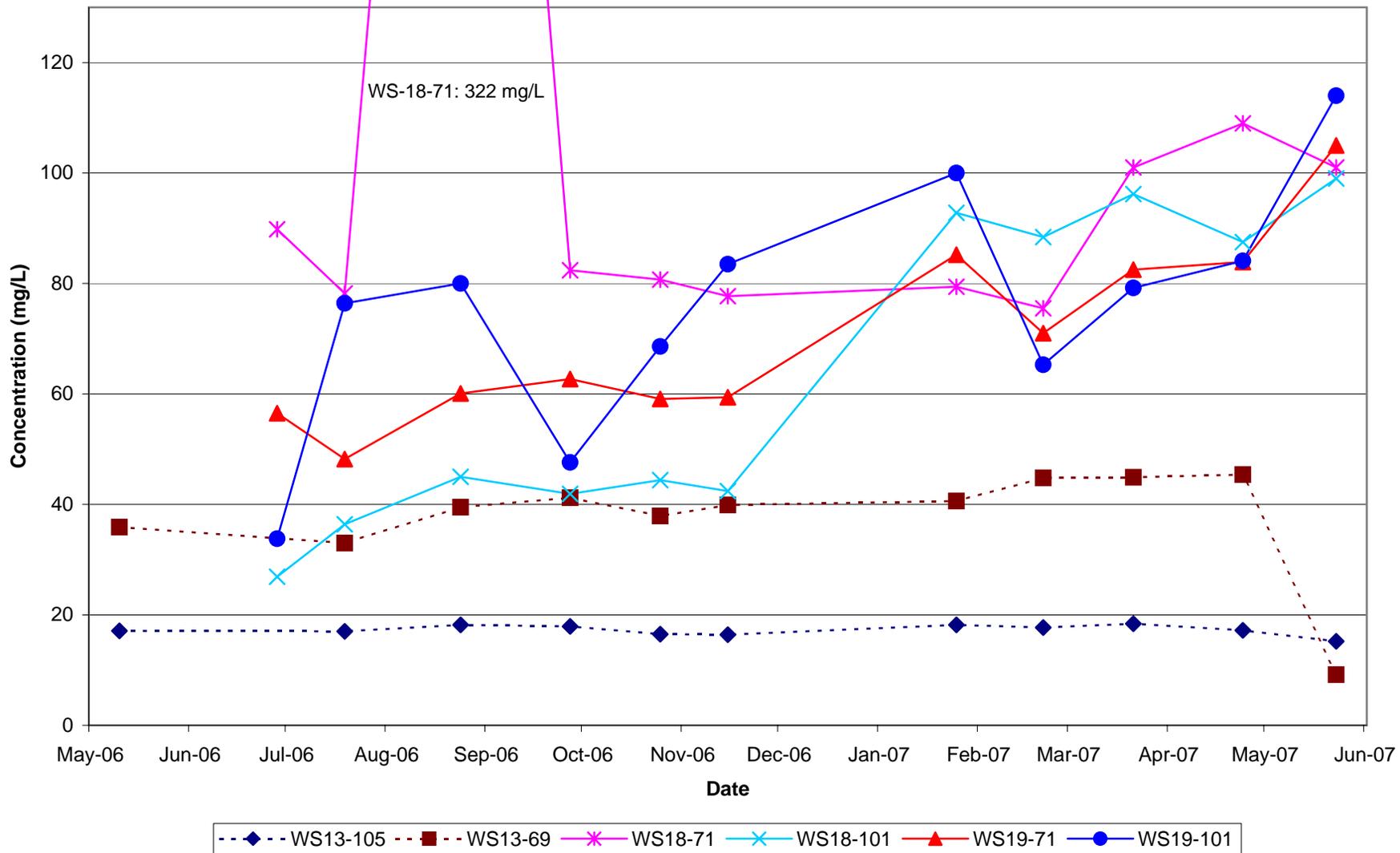


Figure 3-6
WS13-69 — Total Ethenes Concentrations
Siltronic Corporation
Portland, Oregon

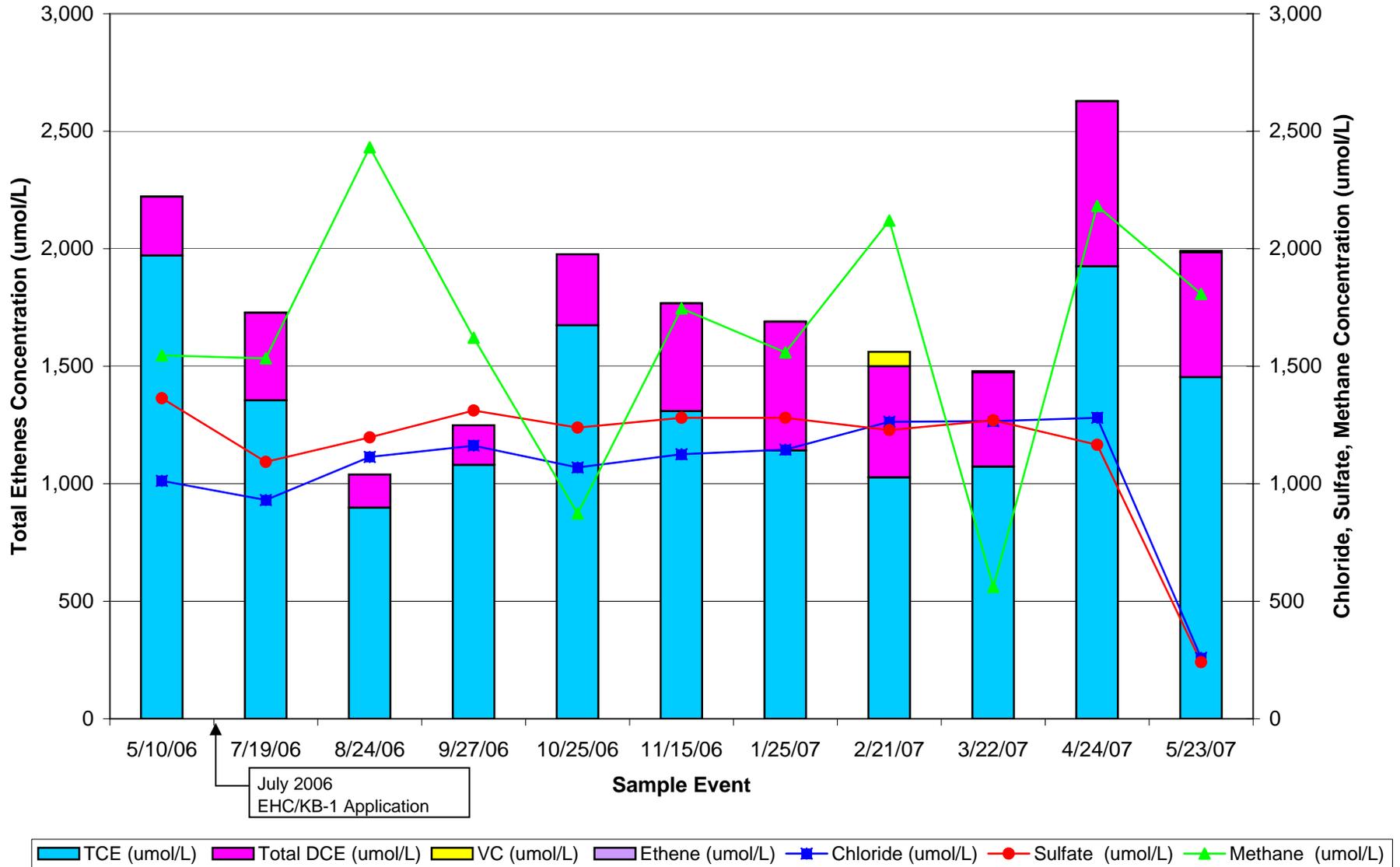


Figure 3-7
WS19-71 — Total Ethenes Concentrations
Siltronic Corporation
Portland, Oregon

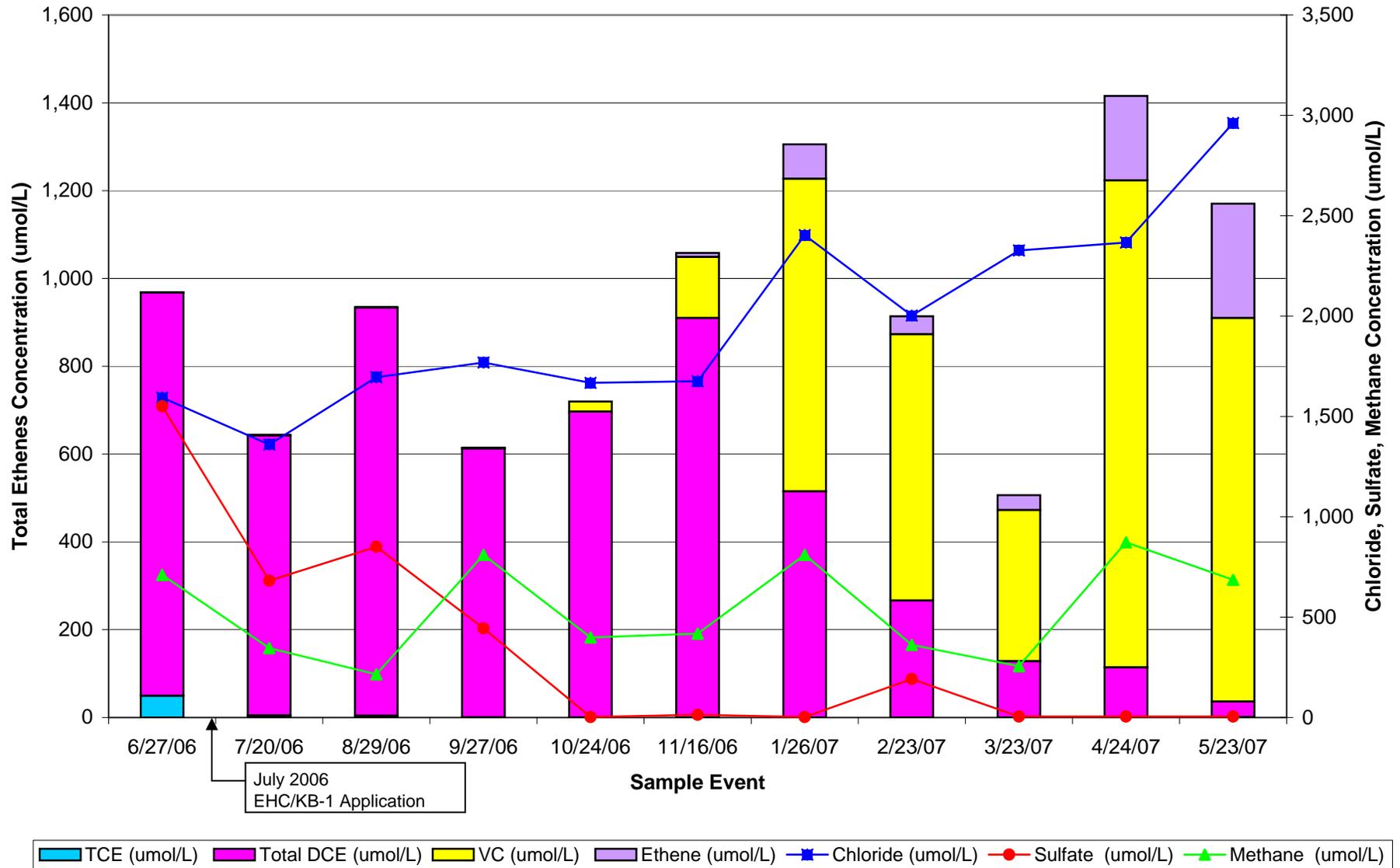


Figure 3-8
WS18-71 — Total Ethenes Concentrations
Siltronic Corporation
Portland, Oregon

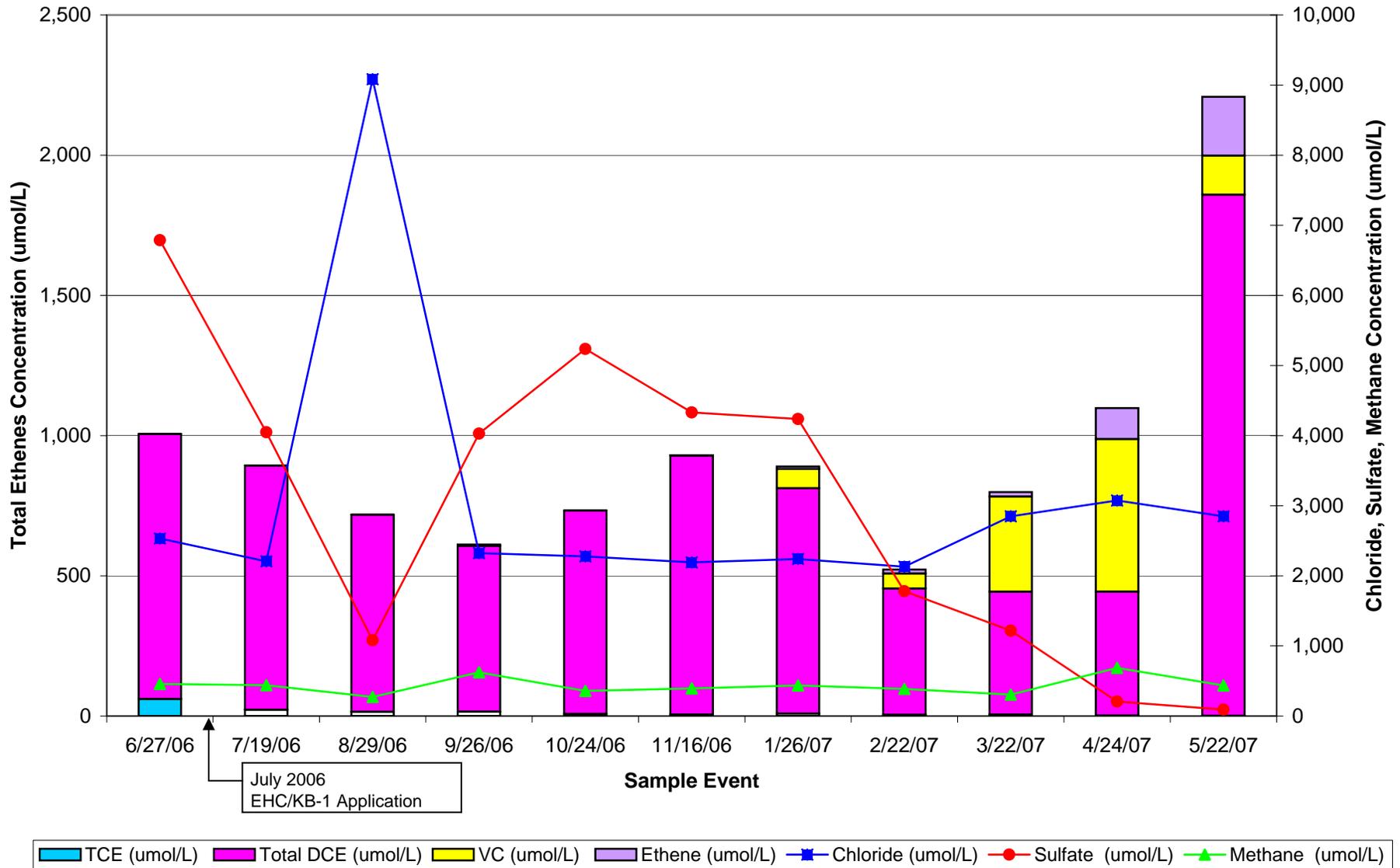


Figure 3-9
WS13-105 — Total Ethenes Concentrations
Siltronic Corporation
Portland, Oregon

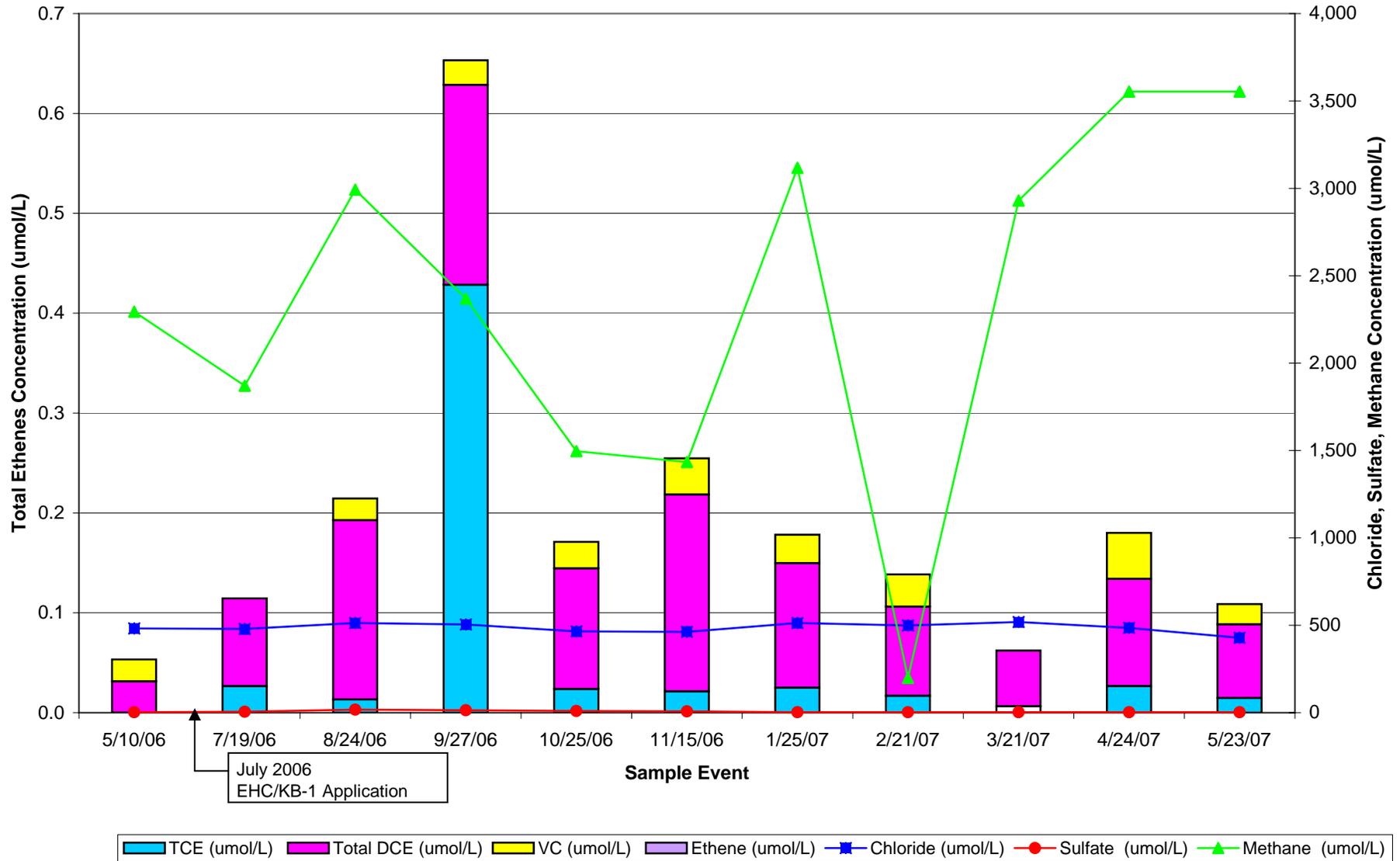


Figure 3-10
WS19-101 — Total Ethenes Concentrations
Siltronic Corporation
Portland, Oregon

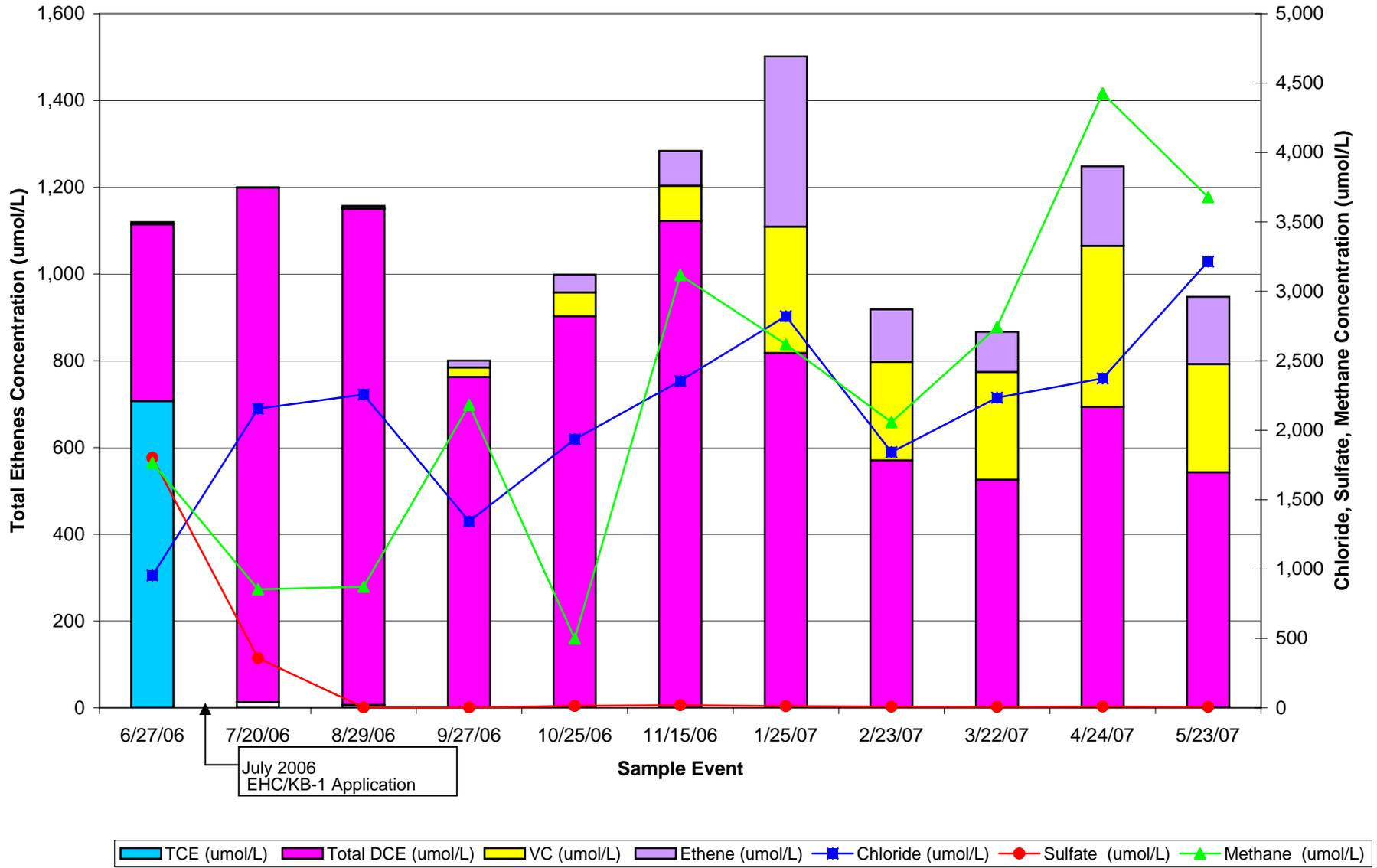


Figure 3-11
WS18-101 — Total Ethenes Concentrations
Siltronic Corporation
Portland, Oregon

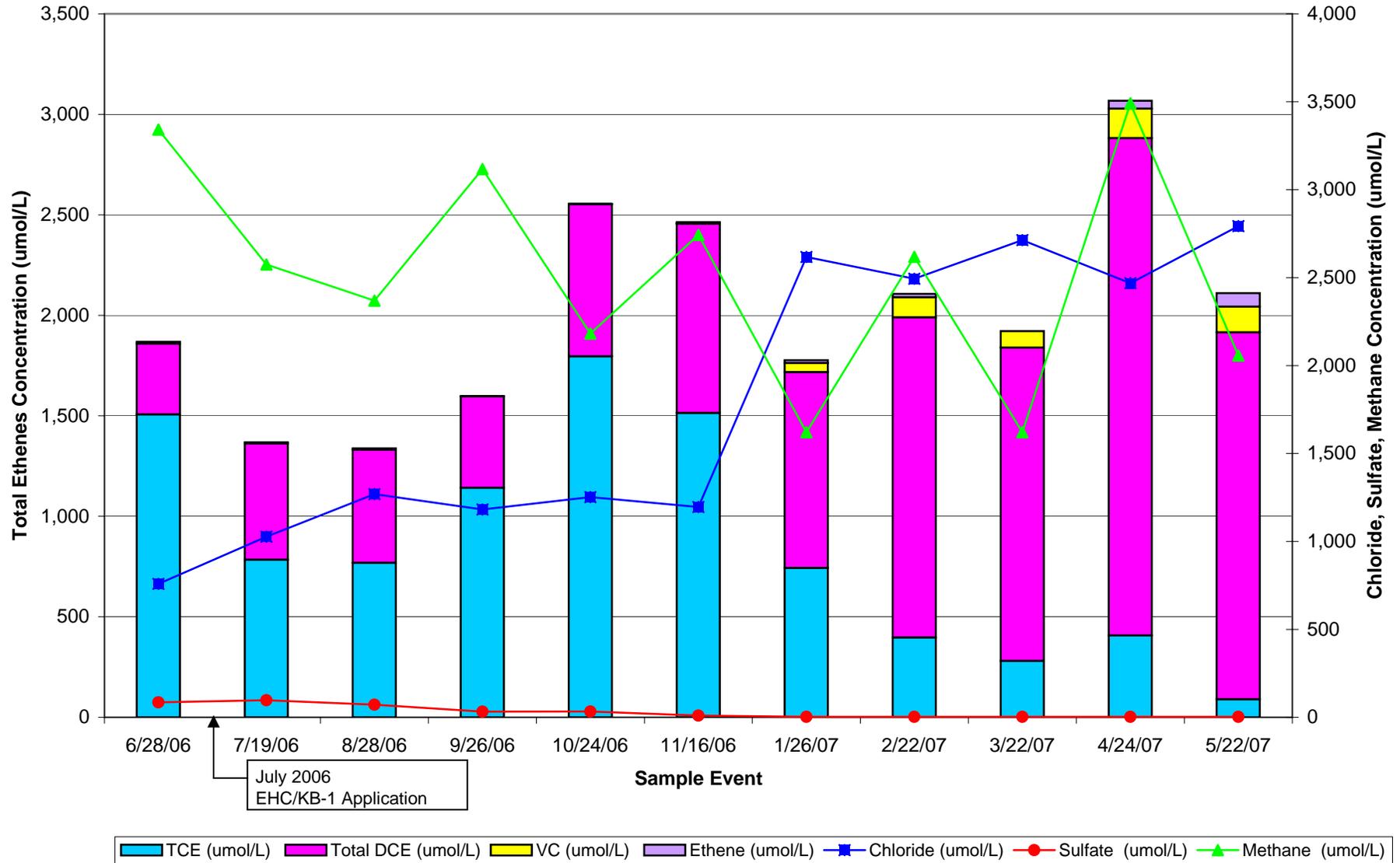


Figure 3-12
SZPSA Dissolved Oxygen Concentration (mg/L)
Siltronic Corporation
Portland, Oregon

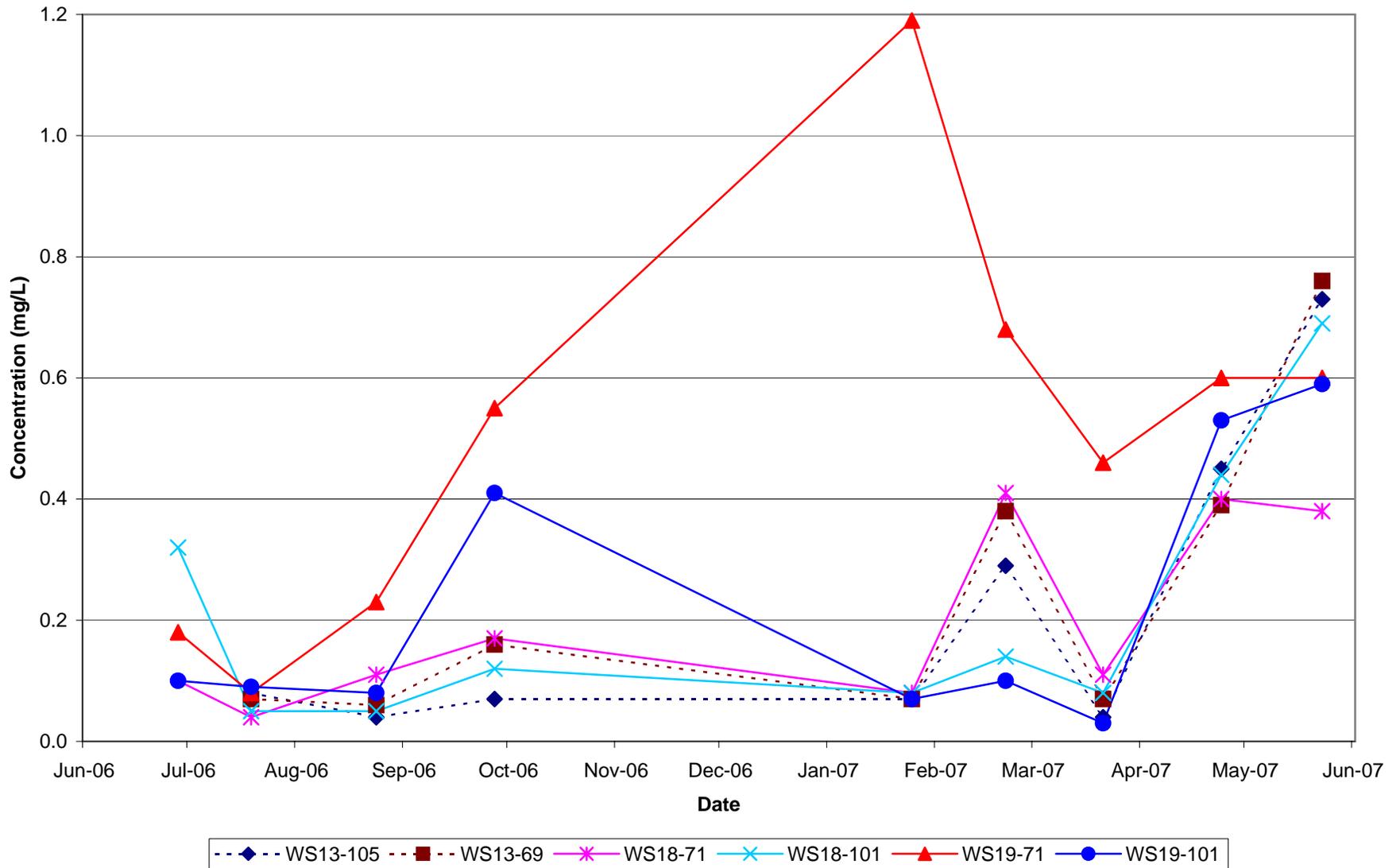


Figure 3-13
SZPSA Oxidation Reduction Potential (mV)
Siltronic Corporation
Portland, Oregon

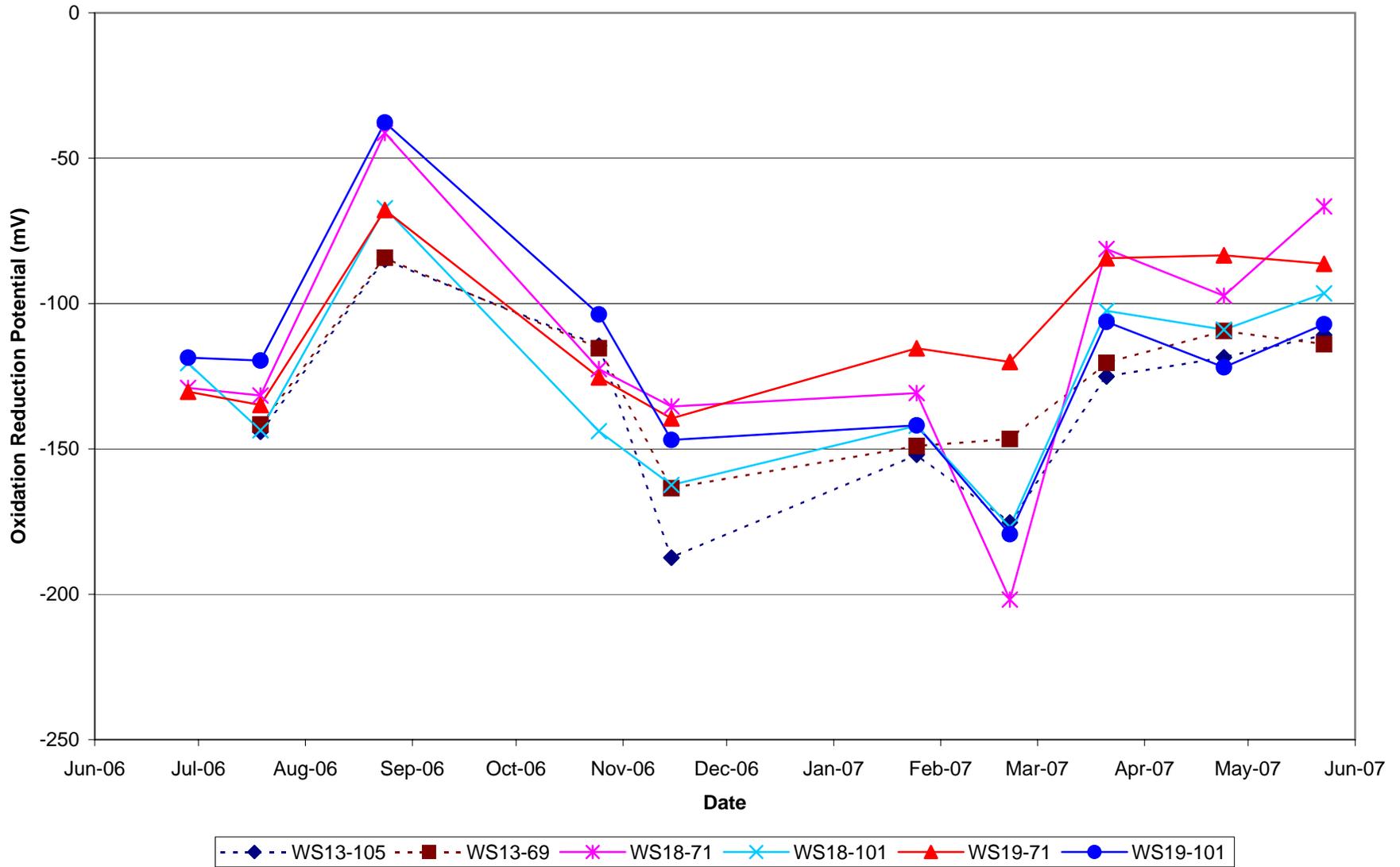


Figure 3-14
SZPSA Sulfate Concentration (mg/L)
Siltronic Corporation
Portland, Oregon

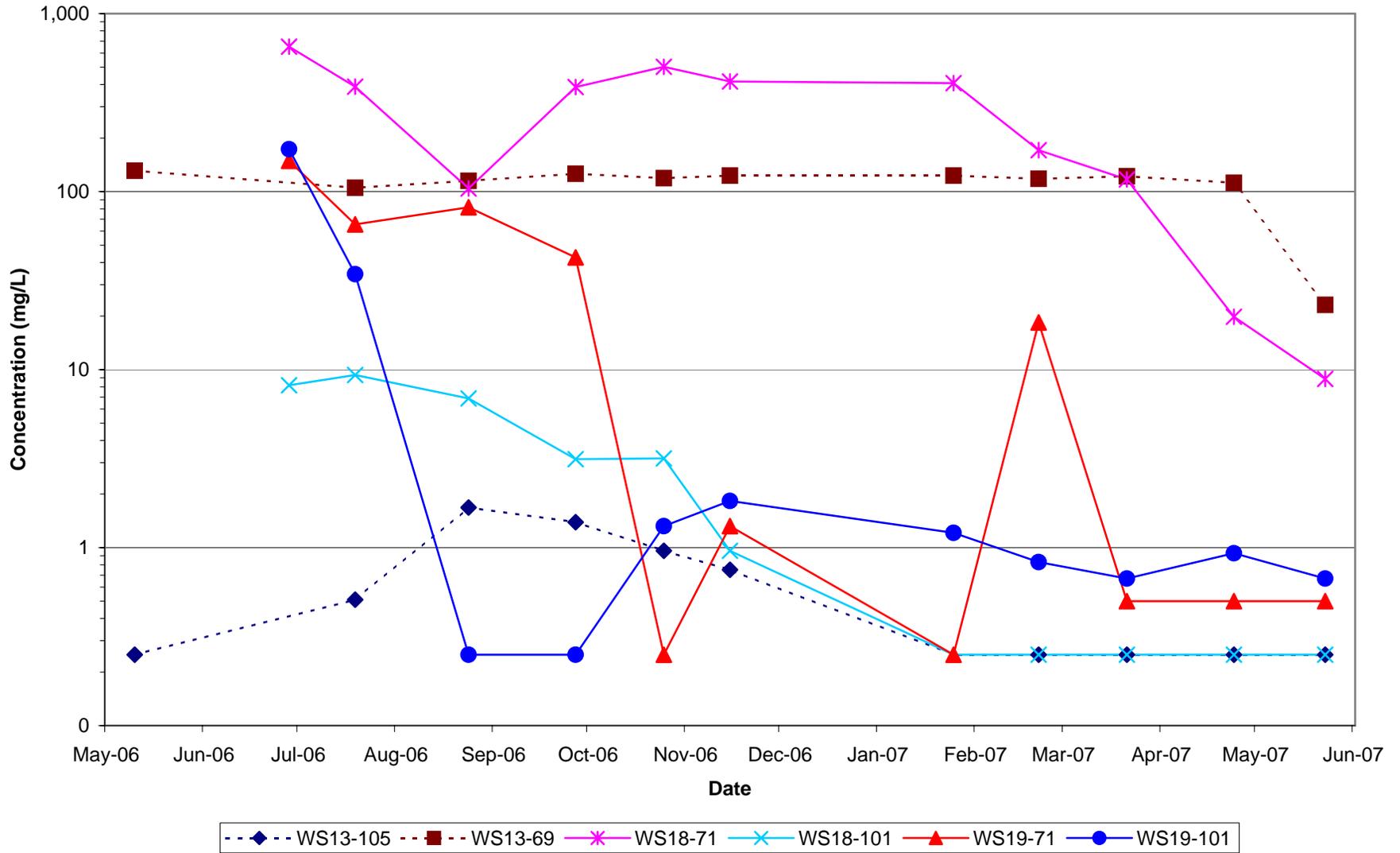


Figure 3-15
SZPSA Methane Concentration (mg/L)
Siltronic Corporation
Portland, Oregon

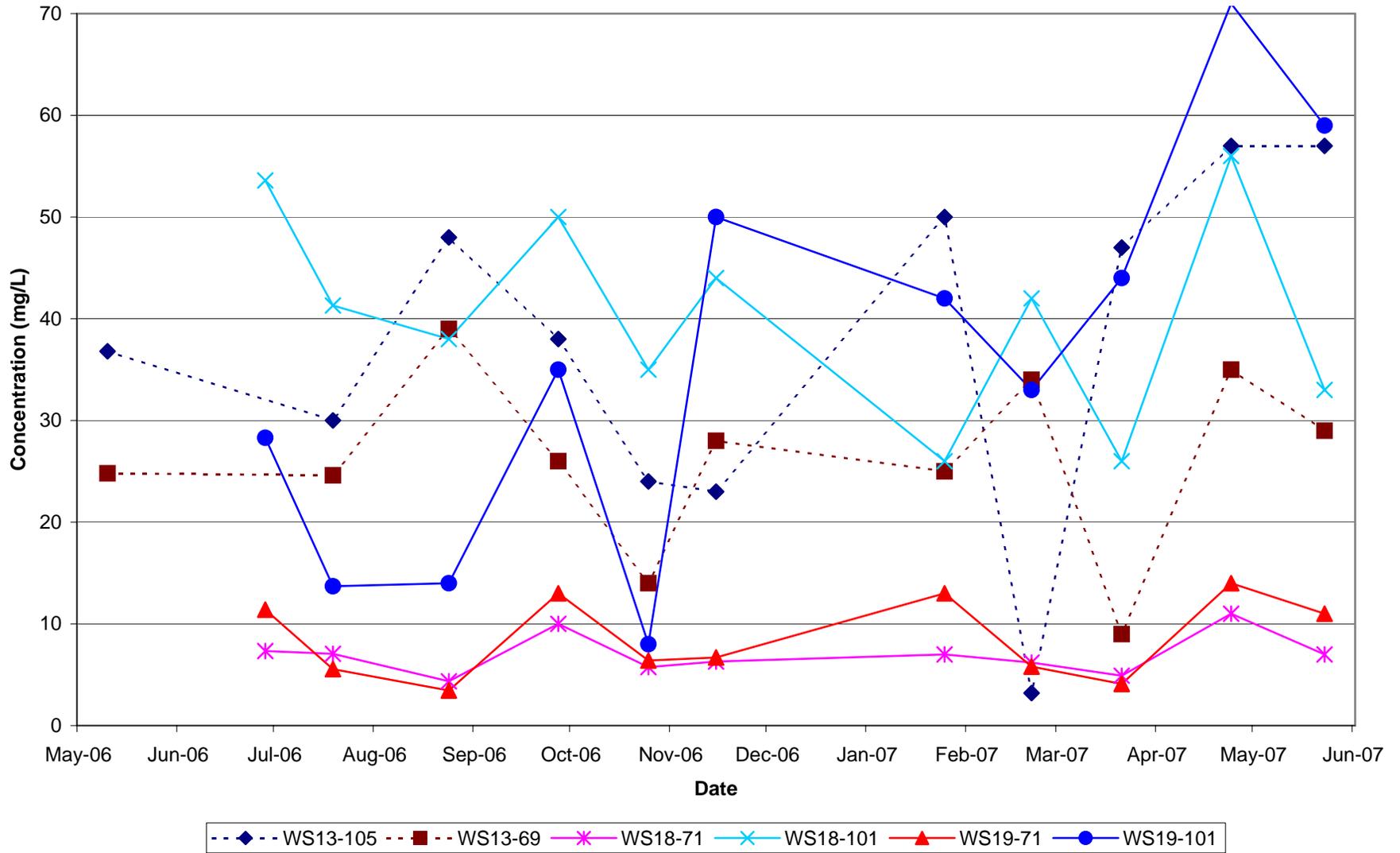


Figure 3-16
SZPSA Ferrous Iron Concentration (mg/L)
Siltronic Corporation
Portland, Oregon

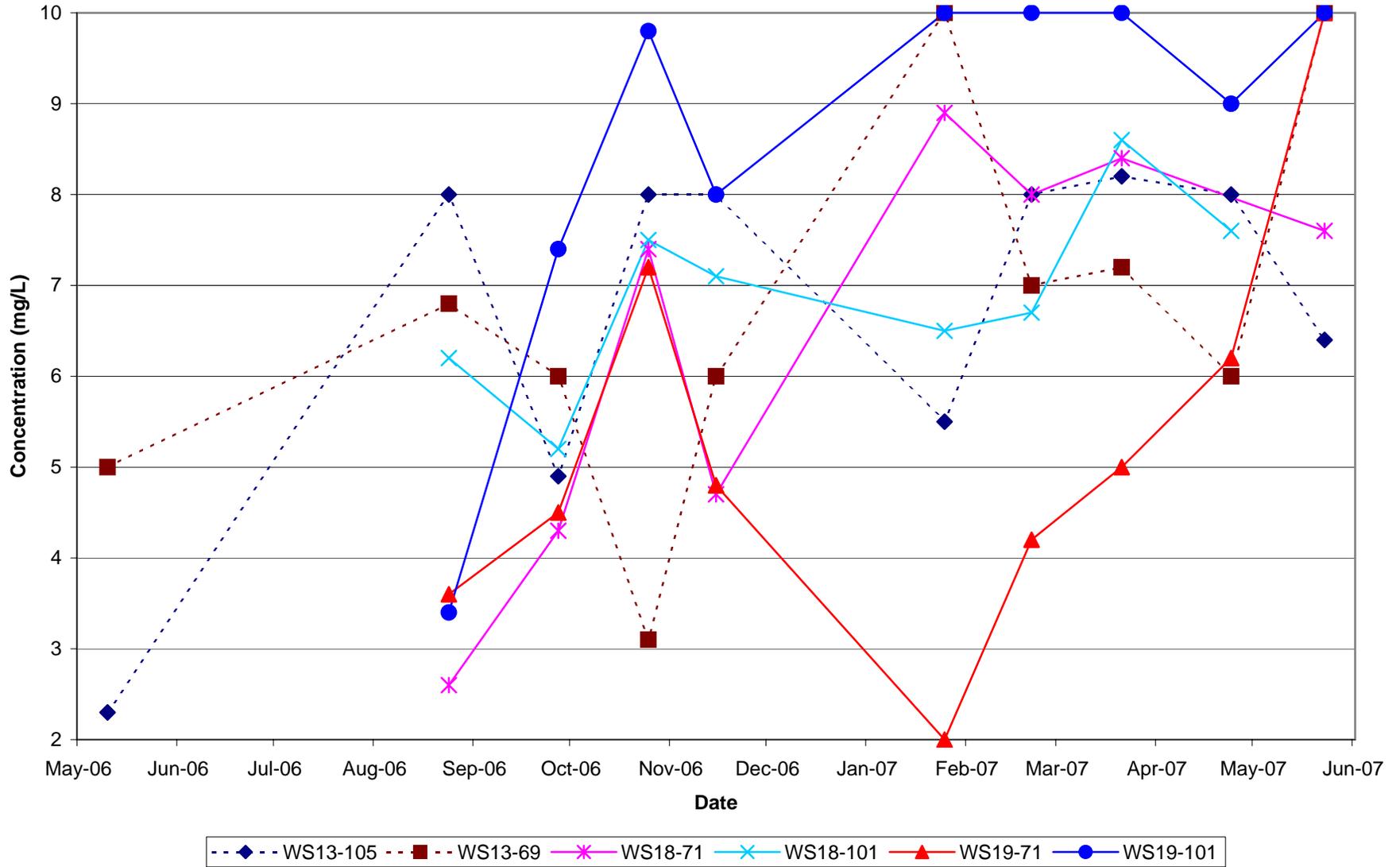


Figure 3-17
SZPSA Biological Cell Counts (cells/L)
Siltronic Corporation
Portland, Oregon

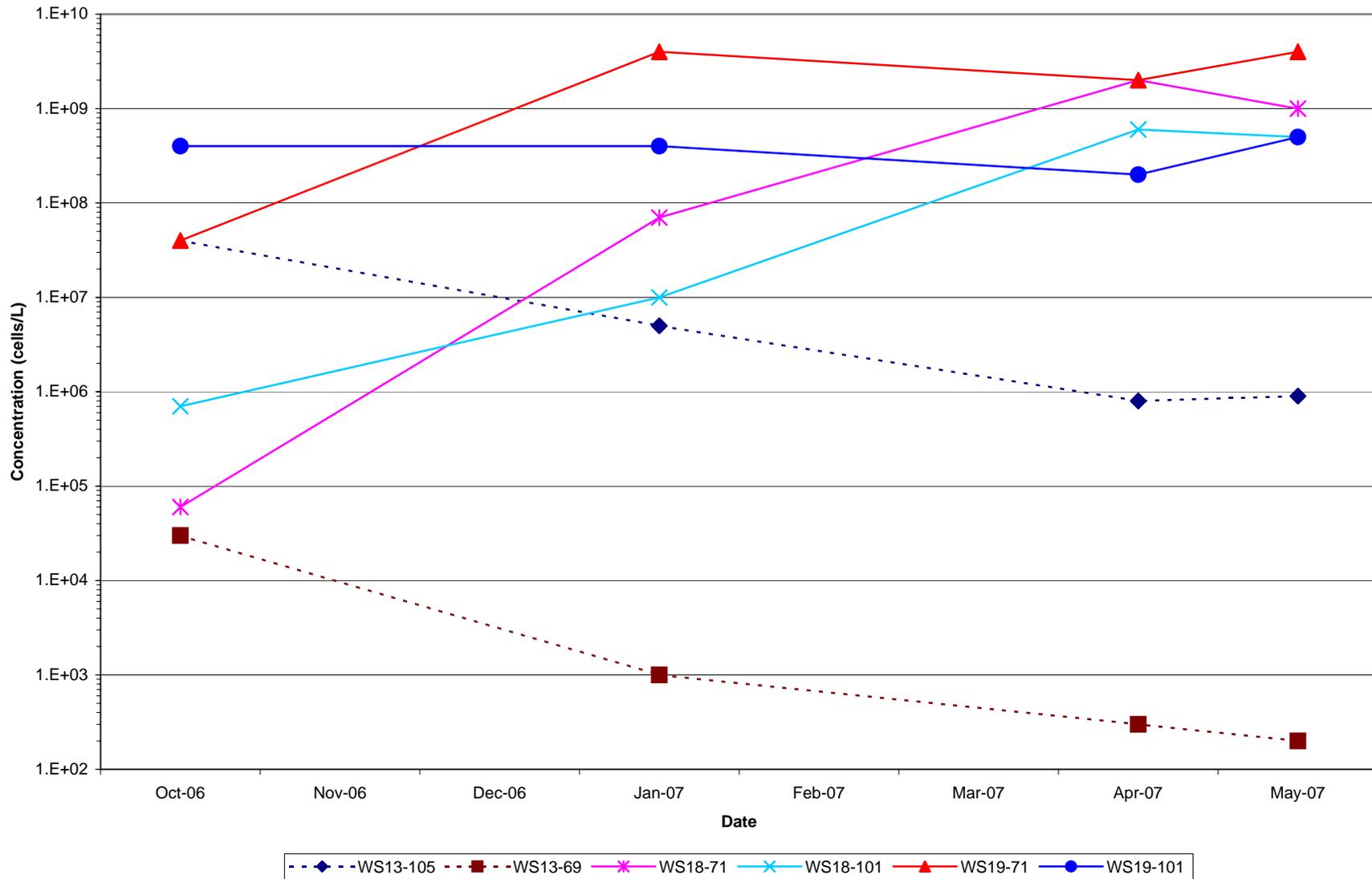


Figure 3-18
SZPSA Benzene Concentration (ug/L)
Siltronic Corporation
Portland, Oregon

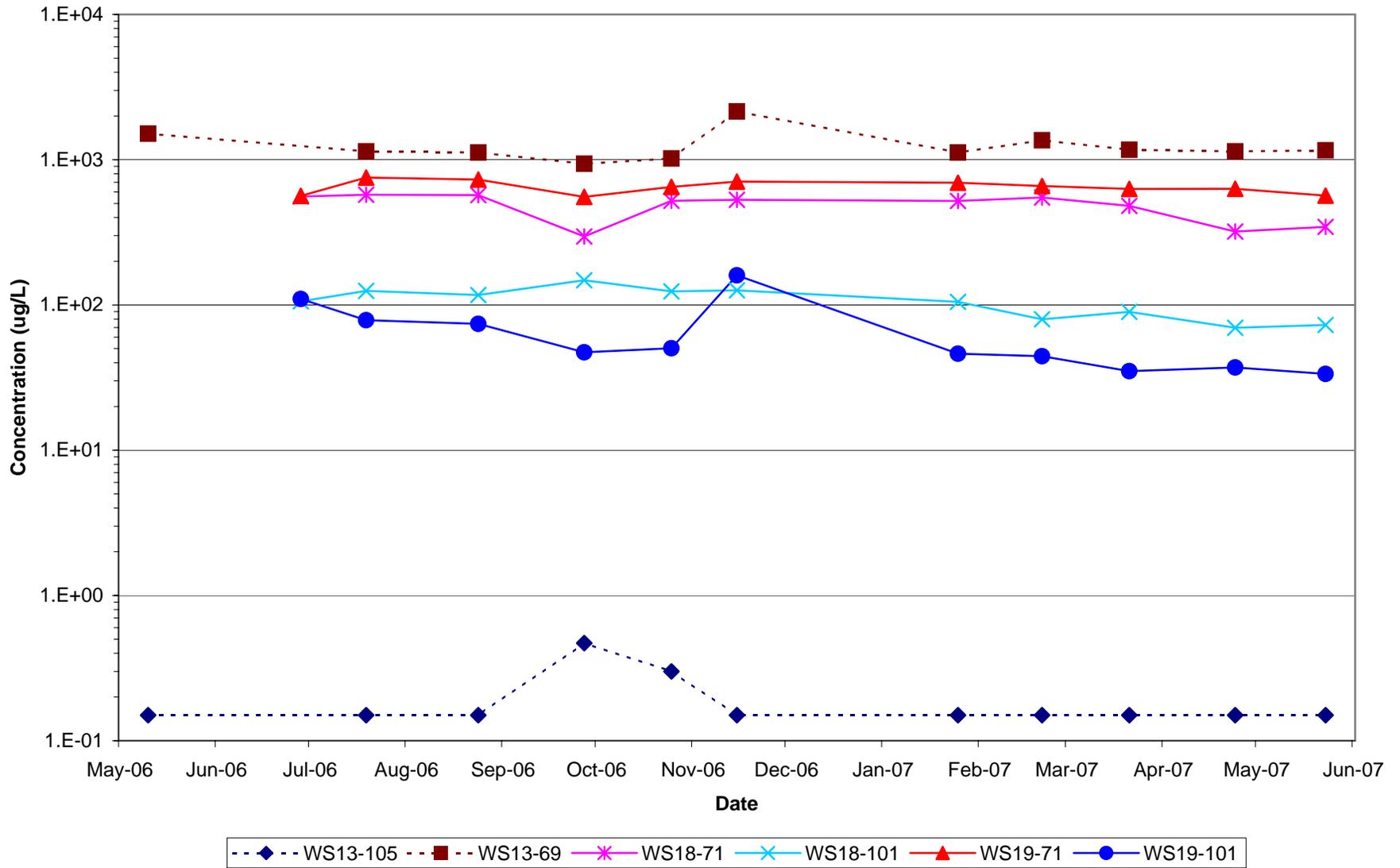


Figure 3-19
SZPSA Naphthalene Concentration (ug/L)
Siltronic Corporation
Portland, Oregon

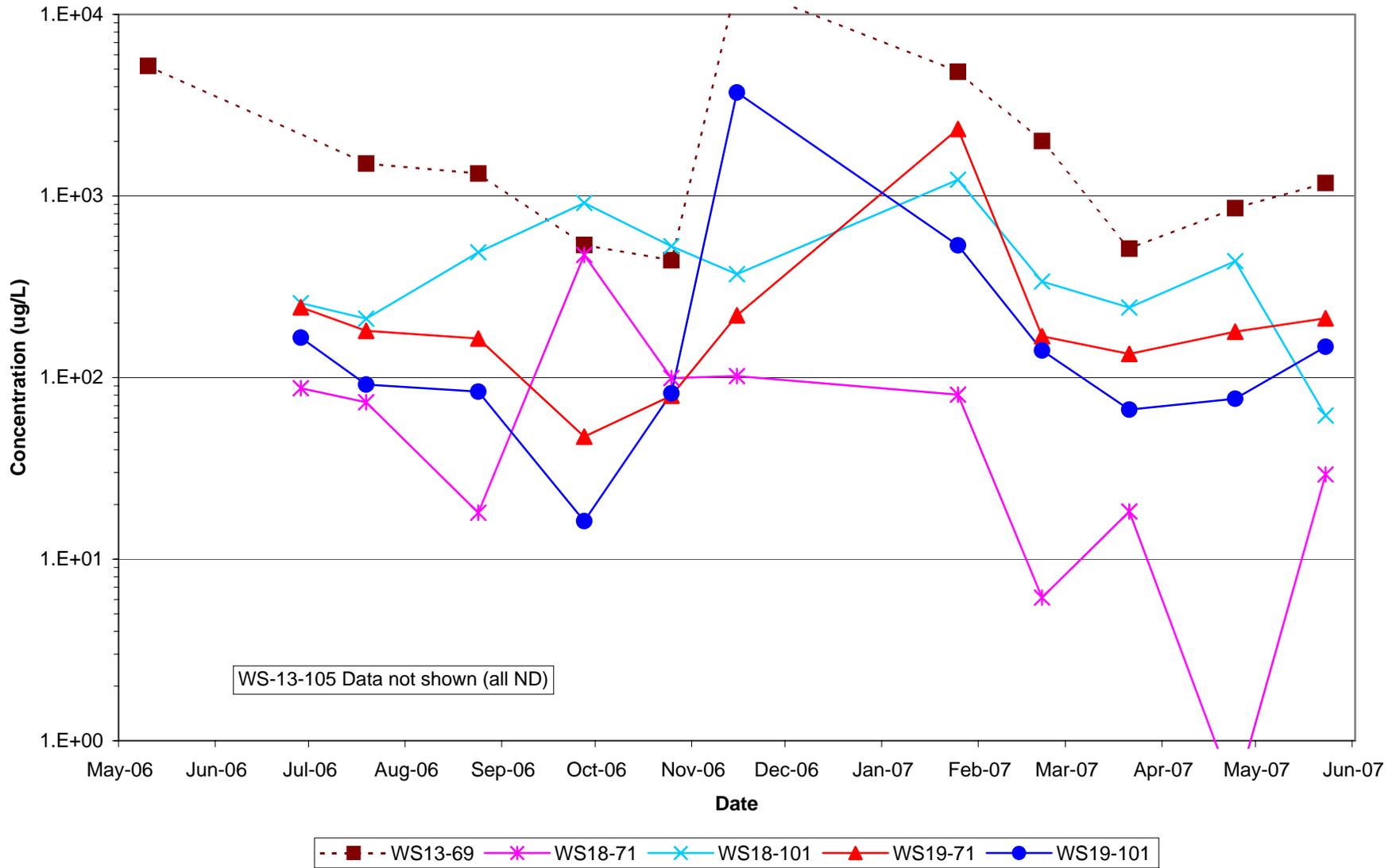


Figure 3-20
SZPSA Total Cyanide Concentration (mg/L)
Siltronic Corporation
Portland, Oregon

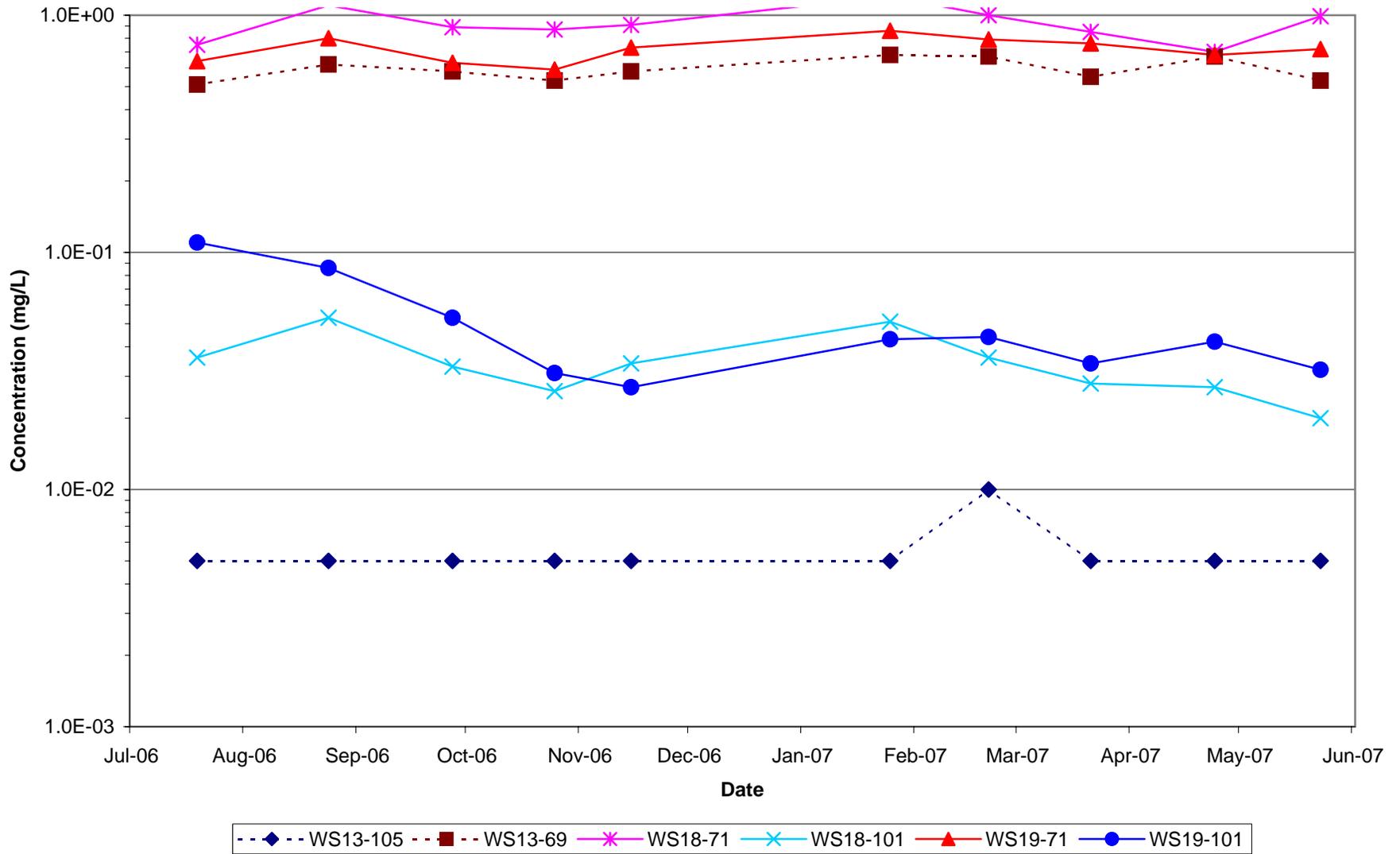


Figure 3-21
SZPSA Free Cyanide Concentration (mg/L)
Siltronic Corporation
Portland, Oregon

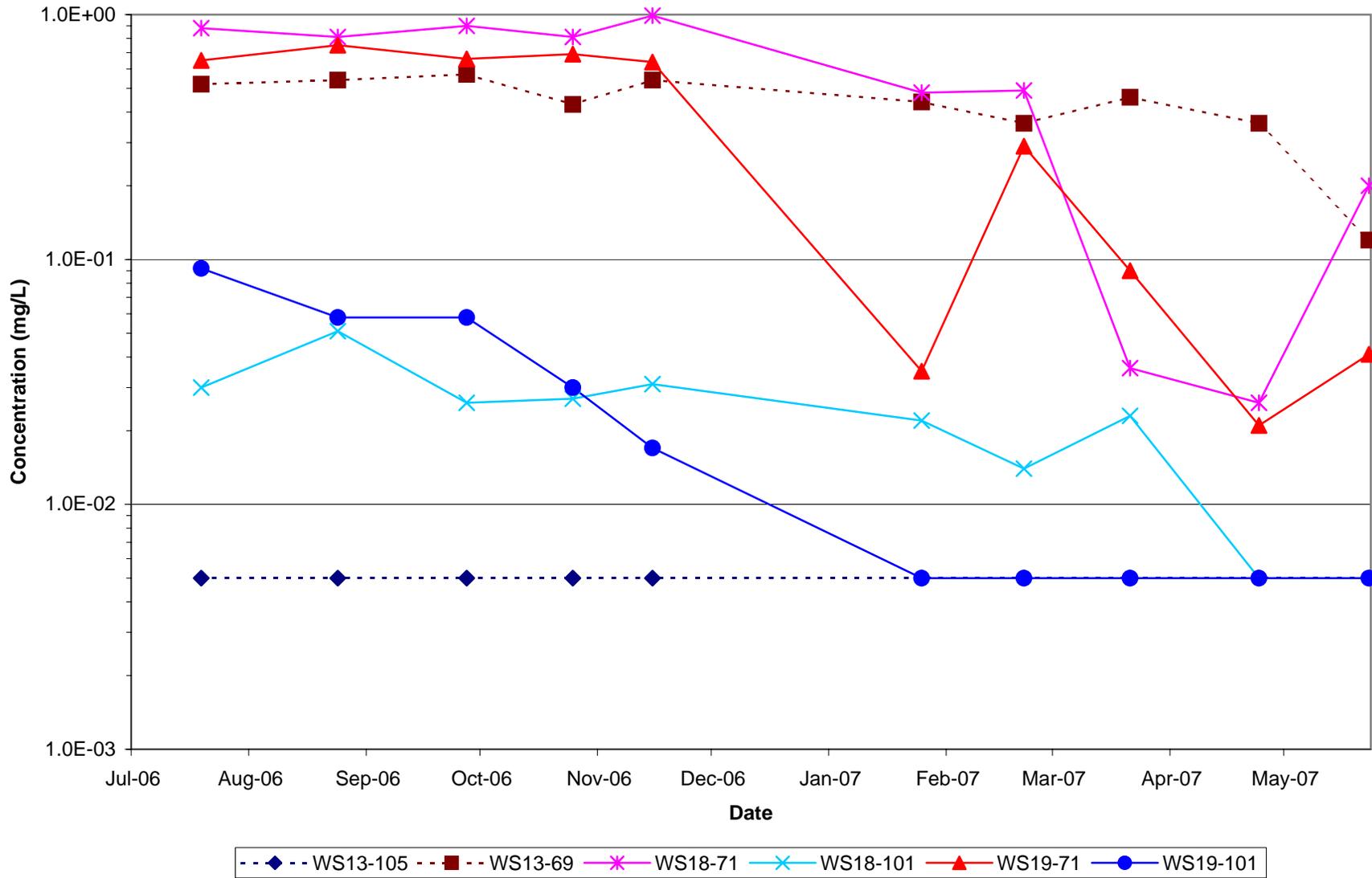


Figure 3-22
SZPSA Arsenic Concentration (ug/L)
Siltronic Corporation
Portland, Oregon

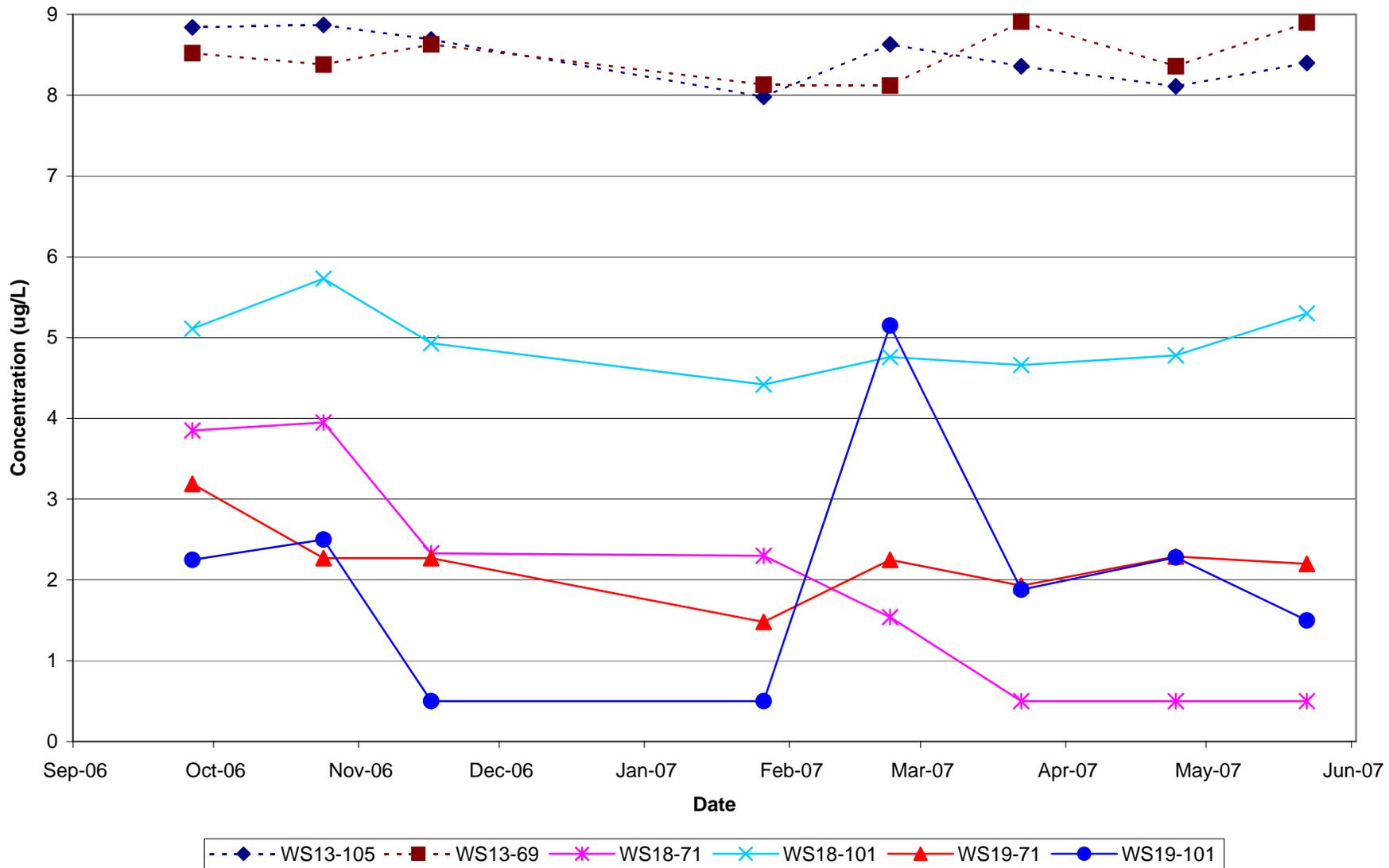


Figure 3-23
SZPSA Manganese Concentration (mg/L)
Siltronic Corporation
Portland, Oregon

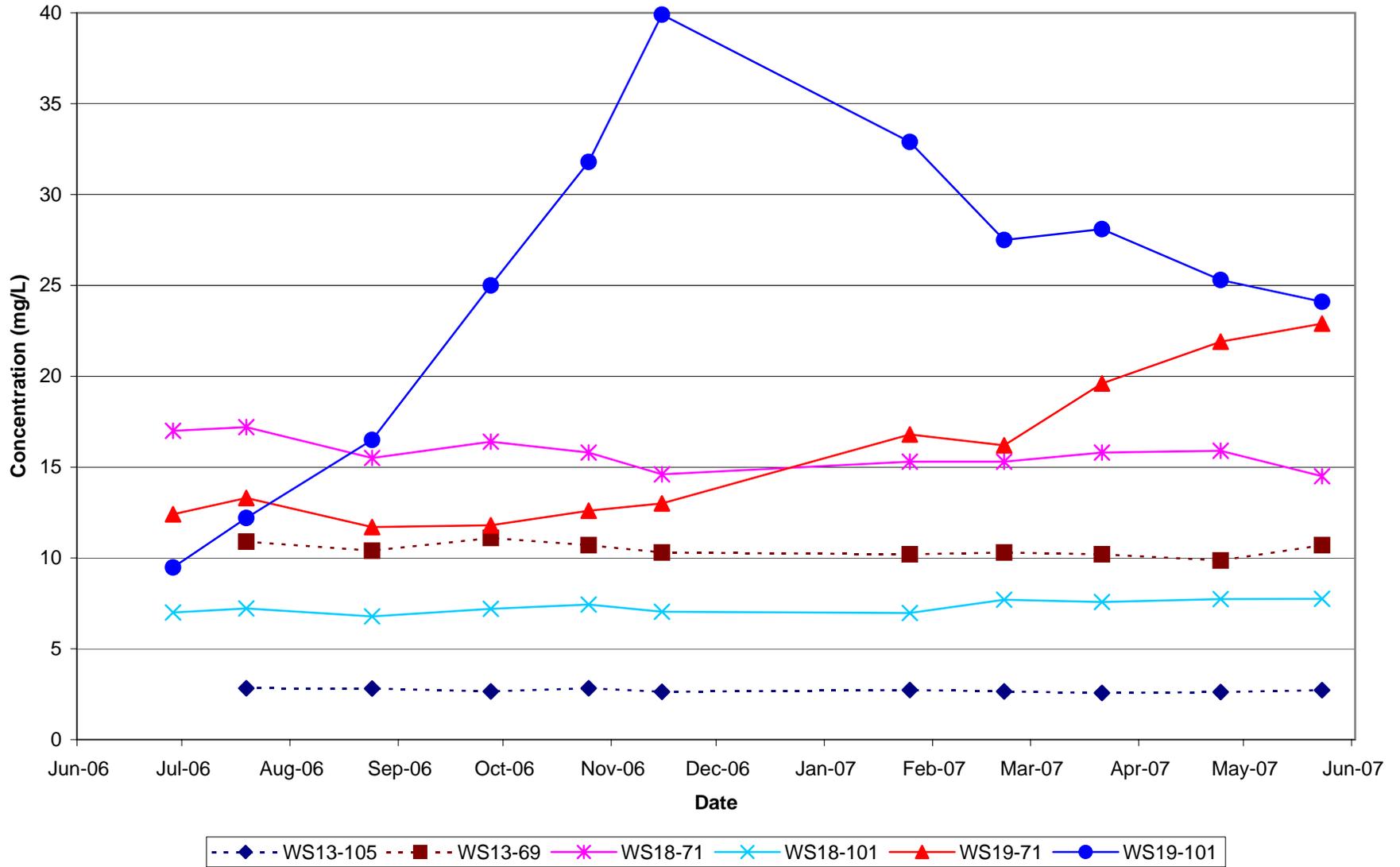


Figure 3-24
SZPSA Total Organic Carbon Concentration (mg/L)
Siltronic Corporation
Portland, Oregon

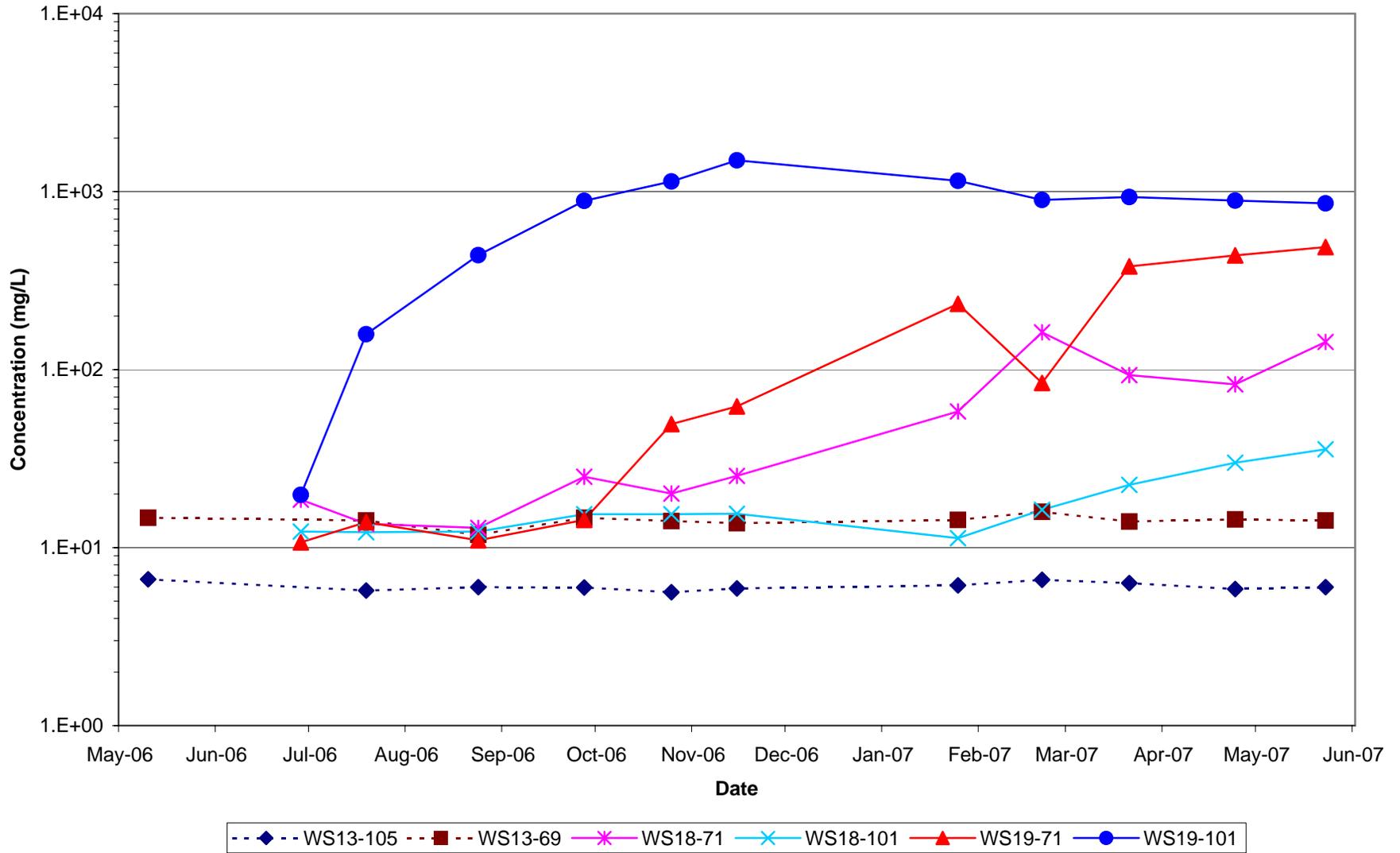


Figure 3-25
SZPSA Total Iron Concentration (mg/L)
Siltronic Corporation
Portland, Oregon

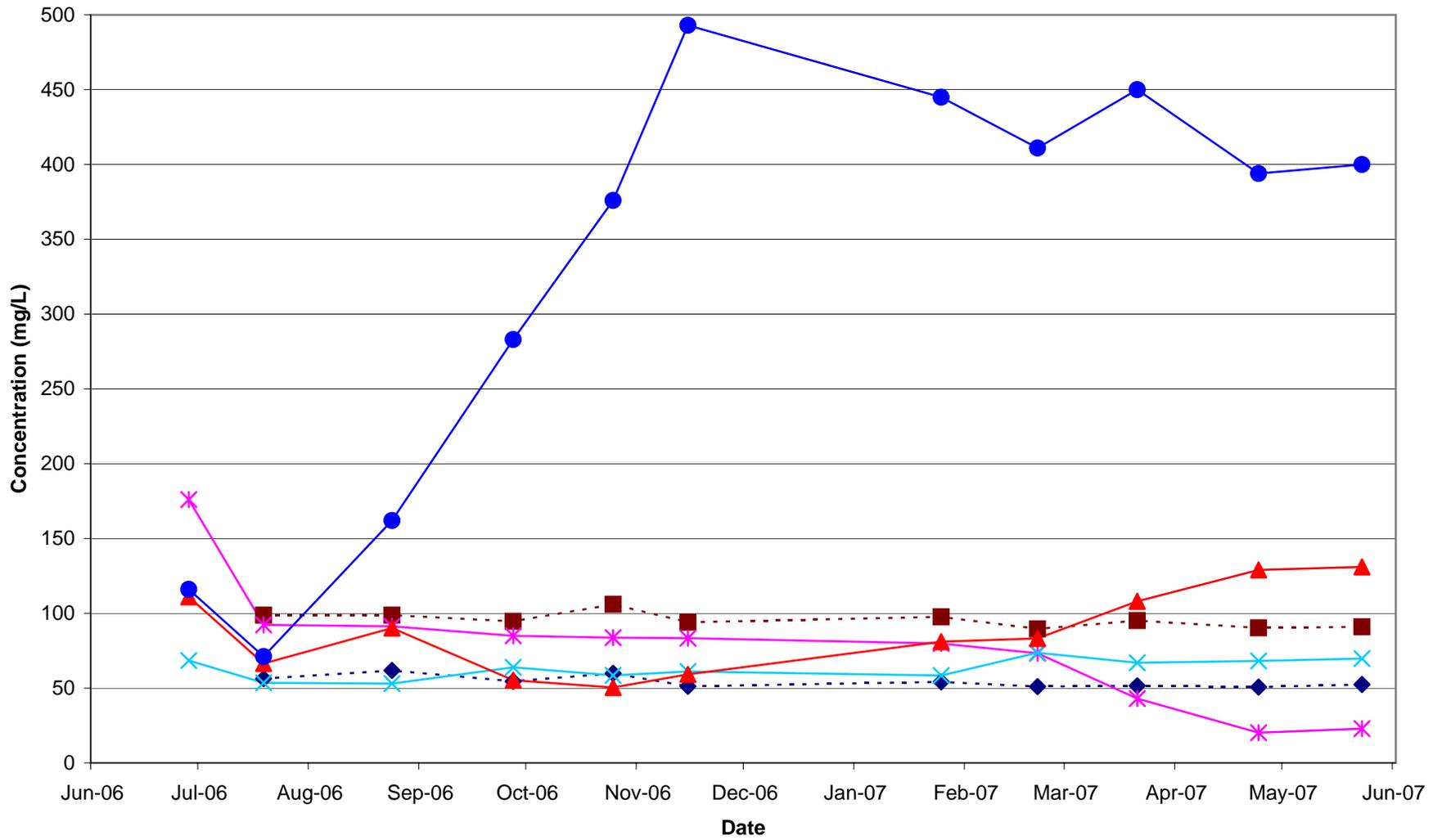


Figure 3-26
RPSA TCE Concentration (ug/L)
Siltronic Corporation
Portland, Oregon

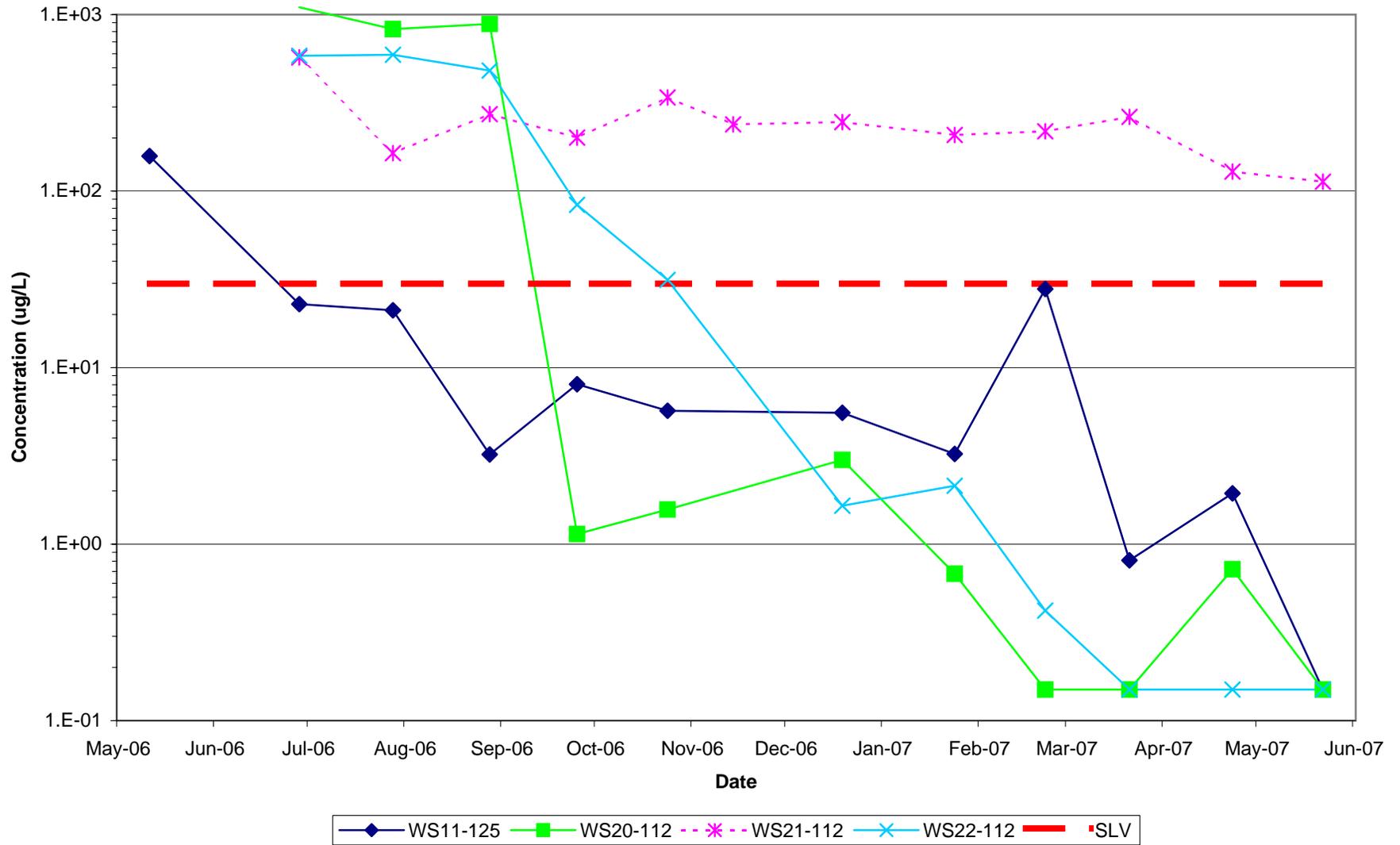


Figure 3-27
RPSA Total DCE Concentration (ug/L)
Siltronic Corporation
Portland, Oregon

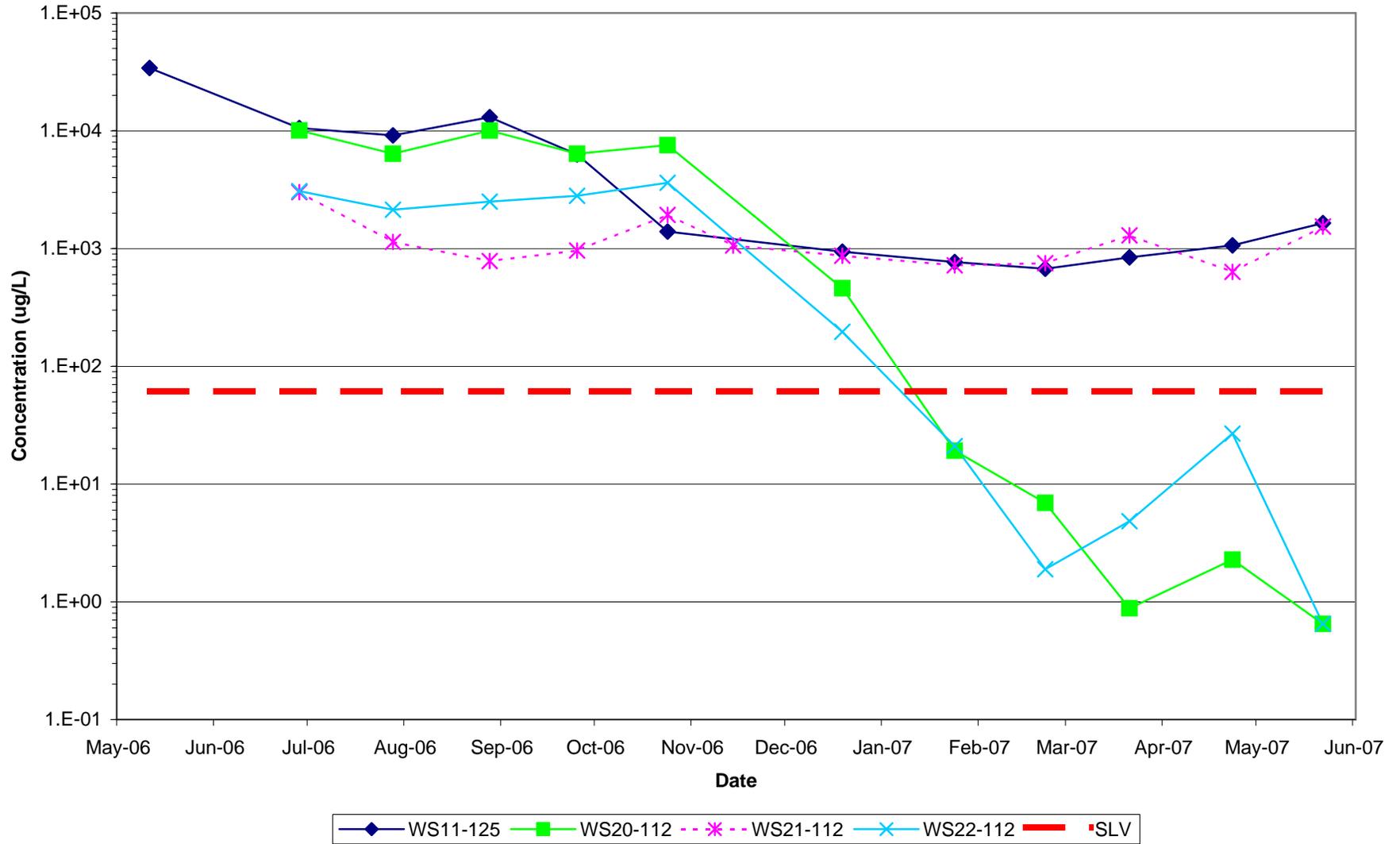


Figure 3-28
RPSA Vinyl Chloride Concentration (ug/L)
Siltronic Corporation
Portland, Oregon

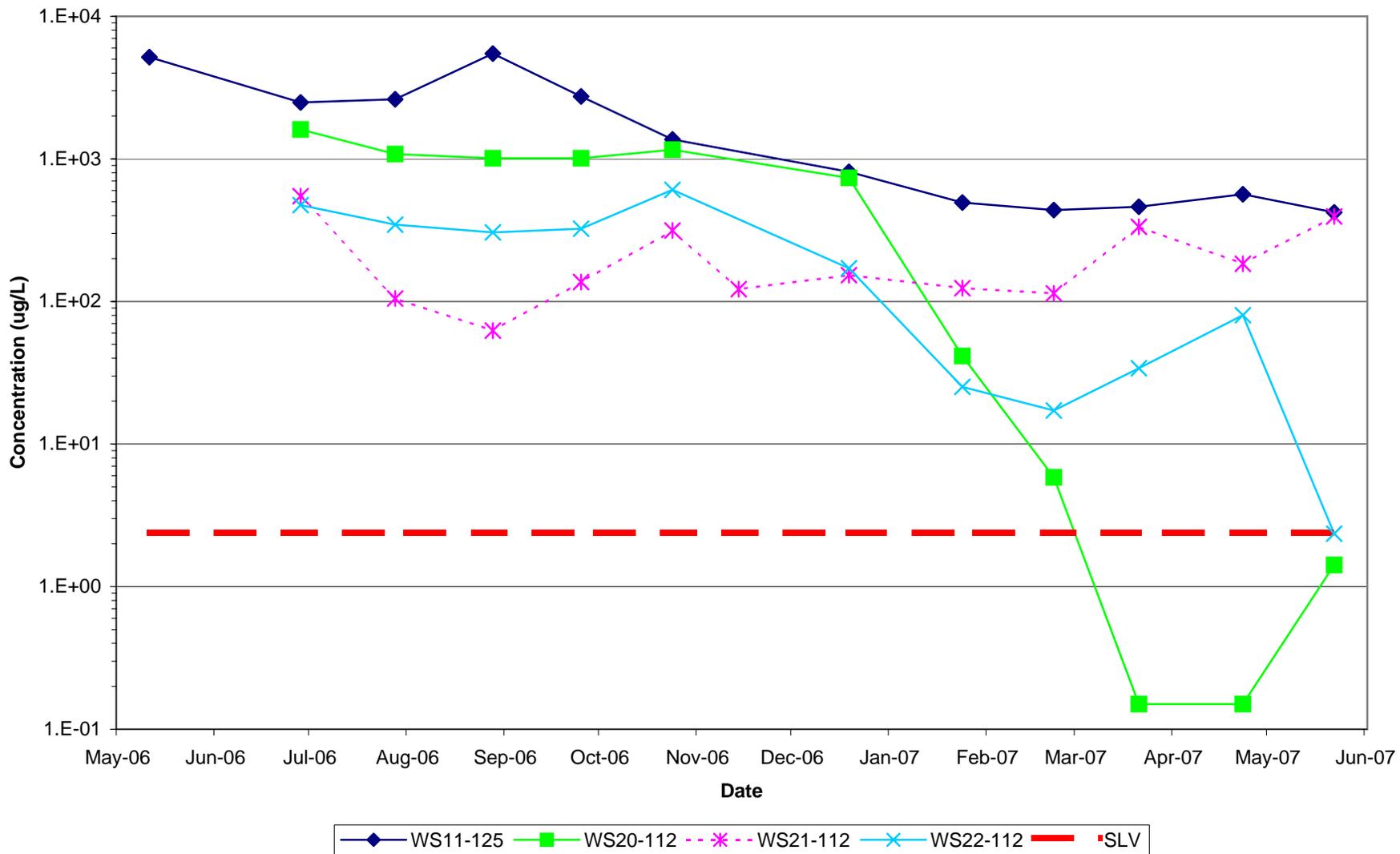


Figure 3-29
RPSA Ethene Concentration (mg/L)
Siltronic Corporation
Portland, Oregon

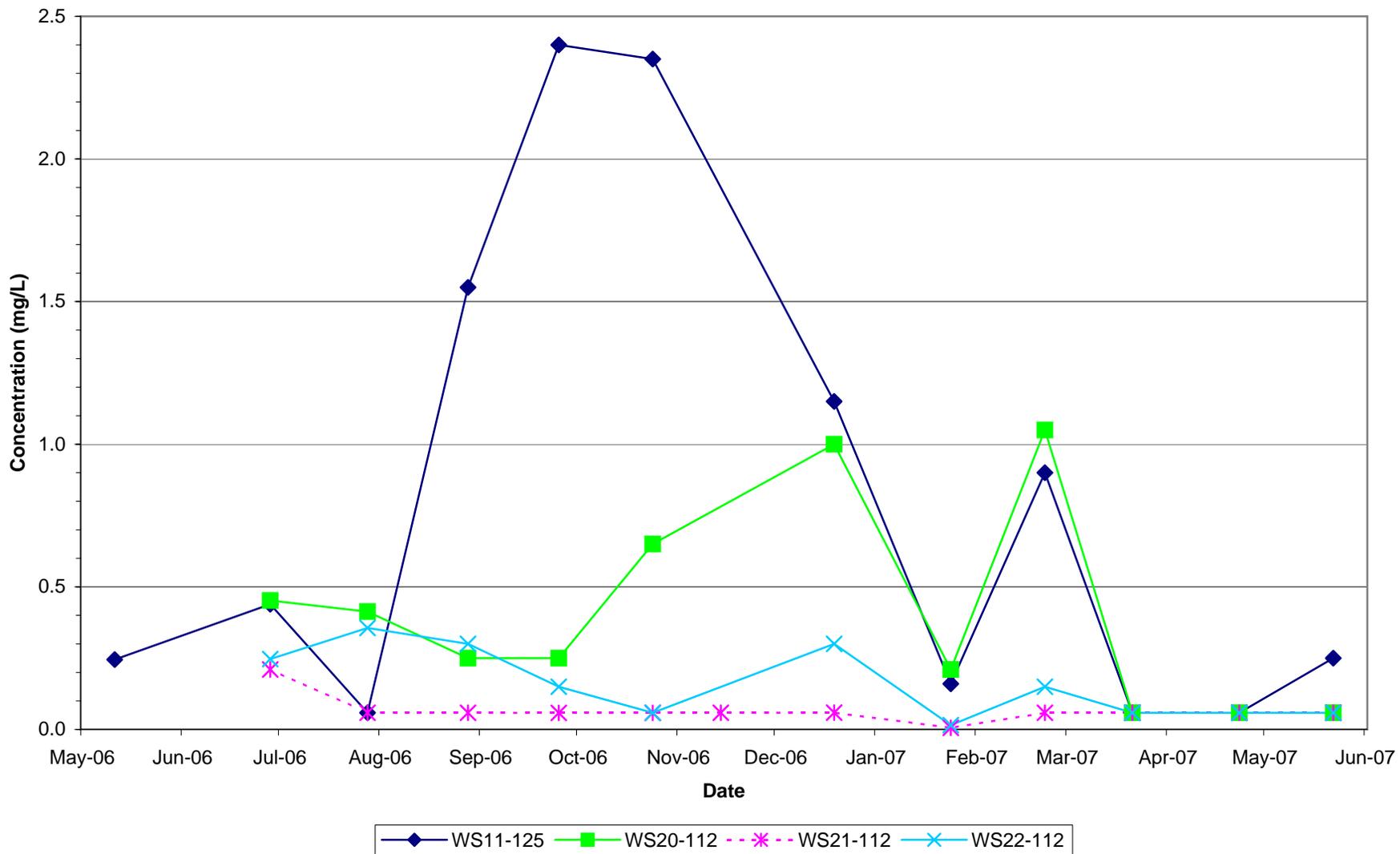


Figure 3-30
RPSA Chloride Concentration (mg/L)
Siltronic Corporation
Portland, Oregon

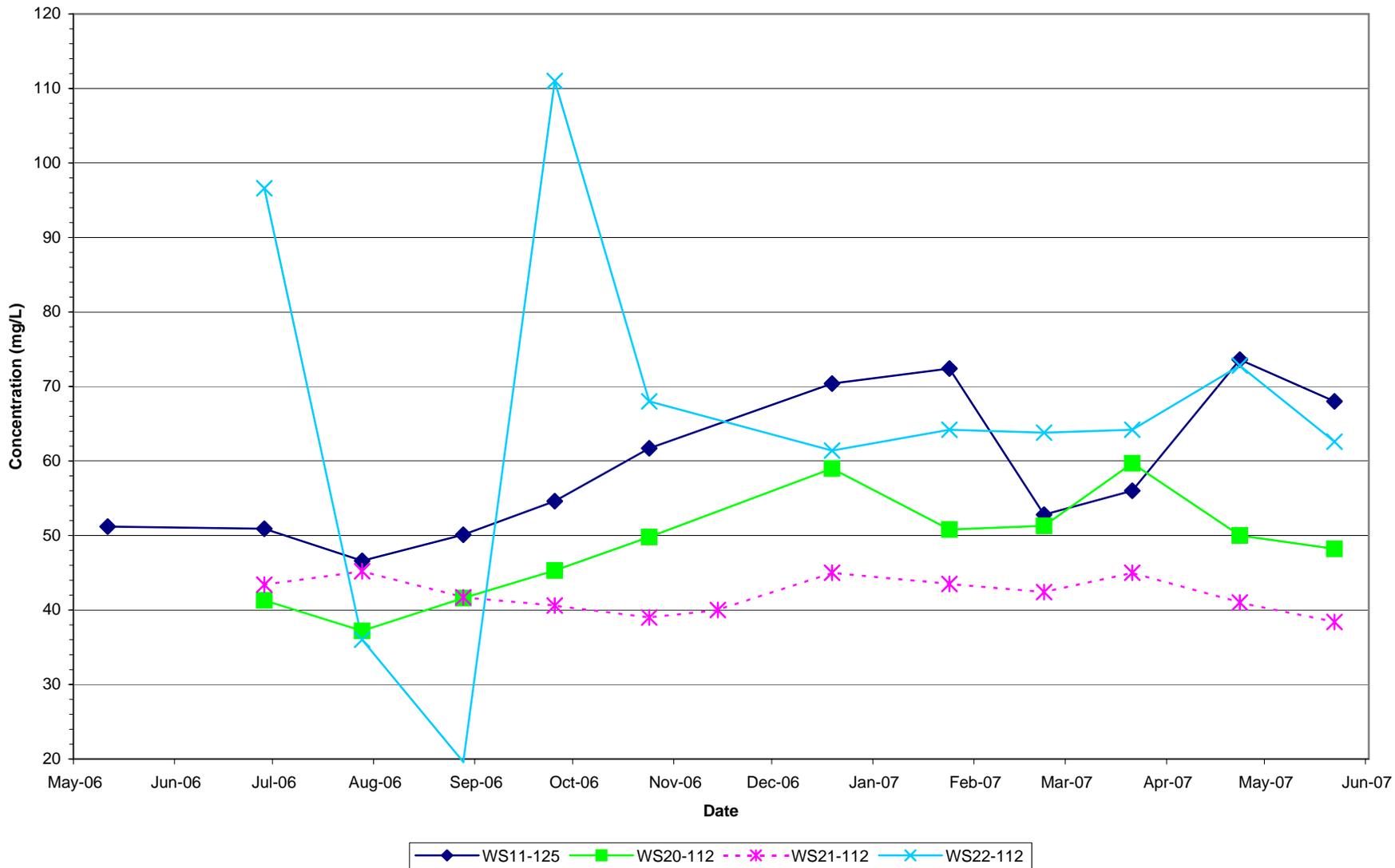


Figure 3-31
WS21-112 — Total Ethenes Concentrations
Siltronic Corporation
Portland, Oregon

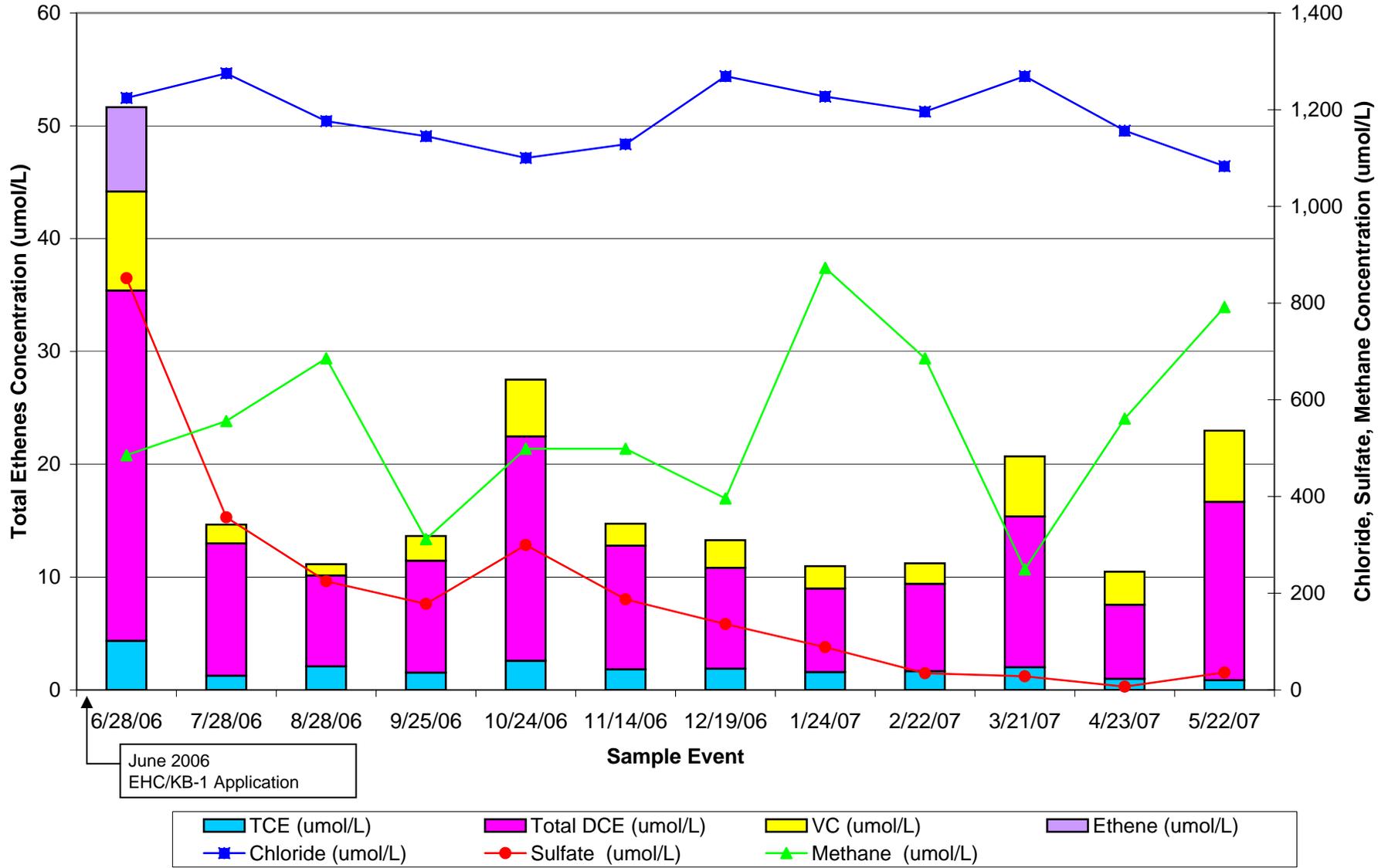


Figure 3-32
WS22-112 — Total Ethenes Concentrations
Siltronic Corporation
Portland, Oregon

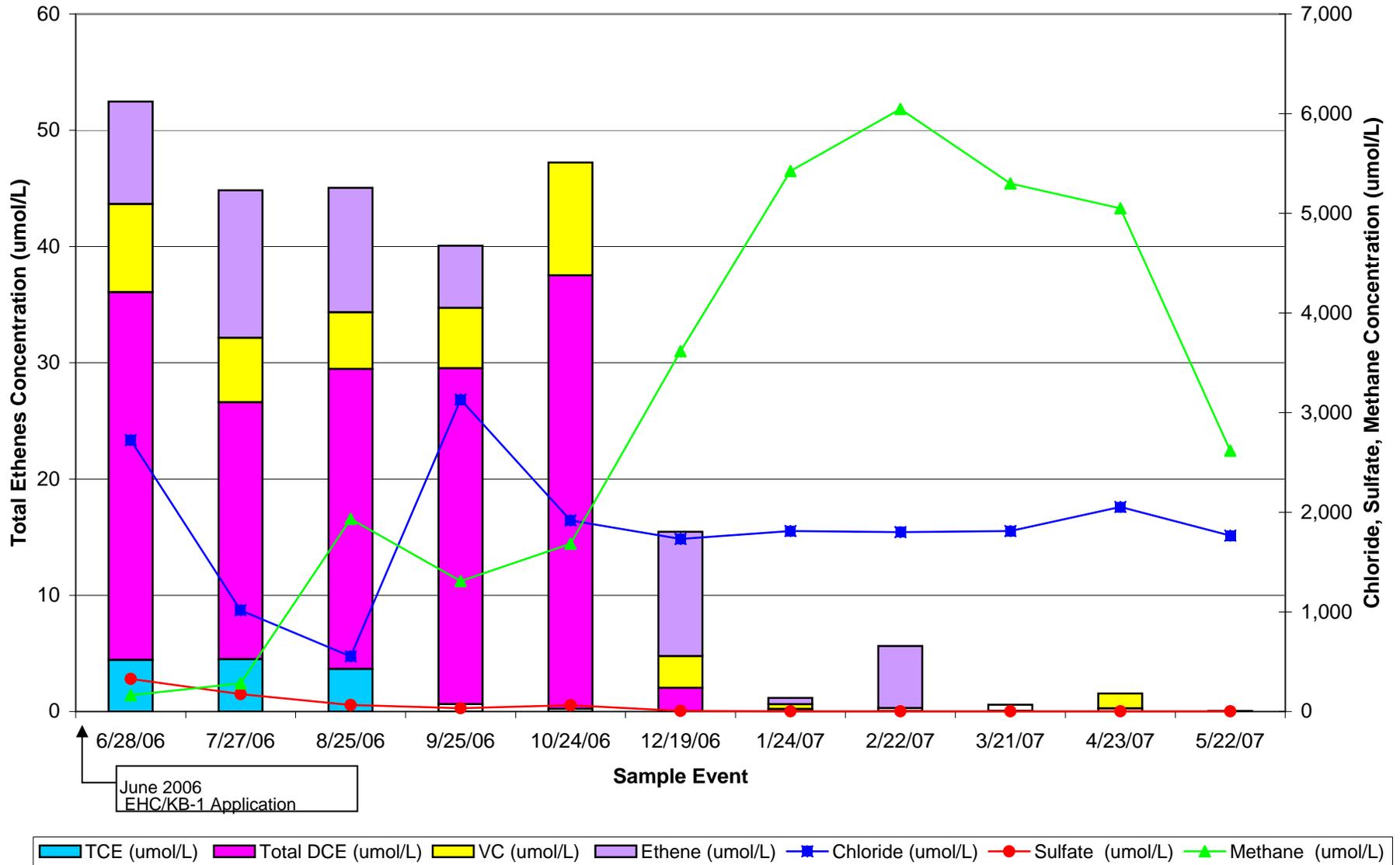


Figure 3-33
WS11-125 — Total Ethenes Concentrations
Siltronic Corporation
Portland, Oregon

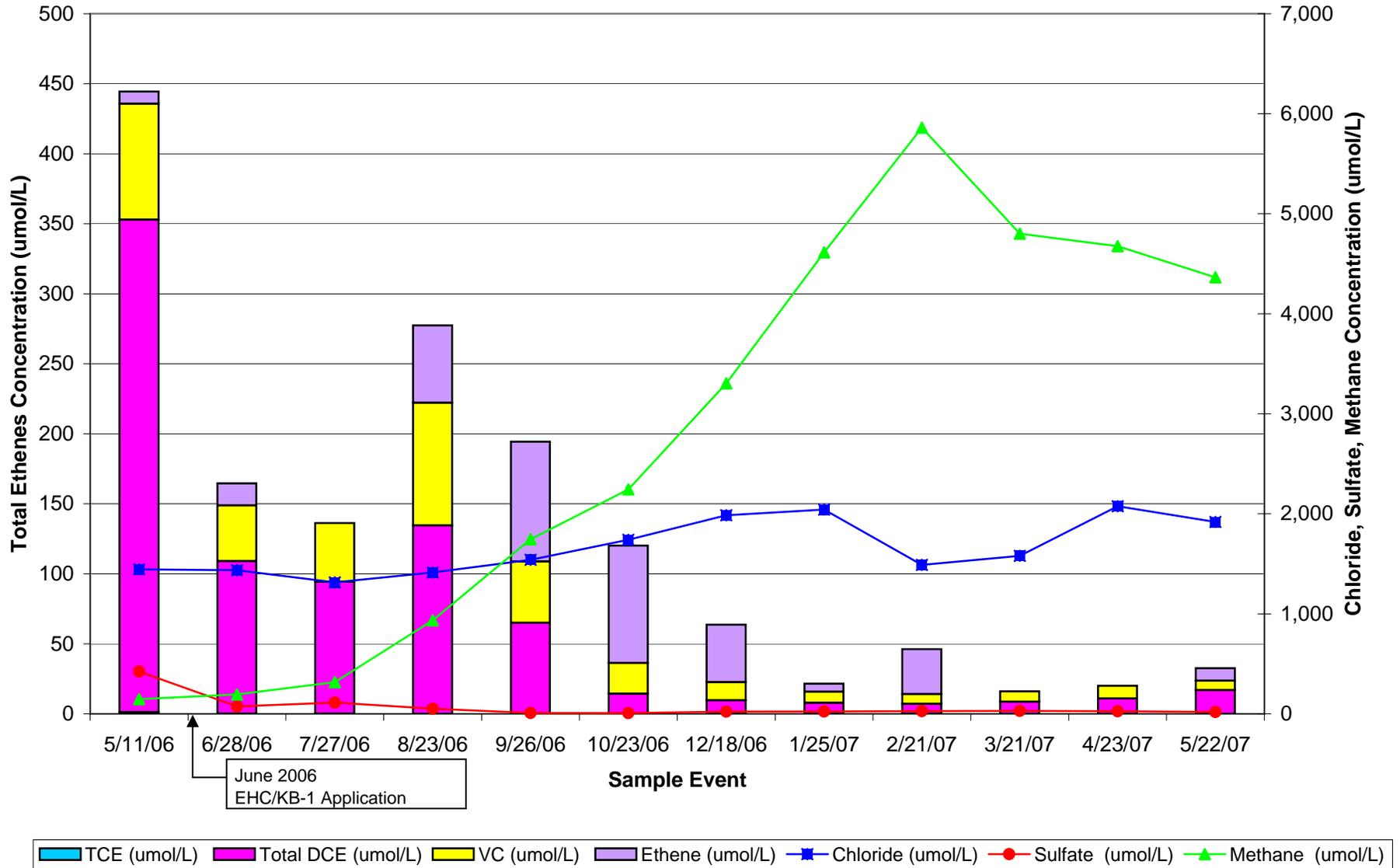


Figure 3-34
WS20-112 — Total Ethenes Concentrations
Siltronic Corporation
Portland, Oregon

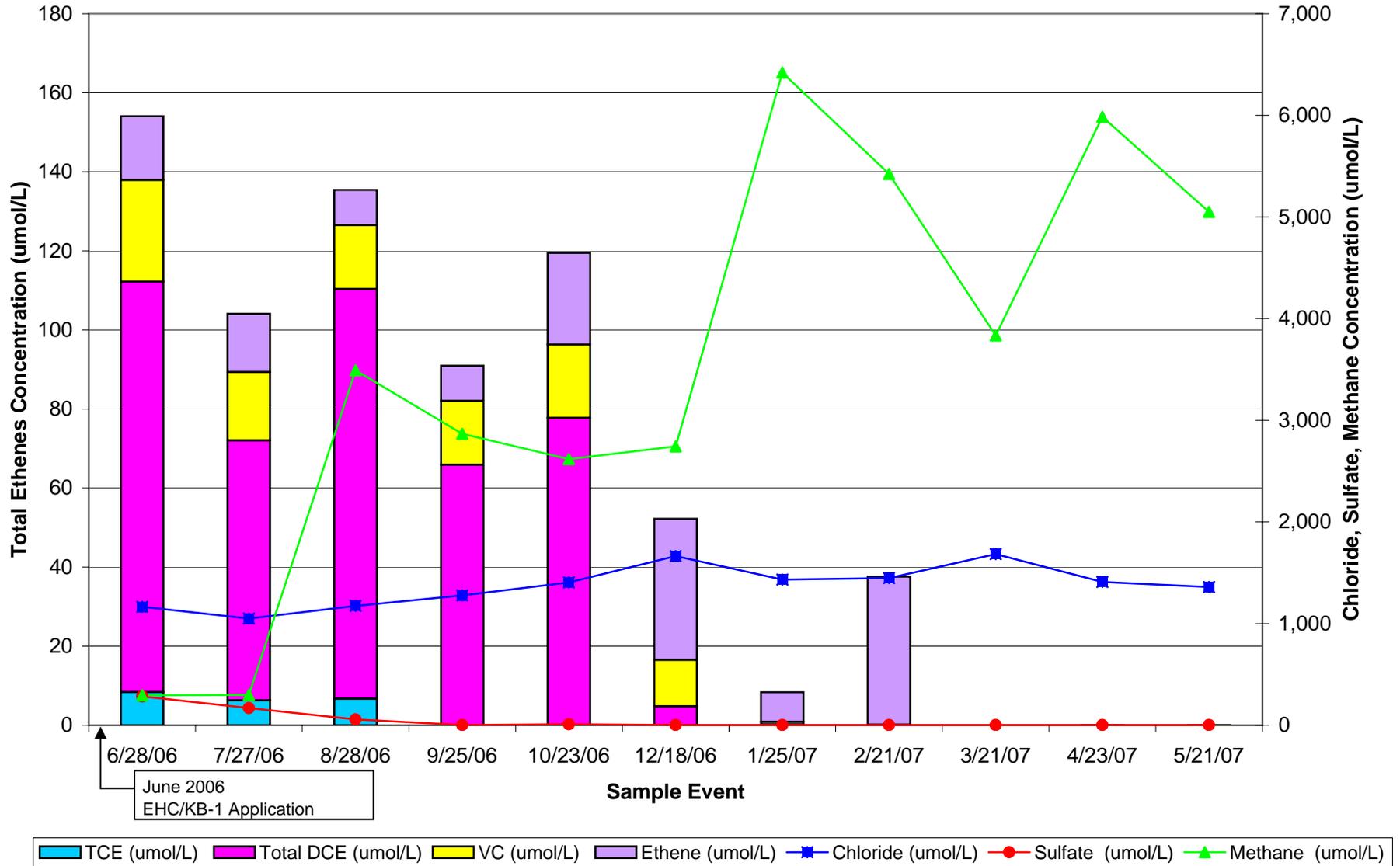


Figure 3-35
RPSA Dissolved Oxygen Concentration (mg/L)
Siltronic Corporation
Portland, Oregon

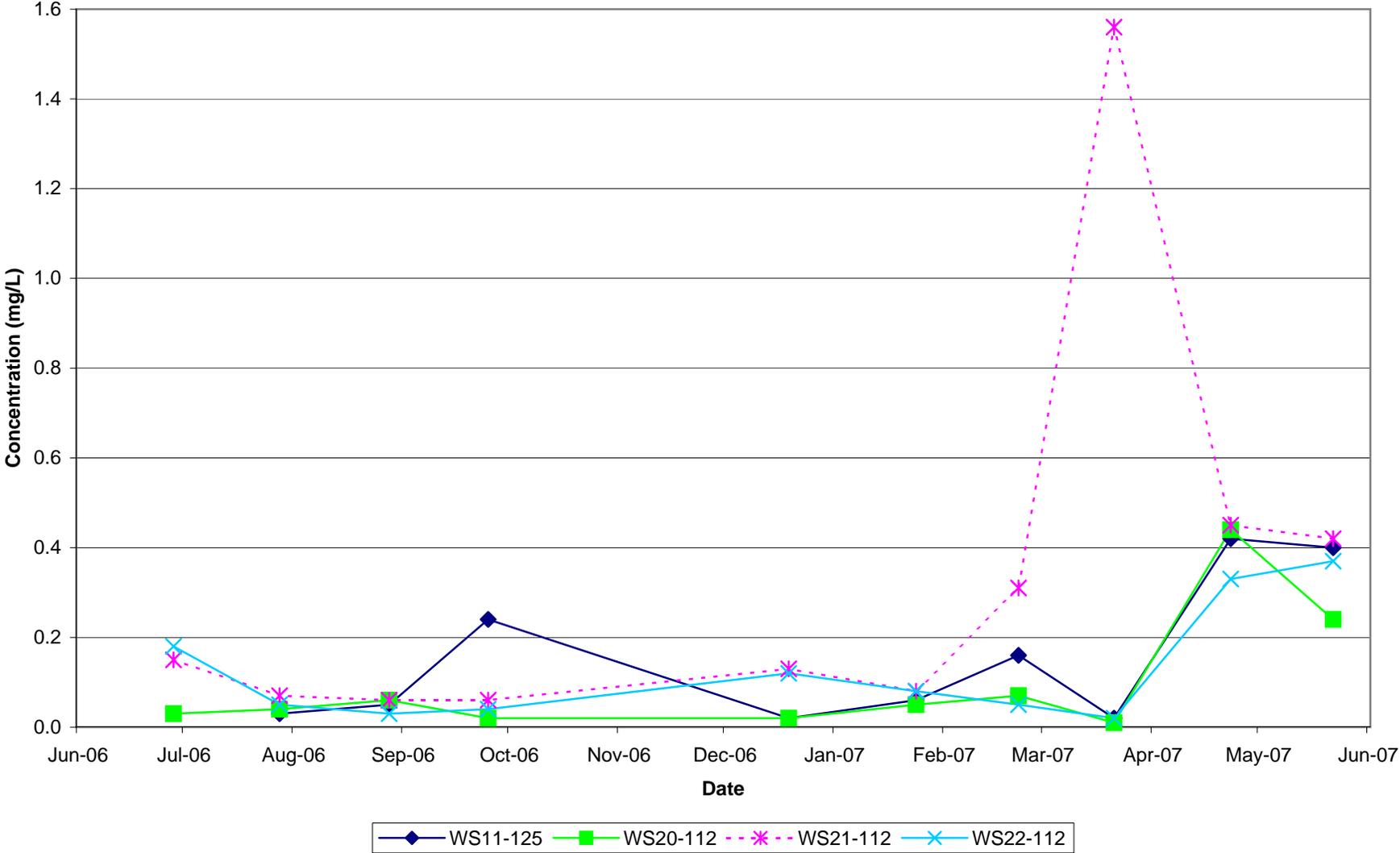


Figure 3-36
RPSA Oxidation Reduction Potential (mV)
Siltronic Corporation
Portland, Oregon

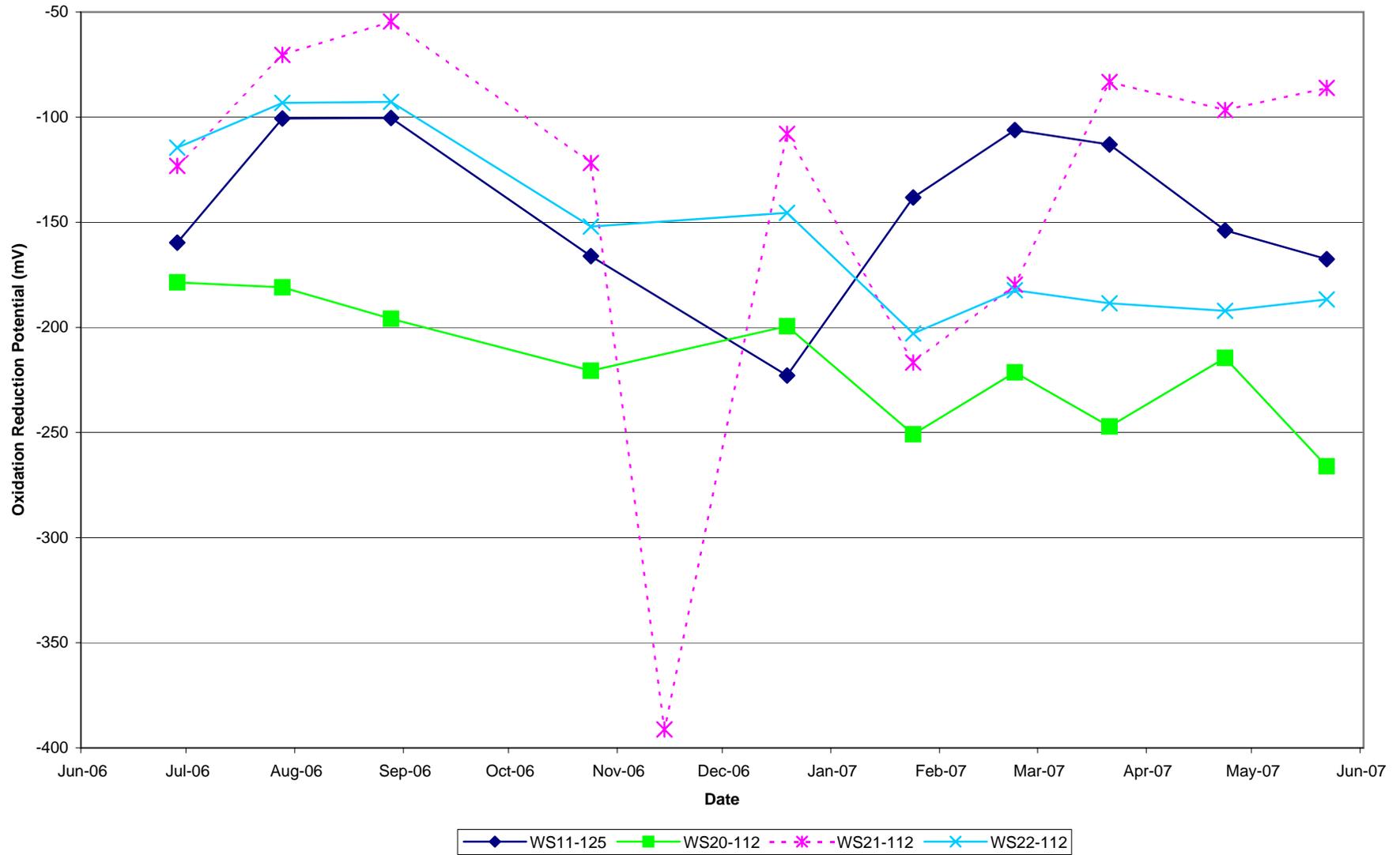


Figure 3-37
RPSA Sulfate Concentration (mg/L)
Siltronic Corporation
Portland, Oregon

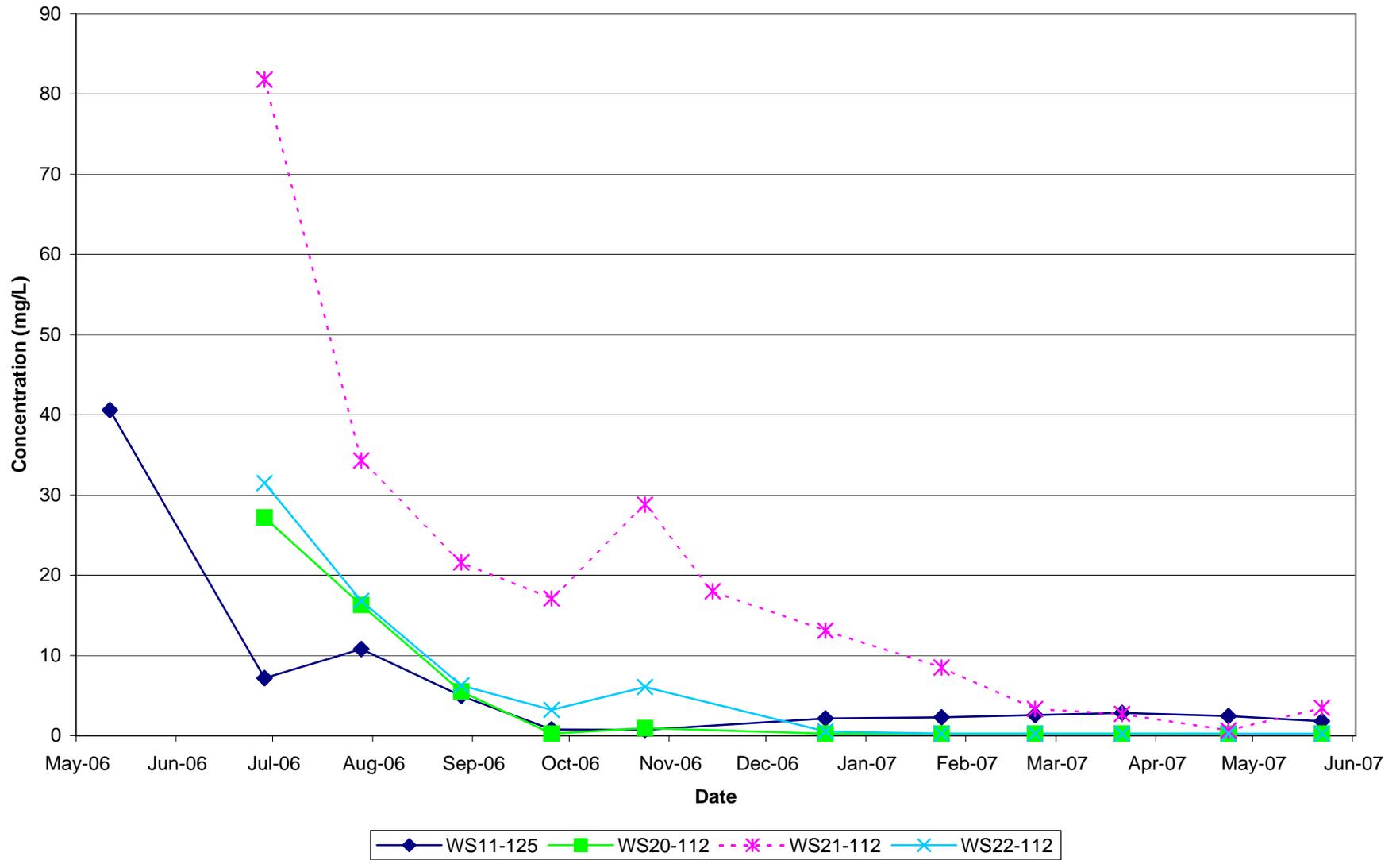


Figure 3-38
RPSA Methane Concentration (mg/L)
Siltronic Corporation
Portland, Oregon

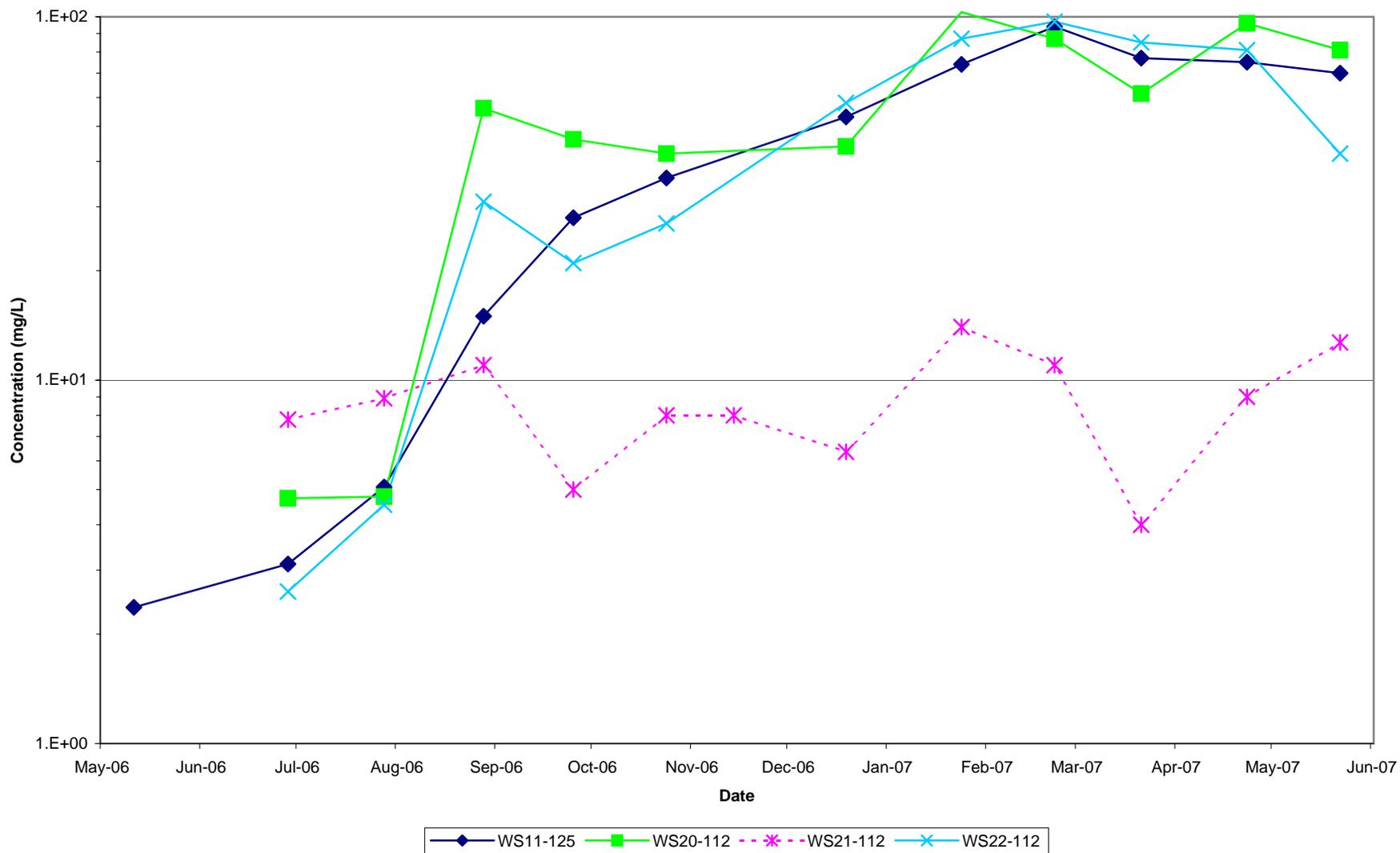


Figure 3-39
RPSA Ferrous Iron Concentration (mg/L)
Siltronic Corporation
Portland, Oregon

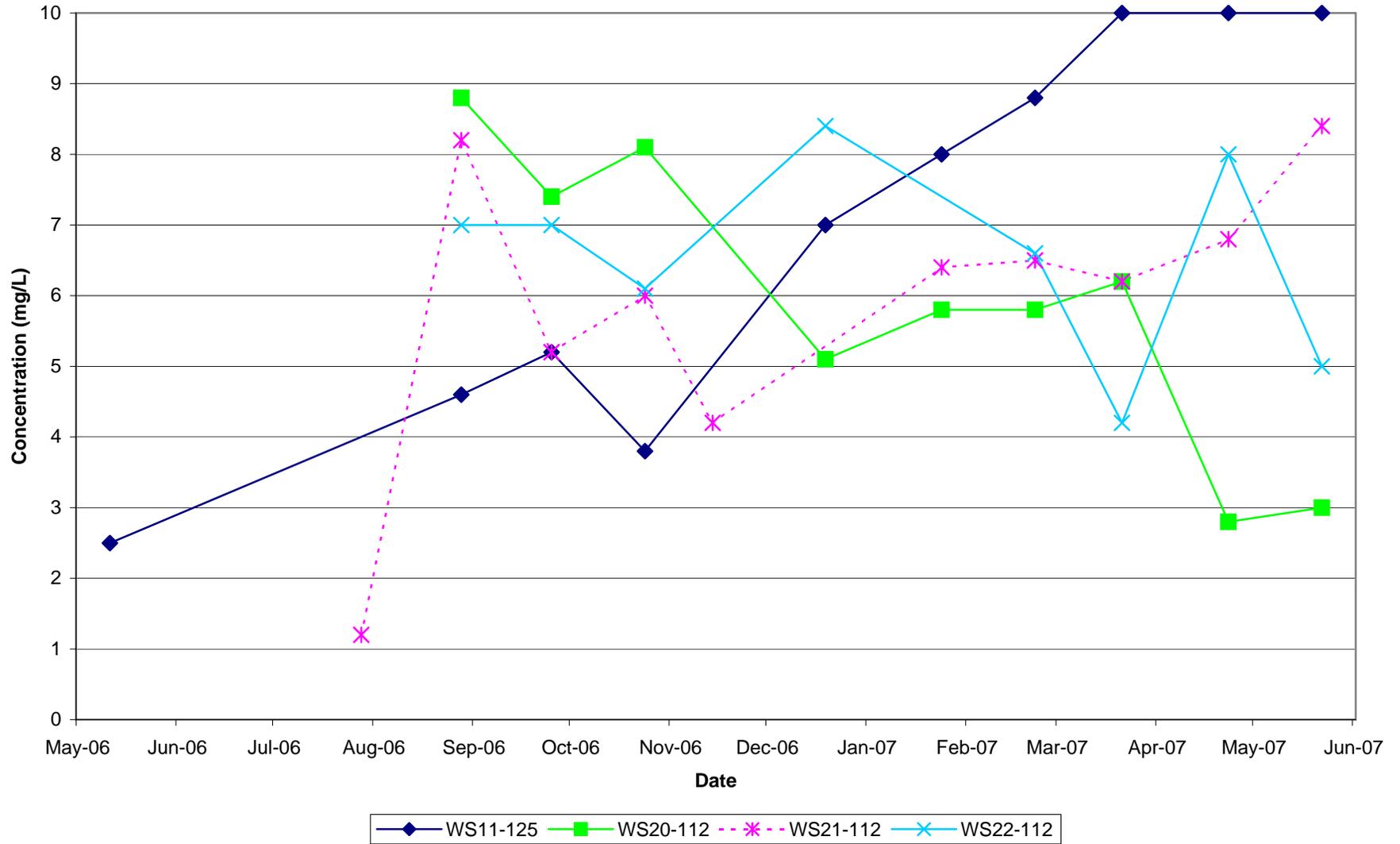


Figure 3-40
RPSA Biological Cell Counts (cells/L)
Siltronic Corporation
Portland, Oregon

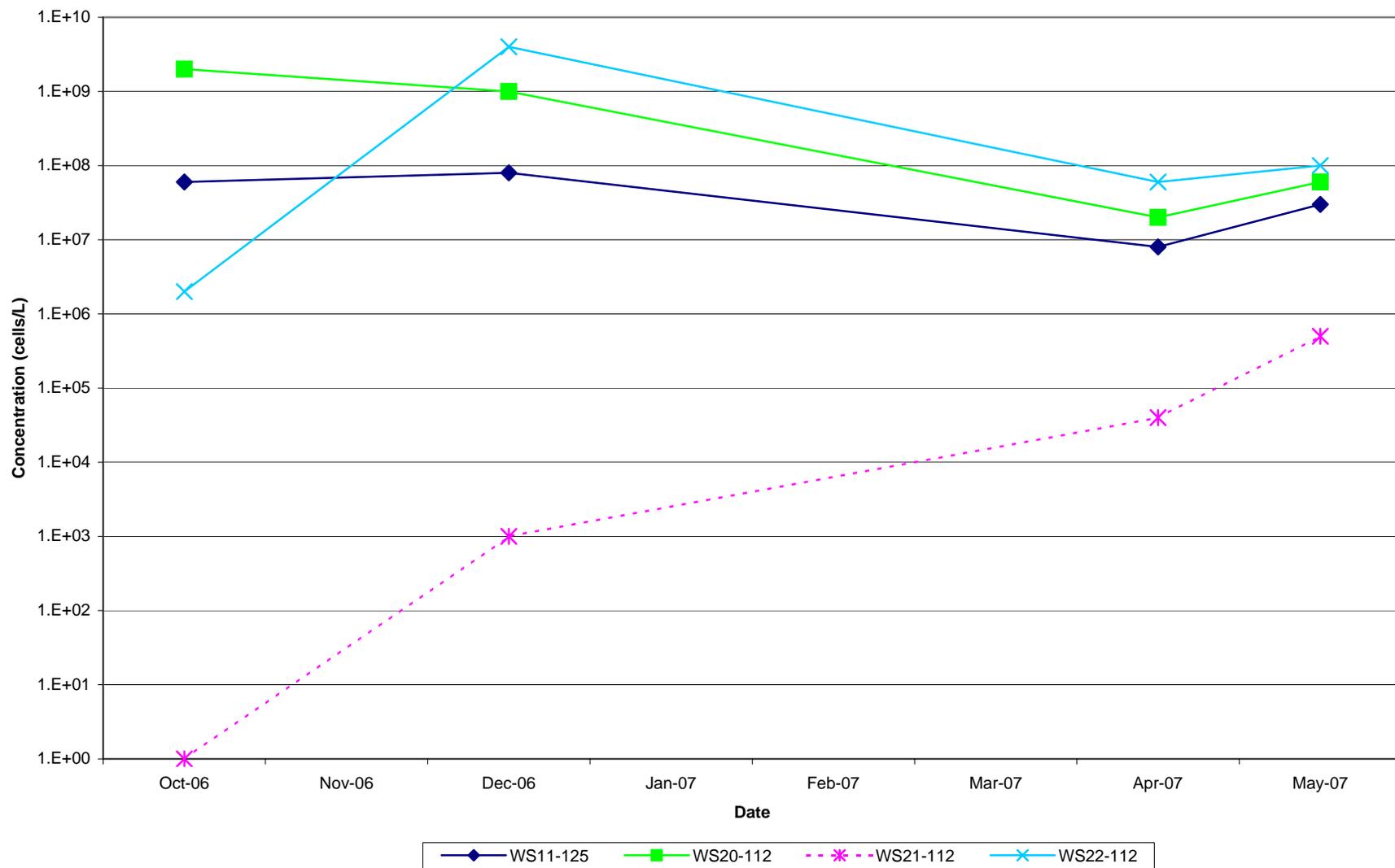


Figure 3-41
RPSA Benzene Concentration (ug/L)
Siltronic Corporation
Portland, Oregon

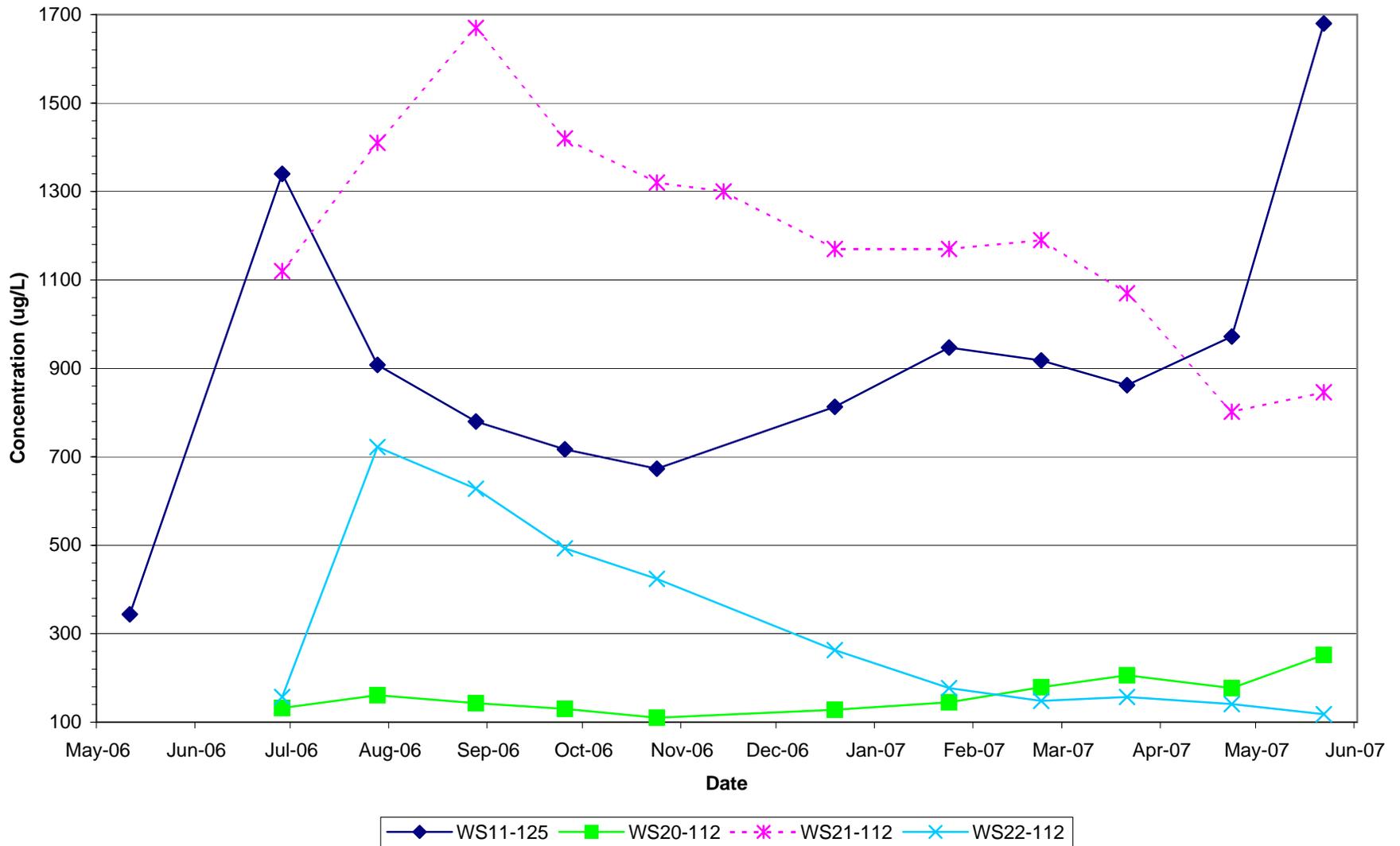


Figure 3-42
RPSA Naphthalene Concentration (ug/L)
Siltronic Corporation
Portland, Oregon

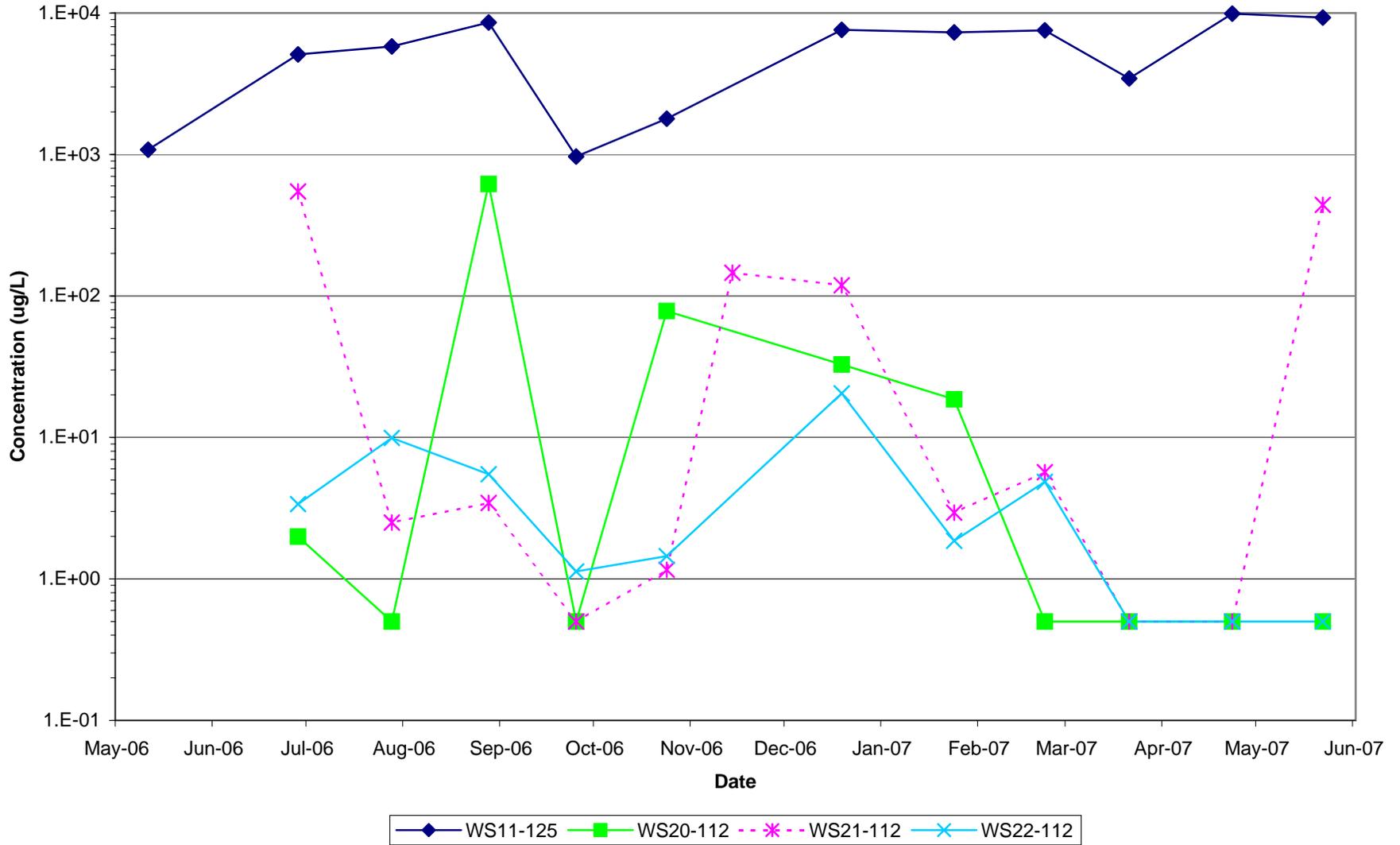


Figure 3-43
RPSA Total Cyanide Concentration (mg/L)
Siltronic Corporation
Portland, Oregon

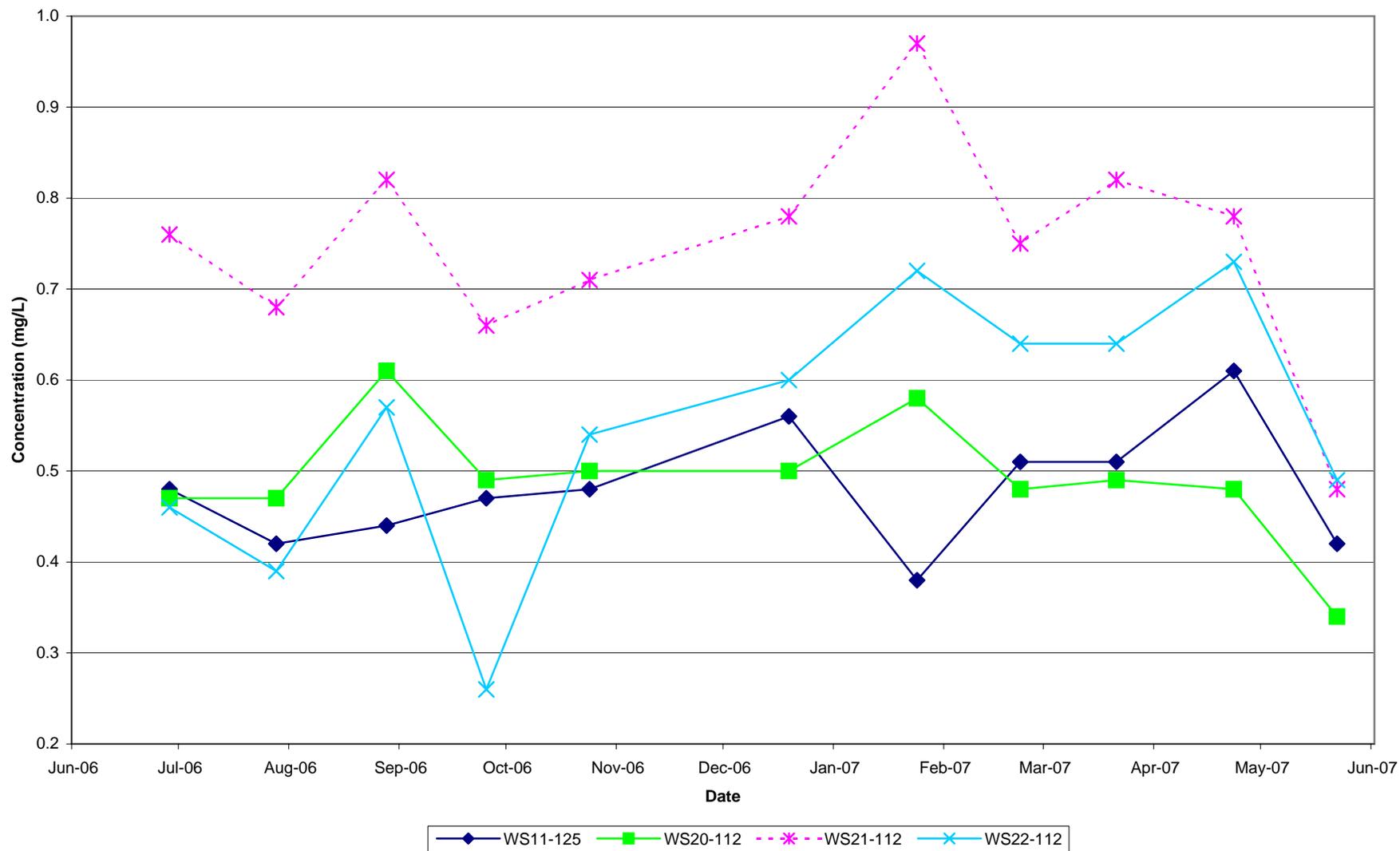


Figure 3-44
RPSA Free Cyanide Concentration (mg/L)
Siltronic Corporation
Portland, Oregon

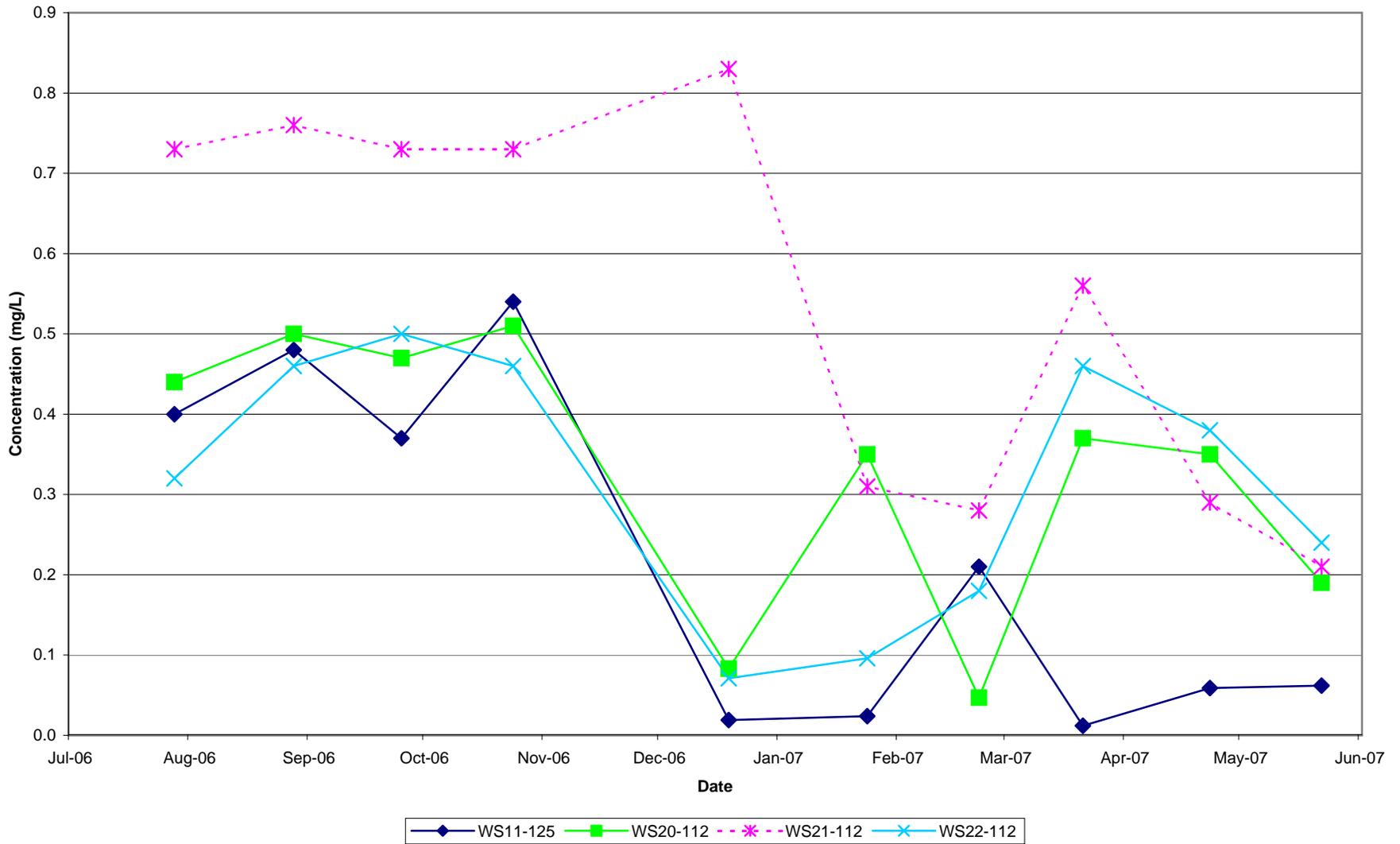


Figure 3-45
RPSA Arsenic Concentration (ug/L)
Siltronic Corporation
Portland, Oregon

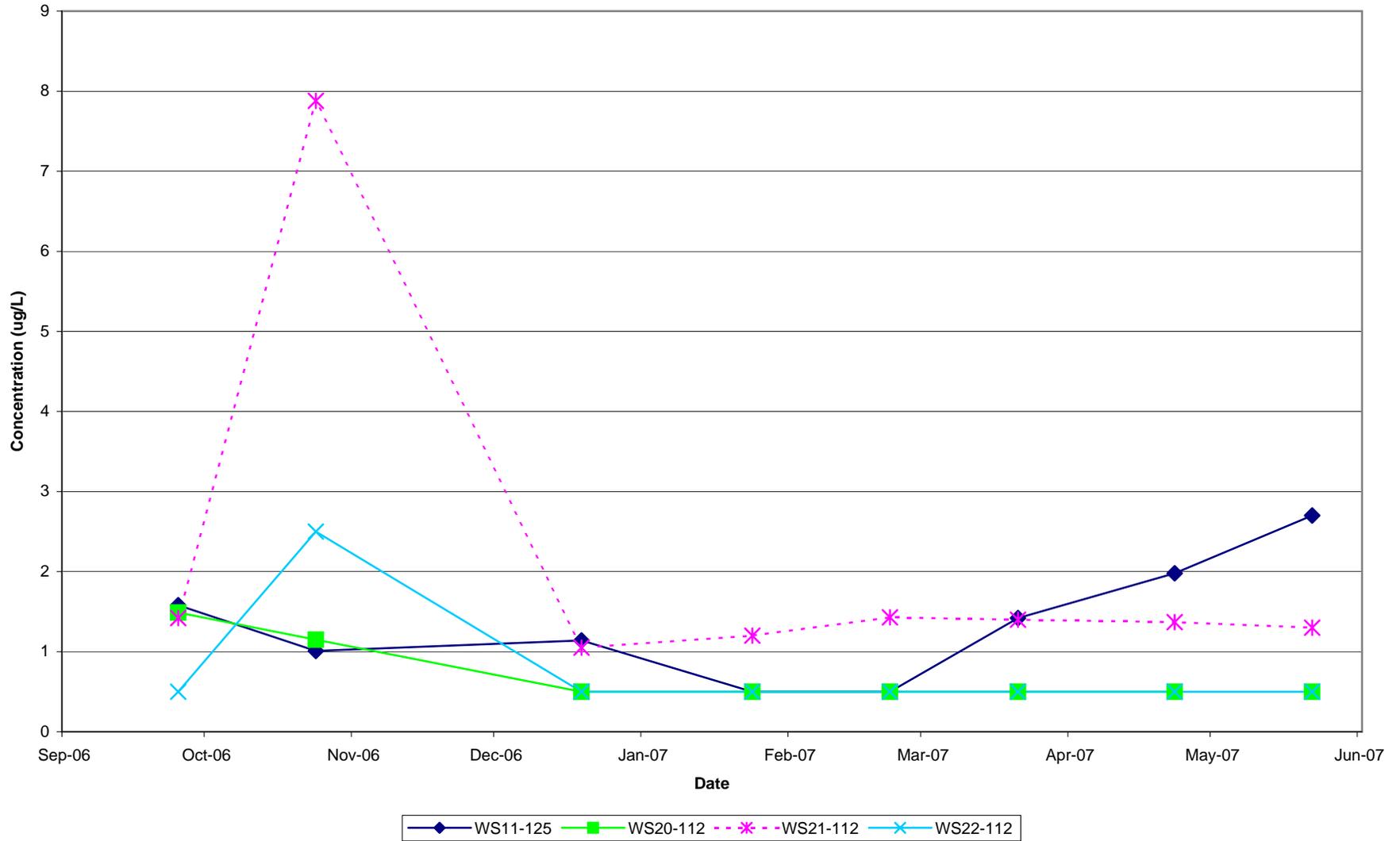


Figure 3-46
RPSA Manganese Concentration (mg/L)
Siltronic Corporation
Portland, Oregon

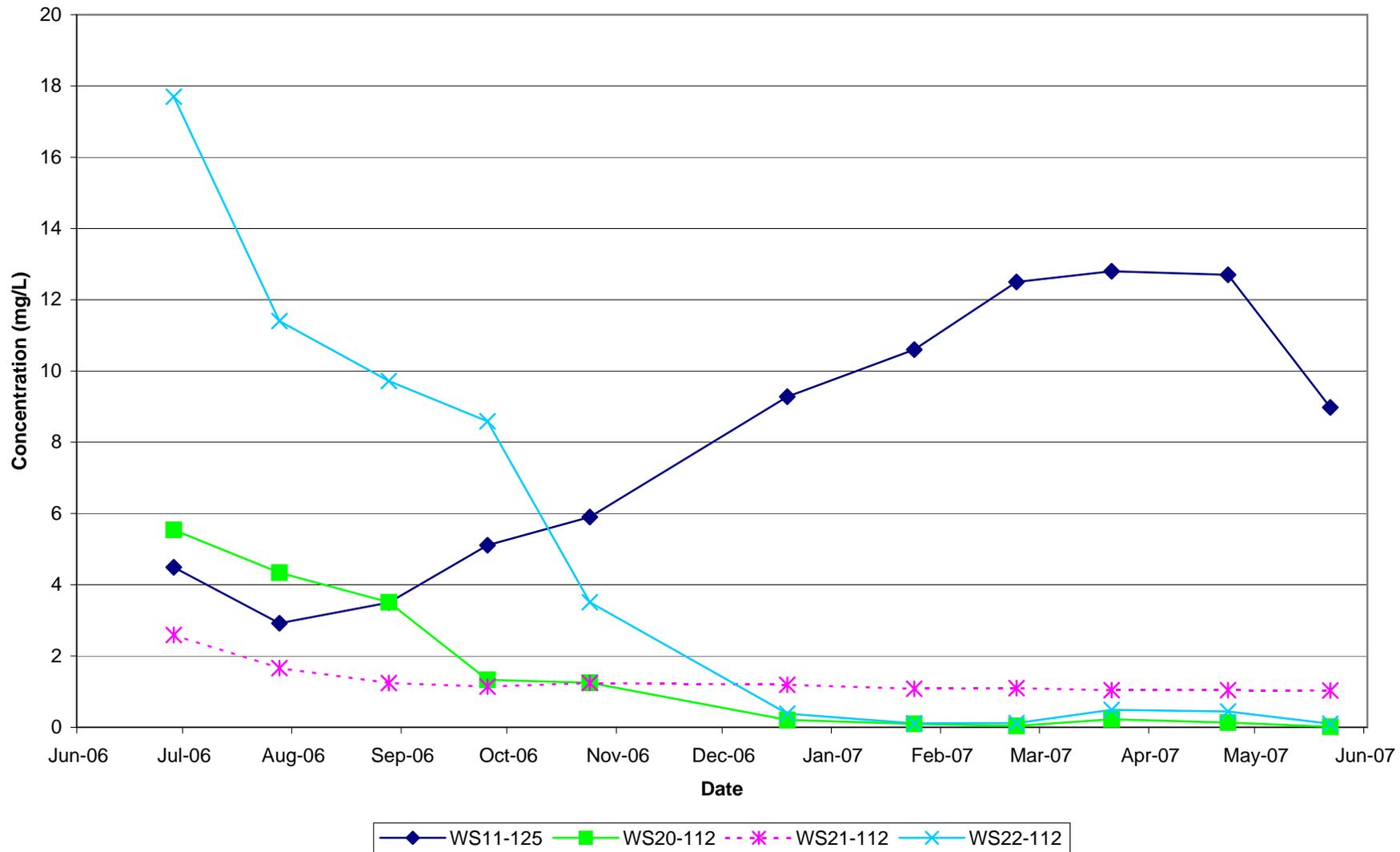


Figure 3-47
RPSA Total Organic Carbon Concentration (mg/L)
Siltronic Corporation
Portland, Oregon

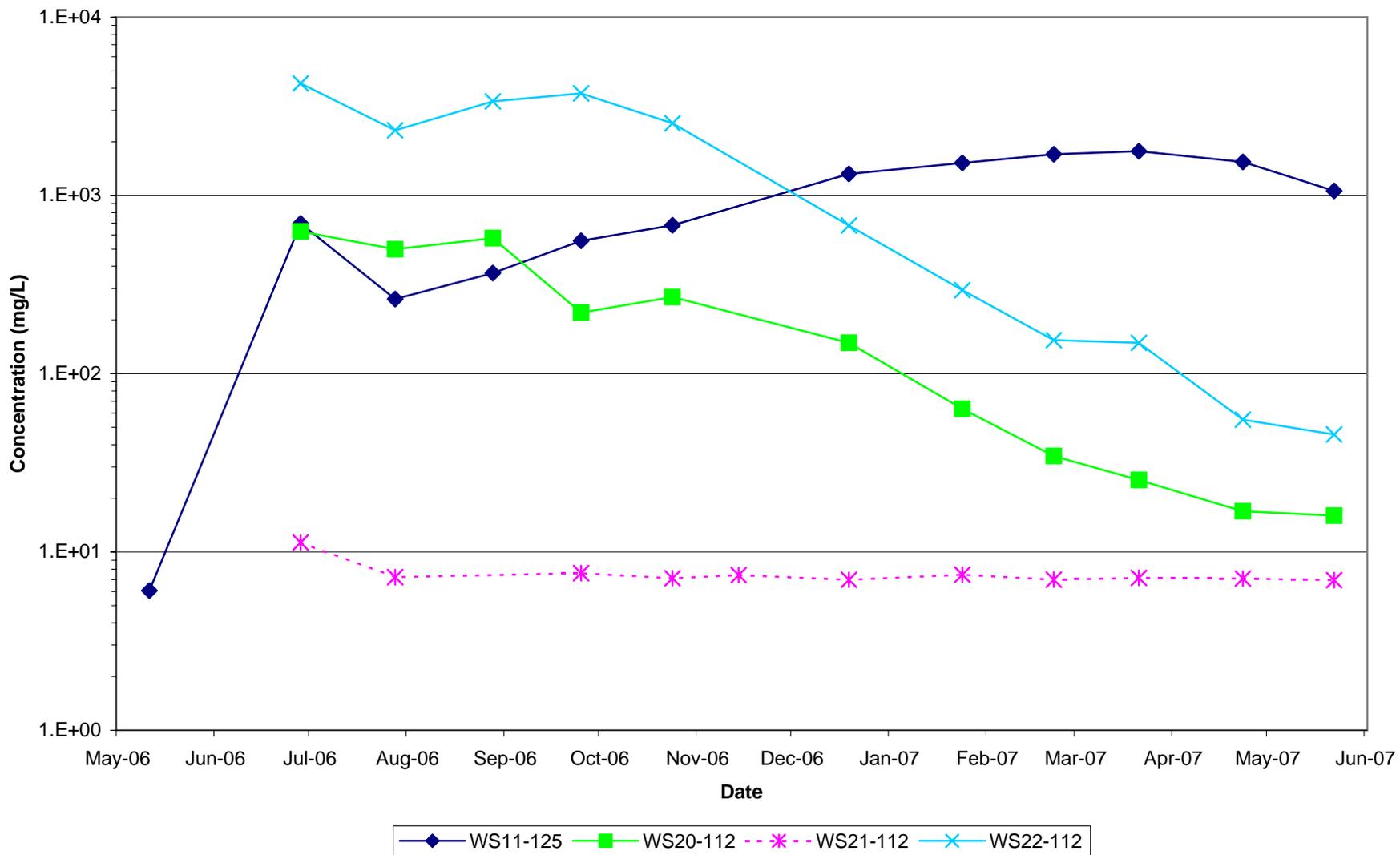


Figure 3-48
RPSA Total Iron Concentration (mg/L)
Siltronic Corporation
Portland, Oregon

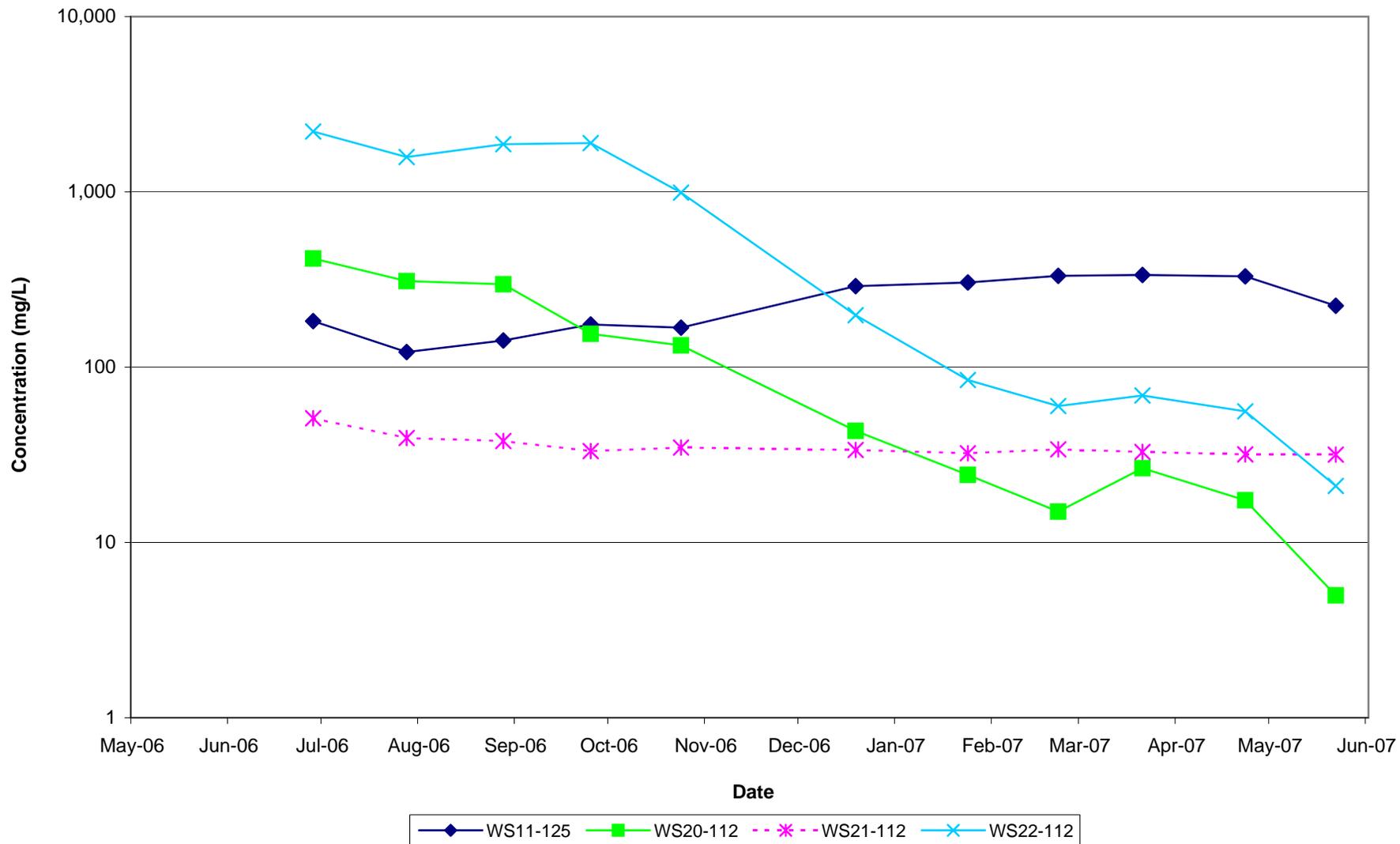
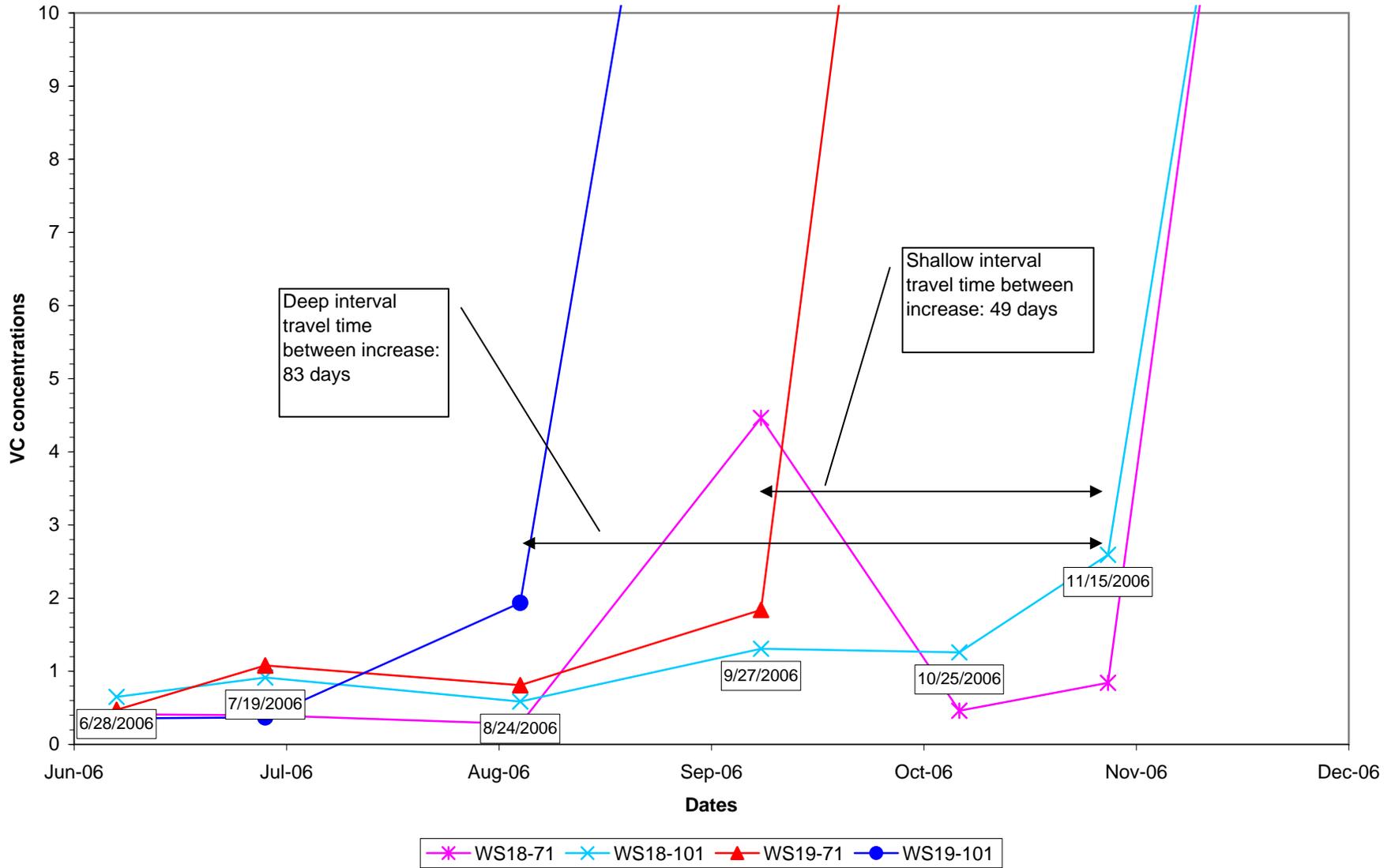


Figure 3-49
SZPSA Travel Time of Vinyl Chloride (umol/L)
Siltronic Corporation
Portland, Oregon



APPENDIX A
BENCH TEST DATA SUMMARIES

APPENDIX B
INJECTION LOGS

APPENDIX C
ANALYTICAL RESULTS



ENVIRONMENTAL & ENGINEERING CONSULTANTS

7223 NE Hazel Dell Avenue, Suite B | Vancouver, Washington 98665 | Phone 360.694.2691 | Fax 360.906.1958 | www.MFAinc.org

August 10, 2007
Project No. 8128.01.10

Mr. Dana Bayuk
Oregon Department of Environmental Quality
2020 SW 4th Avenue, Suite 400
Portland, Oregon 97201-4987

Re: Enhanced In-situ Bioremediation Pilot Study Report
Siltronic Corporation
7200 NW Front Avenue, Portland, OR
ECSI #183

Dear Dana:

On behalf of Siltronic Corporation (Siltronic), Maul Foster & Alongi, Inc. (MFA) encloses with this letter the Enhanced In-situ Bioremediation Pilot Study Report (Report). The Report was prepared consistent with the Enhanced Bioremediation Pilot Study Work Plan (Work Plan). The Work Plan and Report were completed and submitted in accord with the requirements of the *Order Requiring Remedial Investigation (RI) and Source Control Measures* (the Order), Oregon Department of Environmental Quality (DEQ) No. VC-NWR-03-16, issued to Siltronic on February 9, 2004.

As the Report explains, the pilot study has demonstrated that the selected method of enhanced in-situ bioremediation (EIB) is very effective in reducing or eliminating TCE and its degradation products from the contaminant source area and plume. Specifically, the Report concludes as follows:

- 1) Full scale implementation of EIB in the source area, where concentrations of TCE are relatively high and indicative of the potential presence of TCE-DNAPL, will be successful.
- 2) EIB will be successful as a source control remedy, preventing migration of TCE and its degradation products in groundwater at concentrations in excess of JSCS SLVs to the Willamette River.
- 3) Full scale implementation of EIB within the TCE contaminant plume at the riverbank will, over time, reduce or eliminate concentrations of TCE and its degradation products in TZW.

MFA and Siltronic presented these conclusions to DEQ during a meeting on August 1, 2007. At that time, DEQ expressed concern that implementation of EIB at the riverbank could impact the expected performance of a groundwater extraction and treatment system being evaluated by NW Natural (NWN), due to the potential for extraction equipment fouling as a result of elevated iron

concentrations. MFA agrees that elevated iron concentrations could increase the risk of groundwater extraction equipment fouling. However, the likely impact of EIB on the ambient level of dissolved iron in the area groundwater remained an unresolved issue at that meeting.

MFA included total iron in the analytical suite for the pilot study. After further review of these data, and as briefly discussed during the August 1 meeting, MFA concludes that EIB is expected to result in elevated dissolved iron concentrations immediately following injection, but with concentrations dropping to background levels within approximately one year (see Figure 3-48 from the Report, copy attached).

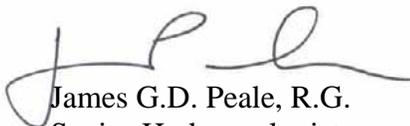
Dissolved iron concentrations of greater than 1 milligram per liter (mg/L) can result in equipment fouling.¹ However, background concentrations of dissolved iron in groundwater beneath the Siltronic site (e.g., WS-21-112 data) and adjacent Gasco and Rhone-Poulenc sites are already well above this threshold.

The Pilot Study data confirm that implementation of EIB, with its temporary impact on iron concentrations, will not increase the already existing potential for fouling of extraction equipment. NWN is evaluating this concern, and is aware of Siltronic's likely proposal to implement EIB at its riverbank as a component of its Source Control Measures in compliance with the Order. EIB's contribution to this potential problem for NWN, if any, would be temporary and can be addressed by a coordinated implementation schedule.

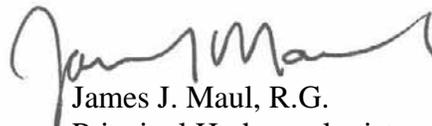
Please call either of us at (971) 544-2139 if you have questions or comments.

Sincerely,

Maul Foster & Alongi, Inc.



James G.D. Peale, R.G.
Senior Hydrogeologist



James J. Maul, R.G.
Principal Hydrogeologist

Attachments: Figure 3-48 RPSA Total Iron Concentration

cc: Tom McCue, Siltronic
Chris Reive, Jordan Schrader
Alan Gladstone and William Earle, Davis Rothwell Earle & Xochihua, P.C.
John Edwards, Anchor Environmental LLC
Bob Wyatt, NW Natural

¹ Driscoll, F.G., 1986, Groundwater and Wells: Johnson Filtration Systems, Inc., St. Paul, MN.

FIGURE

Figure 3-48
RPSA Total Iron Concentration (mg/L)
Siltronic Corporation
Portland, Oregon

