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NATURAL ATTENUATION OF CHLORINATED ETHENE CONTAMINATED GROUNDWATER
AT SITE 11 NSB KINGS BAY GA
11/1/2002
U S GEOLOGICAL SURVEY

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**Natural Attenuation of Chlorinated Ethene-Contaminated Ground Water, Old Camden
County Landfill, Kings Bay Naval Submarine Base, Georgia
August 2001 to August, 2002**

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EXECUTIVE SUMMARY

Monitoring data collected over a four-year period show that a plume of chlorinated ethene-contaminated ground water at Site 11, Kings Bay, Georgia, has contracted significantly following treatment of the contaminant source area by Fenton's Reagent in-situ oxidation. Prior to in-situ oxidation using Fenton's Reagent (January, 1999), concentrations of perchloroethene (PCE) exceeded 3,500 :g/L in the contaminant source area. At this time, the plume emanating from this source area had vinyl chloride (VC) concentrations exceeding 800 :g/L seventy meters downgradient of the source area. Fenton's Reagent treatment lowered concentrations of total chlorinated ethenes in the source area below 100 :g/L, and they have not rebounded above this level since treatment. In the four years following source-area treatment, VC concentrations in the plume have decreased as much as a factor of ten, and the area of the plume has decreased significantly. Much of the concentration declines in the plume can be attributed to the interaction of source-area treatment, the cessation of a previously installed pump-and-treat system, and the significant natural attenuation capacity of this anoxic aquifer. Fenton's Reagent treatment has not measurably altered ambient redox conditions in the aquifer as treated water has moved downgradient, and the natural attenuation capacity has not been diminished. These results show that when natural attenuation mechanisms are relatively efficient, source-area removal actions can be effective in decreasing the areal extent of plumes and contaminant concentrations in chlorinated-ethene contaminated ground-water systems.

INTRODUCTION

A combination of source-area removal by Fenton's Reagent in-situ oxidation, vegetable oil injection, and natural attenuation has been selected by Southern Division NAVFACENGCOM and by Georgia Department of Environmental Protection as corrective actions for chlorinated ethene-contaminated ground water at the Old Camden County Landfill, Naval Submarine Base, Kings Bay, Georgia. A comprehensive sampling and analysis program is being carried out by the U.S. Geological Survey to assess the effectiveness of this remedial strategy. This report summarizes the results of the fourth year (August, 2001 to August 2002) of monitoring at this site.

The effectiveness of removing residual dense non-aqueous phase liquids (DNAPLs) from the source zones of chlorinated ethene-contaminated aquifers is currently a topic of technical debate. The regulatory community has consistently maintained that the removal of contaminant mass from source areas is a preferred remedial approach (U.S. EPA, 1999; Interstate Technology and Regulatory Cooperation, 2001). On the other hand, direct observation of DNAPLs in aquifer sediments (Parker and Cherry, 1999), and numerical simulations of DNAPL behavior (Freeze and McWhorter, 1997; Sale and McWhorter, 2001) suggests that source-removal actions may not be effective for controlling contaminant concentrations in plumes emanating from source areas (Cherry, Fenster, and McKay, 1992). Thus, the effectiveness of source-area treatment technologies for restoring contaminated ground-water systems is presently controversial (Jackson, 2001). Ultimately, this controversy will be settled by actual observations in aquifers where source-area treatment actions have been made, and where long-term monitoring documents how ground-water systems respond to such treatment. The purpose of this report is to

document the observed behavior of a chlorinated ethene contaminant plume following source-area treatment using Fenton's Reagent in-situ oxidation in a shallow coastal plain aquifer. The results suggest that, when ground-water systems have a significant natural attenuation capacity, source area treatment can lead to the contraction of contaminant plumes and to significant declines in contaminant concentrations in time frames of less than five years.

METHODS AND MATERIALS

Geology, hydrology, and site history

The site is an abandoned landfill known as the Old Camden Road Landfill, located at the Naval Submarine Base (NSB) Kings Bay, Georgia. A map of the site showing the location of the contaminant source area and the locations of monitoring wells is shown in Figure 1. This site is underlain by sediments of back-barrier island and barrier island origin. The most permeable sands underlying the site are present between depths of 10 and 13 meters below land surface, and record sedimentation of a prograding barrier island. This permeable zone is underlain and overlain by finer-grained sands, clays, and organic-rich sediments of back-barrier origin that exhibit lower hydraulic conductivity. Aquifer tests and slug tests at this site indicate that hydraulic conductivities of the permeable sands range from 0.6 to 10 m/d. The lithology of these sands suggest that the permeable aquifer is characterized by higher hydraulic conductivities ($K \sim 10$ m/d) relative to overlying and underlying sands. Because of its relative permeability, the aquifer is a preferential pathway for horizontal ground-water flow and contaminant transport in this system, and ground-water velocities are estimated to range from 30 to 60 m/y. Overlying the aquifer at depths of approximately 3-5 meters below land surface is a layer of organic-rich sands. This organic-rich layer has the important effect of removing dissolved oxygen from recharging water and producing uniformly anoxic conditions in the permeable zone.

The Old Camden Road landfill was used to dispose of municipal waste between 1974 and 1981. Trenches were excavated to a depth of between 2 and 4 meters, filled with waste, and covered with fill. At some time during waste-disposal operations, PCE was released at the landfill. The areal distribution of the PCE source area (Fig. 1) was previously identified by

direct-push sampling of ground water and aquifer sediments (Chapelle and Bradley, 1998).

Prior to 1998, a discrete plume of chlorinated ethene-contaminated ground water emanated from the source area and flowed toward the northwest, and was first identified by direct push methods (ABB Environmental Services, Inc., 1997). In January of 1999, a series of Fenton's Reagent injections were undertaken to oxidize chlorinated ethenes in-situ. At that time, a comprehensive monitoring program was undertaken to assess the efficiency of this remedial strategy.

Water Chemistry Sampling

Ground-water samples for measurement of chlorinated ethenes and redox-sensitive parameters were collected quarterly between 1998 and 2002 from a network of monitoring wells used to further delineate the areal extent of the plume (Fig. 1). These small-diameter (2.52 cm) monitoring wells were screened between 11 and 13 meters below land surface in the contaminant-bearing high-permeability zone. During sampling, each well was purged with a peristaltic pump until stable measurements of water temperature, conductivity, and pH were obtained. Samples for analysis of chlorinated ethenes (EPA method 8260) were collected in 40-ml glass vials, preserved with HCl, and capped with Teflon-lined septa for transport to the laboratory. Dissolved hydrogen (H_2) was measured using the gas-stripping procedure described in Chapelle et al. (1997). Concentrations of dissolved Fe(II), sulfide (Hach Co., 1989), and oxygen (Chemetrics Inc.) were measured in the field using colorimetric methods. Sulfate concentrations were measured using anion exchange chromatography with conductivity detection (Dionex Inc.). Samples for the analysis of methane were collected by filtering 4 mls of ground water (0.2 μ m filters) into sealed 20 ml serum vials. In the laboratory, methane in the headspace of the vial was measured using gas chromatography with thermal conductivity

detection. The amount of methane in ground water was then calculated from the headspace methane concentration using the Henry's law partition coefficient between the gaseous and dissolved phases. Determination of predominant terminal electron-accepting processes was based on consumption of electron acceptors such as dissolved oxygen and sulfate, production of final products such as ferrous iron, sulfide, and methane, and concentrations of the intermediate product hydrogen (Chapelle et al., 1995).

Results and Discussion

Monitoring Well Results

The locations of monitoring wells relative to the contaminant source area as it existed prior to in-situ oxidation, are shown in Figure 1. Ground-water chemistry data documenting ambient redox conditions in the plume are shown in Tables 1-4, and data documenting concentrations of chlorinated ethenes are shown in Tables 5-8. The following discussion highlights observed trends in redox conditions and concentrations of contaminants as they relate to the efficiency of the Fenton's Reagent treatment/natural attenuation remedial strategy.

Concentrations of vinyl chloride (VC) in the plume as measured in August of 1998, prior to Fenton's Reagent treatment, are shown on Figure 2. Concentrations of VC were as high as 792 :g/L (well USGS-5), and were also relatively high (683 :g/L) in the plume adjacent to the neighborhood (well USGS-10). In contrast, plume concentrations of VC in August, 2002, are shown on Figure 3. These results clearly show that the size of the plume has contracted significantly in the four years since treatment, and that concentrations of contaminants in the plume that remains have also decreased. For example, concentrations of VC in water produced from well USGS-5 decreased from 792 :g/L in 1998 to 43.5 :g/L in 2002. Similarly, in water produced from monitoring well USGS-10, VC concentrations decreased from 683 :g/L in 1998 to 30.1 :g/L in 2002. In 1998, all 15 monitoring wells had measurable concentrations of VC. By 2002, VC was below the detection level for 12 of 16 monitoring wells.

A more detailed evaluation of contaminant concentration changes in the plume after Fenton's Reagent treatment can be gained by considering water-chemistry trends at individual monitoring wells. For example, for monitoring well USGS-3, which is representative of the line

of monitoring wells closest to the contaminant source area (Fig. 1), concentrations of sulfate and chlorinated ethenes over time before and after Fenton's Reagent treatment are shown in Figure 4. Because iron sulfate is an important component of Fenton's Reagent, and because background concentrations of sulfate are relatively low at this site (0-10 mg/L), sulfate is a useful tracer for ground water that has been impacted by treatment. After treatment (January, 1999), concentrations of sulfate were observed to increase steadily for two years (Fig. 4A), and then, beginning in early 2001, decline. This shows a "pulse" of high-sulfate water, indicative of Fenton's Reagent, moved through the first line of monitoring wells soon after treatment. Concurrent with increasing concentrations of sulfate, concentrations of VC (Fig. 4A), trichloroethene (TCE), and cis-dichloroethene (cis-DCE) were observed to decline below measurable levels (Fig. 4B). These data clearly show that Fenton's Reagent treatment was effective in removing chlorinated ethenes from ground water, and that treated ground water moving downgradient from the treatment zone immediately began to shrink the plume.

Concentrations of sulfate and chlorinated ethenes in well KBA-13A (Fig. 1), which is approximately 50 meters downgradient of the first line of monitoring wells, shows a pattern consistent with the transport of Fenton's Reagent-treated water progressively moving downgradient over time. For more than a year, sulfate concentrations remained at background levels (~ 1 mg/L), and while concentrations of VC apparently decreased, they remained in the 20-60 :g/L range. In early 2000, sulfate concentrations began to rise rapidly, indicating the arrival of Fenton's Reagent-treated ground water. When sulfate concentrations peaked in mid-2001, concentrations of VC had decreased below detectable levels (Fig. 4A). Concentration trends of TCE and cis-DCE show a more complex pattern (Fig. 4B). When sulfate-bearing water

arrived at KBA-13A, concentrations of TCE appeared to increase over pre-injection levels. It wasn't until late in 2001 that concentrations of TCE began to decrease significantly. The pattern exhibited by cis-DCE is similar to that of VC, showing continual concentrations decreases after the arrival of sulfate-bearing treated water.

The second line of monitoring wells, located immediately downgradient of KBA-13A, also shows a time-dependent pattern of sulfate and chlorinated ethene concentration changes. At well USGS-5, concentrations of sulfate did not begin to increase until late 2001 (Fig. 6A). Vinyl chloride concentrations, however, began to decrease in 1999, long before evidence of treated ground-water arrived at well USGS-5. Concentrations of VC were approximately 60 :g/L when sulfate concentrations began to rise, and have declined since then. Concentrations of TCE were never measurable in water produced from USGS-5 due to the relatively efficient reductive dechlorination characteristic of this site (Chapelle and Bradley, 1998). Interestingly, however, concentrations of cis-DCE, which declined in the same manner as VC concentrations prior to arrival of treated water, actually began to increase when treated water reached well USGS-5 (Fig. 6B).

Concentration changes of chlorinated ethenes in the third line of monitoring wells are shown in Figures 7 and 8, and have different patterns than observed in the first two lines of monitoring wells. Well USGS-9 (Fig. 7) shows a trend of decreasing VC and cis-DCE concentrations, a trend observed in six of the seven downgradient monitoring wells. In the case of wells USGS-8, USGS-9, USGS-12, USGS-13, and USGS-14, concentrations of VC have decreased below the detection level, and concentrations of cis-DCE have decreased as well. The sole exception is well USGS-11 (Fig. 8), where concentrations of VC and cis-DCE have

increased since late 2000.

In contrast to the marked and systematic changes in chlorinated ethene concentrations over time in the plume, redox conditions in the plume have remained relatively unaltered over time. There is little difference in observed concentrations of redox-sensitive solutes in ground water produced from the monitoring wells, and these patterns can be illustrated by trends observed at well KBA-13A. The water was initially anoxic, and has remained so since Fenton's reagent injection (Fig. 9A). When the pulse of treated water arrived at KBA-13A in early 2000, concentrations of iron and sulfate increased (Fig. 9B). As the treated water moved through the well, concentrations of methane decreased rapidly (Fig. 9C). Concentrations of sulfide were initially low, showed a single very distinctive spike in January 2001 when the treated water arrived, and then returned to low concentrations. Most significantly, concentrations of dissolved hydrogen, while showing considerable variability, have remained between the 0.2 nM concentrations characteristic of Fe(III)-reducing conditions, and the 2 nM concentrations characteristic of sulfate-reducing conditions. This indicates a system in which redox conditions are poised between Fe(III)-reduction and sulfate-reduction, and that these conditions did not change when the pulse of treated water moved through the well. Similar patterns of redox-sensitive solutes, indicating relatively unchanged redox conditions over time, were observed in all of the monitoring wells.

Factors Affecting Plume Contraction

The results of this four-year monitoring effort clearly show that the plume of chlorinated ethenes has contracted significantly since Fenton's Reagent treatment (Figs. 2, 3). The immediate decrease in contaminant concentrations in the first line of monitoring wells (Fig. 4),

which is concomitant with increasing sulfate concentrations, reflects the destruction of chlorinated ethenes in ground water by Fenton's Reagent. Similarly, the decrease of VC concentrations associated with the arrival of treated ground water at KBA-11-13A can be attributed to Fenton's Reagent treatment. The more delayed concentration decreases of cis-DCE and TCE at well KBA-11-13A may indicate that Fenton's treatment was less effective for more oxidized chlorinated ethenes. Alternatively, it may reflect desorption and/or remobilization of cis-DCE and TCE from aquifer solids by Fenton's Reagent-treated water moving through the aquifer. Regardless of the origin of this delayed response, concentrations of cis-DCE and TCE had also declined relative to their starting point by August, 2002.

Interpretation of observed VC and cis-DCE concentration changes at well USGS-5 in the second line of monitoring wells is less straightforward. Concentrations of VC and cis-DCE began to decline immediately after Fenton's Reagent injection (Fig. 6) more than two years before sulfate concentrations indicated the arrival of treated water. Similarly, observed concentration trends in the third line of monitoring wells, USGS-9 (Fig. 7) and USGS-11 (Fig. 8), exhibit changes that cannot be due to Fenton's Reagent treatment, since high-sulfate ground water had not yet arrived. Specifically, concentrations of cis-DCE and VC have decreased below measurable levels at well USGS-9 (Fig. 7), whereas concentrations have increased at well USGS-11.

In the mid-1990's, prior to initiation of Fenton's Reagent treatment, a pump-and-treat system was installed at this site as an interim remediation measure. One of the pumping wells was located in the downgradient part of the site within five meters of well USGS-13. The effects of this pumping well were twofold: First, pumping tended to change directions of ground-water

flow, drawing the plume to the south. Secondly, the pumping tended to increase rates of ground-water flow away from the landfill toward the second and third lines of monitoring wells (Fig. 1). When pumping ceased in August of 1998, in preparation for Fenton's Reagent treatment, the flow system returned to pre-pumping conditions. This, in turn, decreased rates of ground-water flow away from the landfill, and tended to shift the plume slightly to the north. Because the natural attenuation capacity is a function of ground-water flow rates (Chapelle and Bradley, 1998), the decrease in ground-water flow rates would also tend to decrease concentrations of chlorinated ethenes reaching the downgradient wells. This, in turn, may explain the patterns of decreasing chlorinated ethene concentrations observed in wells USGS-5 (Fig. 6) and USGS-7 (Fig. 7). Similarly, the northward shift of the plume following pumping secession probably explains observed increases in chlorinated ethenes at well USGS-11 (Fig. 8), as well as contributing to concentration declines at well USGS-7 (Fig. 7).

In either case, the observed concentration declines in wells that Fenton's Reagent-treated ground water has not yet reached can be attributed to ongoing natural attenuation processes. A characteristic of this naturally anoxic aquifer is that sequential reductive dechlorination of PCE and TCE near the landfill, followed by oxidation of cis-DCE and VC downgradient, leads to highly efficient natural attenuation (Chapelle and Bradley, 1998). One unknown about Fenton's Reagent treatment was how it would affect these naturally efficient biodegradation processes. The monitoring data indicate that the Fenton's Reagent treatment has not measurably altered redox conditions downgradient of the treatment zone (Fig. 9), and that contaminant biotransformation processes and the resulting natural attenuation, have not rendered less effective (Fig. 5). In both the Fenton's Reagent-affected portion of the plume (Figs. 5, 6) and in

the portion of the plume unaffected by Fenton's Reagent (Fig. 7), much of the observed contaminant concentration decreases can be attributed to ongoing natural attenuation processes. These observations, in turn, suggest that Fenton's Reagent treatment has not decreased the natural attenuation capacity of this system.

Future Monitoring

While monitoring data clearly show that concentrations of chlorinated ethenes at this site have decreased dramatically, ground-water containing VC concentrations above regulatory limits is still present in parts of the plume. Future monitoring is needed to assess the continued effectiveness of the remedial strategy at this site. In particular, the time required for VC concentration limits in the downgradient line of wells to reach regulatory compliance is of particular interest. Quarterly monitoring of this site will continue during 2003. When this monitoring is completed, the data should be assessed to determine if a change from quarterly to semi-annual monitoring will adequately monitor the site.

CONCLUSIONS

Long-term monitoring data from site 11, Subase King's Bay, shows that the dual remedial strategy of Fenton's Reagent treatment and monitored natural attenuation has led to significant contraction of the contaminant plume over time. Concentrations of contaminants in the source area remain below the target of 100 µg/L, and concentrations of vinyl chloride have decreased as much as 10-fold in the plume since treatment. The contraction of the contaminant plume with associated decreases in contaminant concentrations can be attributed to (1) movement of Fenton's Reagent-treated ground water downgradient from the treatment zone, (2) the lack of change of ambient redox conditions since Fenton's Reagent treatment, and the continued efficiency of chlorinated ethene biotransformations processes at this site. This observed behavior, which could not be predicted a priori, indicates that the natural attenuation of chlorinated ethenes in the plume have not been diminished by Fenton's Reagent treatment, and (3) cessation of the interim pump-and-treat remediation system, which altered directions and rates of ground-water flow, leading to less efficient natural attenuation at this site. When pump-and-treat system was discontinued, the net result was an increase in the natural attenuation capacity of the system, and associated decreases in contaminant concentrations in the downgradient part of the plume. The results show that DNAPL-removal strategies can be effective for site remediation when associated natural attenuation processes in a ground-water system remain active.

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Table 1.--Redox parameters for NAS Kings Bay 8/14/01.

Sample	DO (mg/L)	Fe(II) (mg/L)	HS (mg/L)	pH (units)	H ₂ (nM)	CO (nM)	DIC (mg/L)	CH ₄ (mg/L)	Cl ⁻ (mg/L)	NO ₃ ⁻ (mg/L)	SO ₄ ⁼ (mg/L)	Temp (°C)
KBA-11-34	0.0	2.13	0.182	3.82	5.0	0.56	605	1.1	8.3	bd	508	25.7
USGS-1	0.0	43	0.005	4.12	--	---	514	0.4	9.3	bd	296	24.0
USGS-2	0.0	165	0.013	3.88	0.25	4.23	549	1.0	9.5	bd	2105	23.7
USGS-3	0.0	167	0.007	4.17	1.13	2.92	524	0.7	8.9	bd	1731	24.5
USGS-15	0.0	156	0.011	3.86	--	--	521	0.7	8.8	bd	1610	24.3
KBA-11-13A	0.0	191	0.060	4.74	0.56	5.33	554	1.5	9.5	bd	1465	24.1
USGS-4	0.0	0.74	0.485	5.92	---	---	584	5.4	9.8	bd	11.8	24.3
USGS-5	0.0	0.10	0.582	5.83	1.77	3.09	599	6.1	9.8	bd	0.6	24.7
USGS-6	0.0	0.16	0.657	5.79	1.26	3.69	564	4.1	7.8	bd	3.3	25.6
USGS-7	0.0	0.05	0.579	5.90	---	----	570	5.0	8.7	bd	1.6	24.9
USGS-8	0.0	0.04	5.025	5.76	---	----	532	2.5	10.7	bd	6.5	24.2
USGS-9	0.0	0.01	0.261	5.62	---	---	478	1.4	9.2	bd	5.8	24.5
USGS-10	0.0	0.04	0.640	5.66	0.50	4.28	550	4.7	18.1	bd	7.2	25.0
USGS-11	0.0	0.08	0.566	5.58	0.51	2.56	590	4.8	16.9	bd	6.0	24.5
USGS-12	0.0	0.02	0.328	5.52	0.24	3.31	523	3.3	10.5	bd	11.2	25.0
USGS-13	0.1	0.22	0.107	5.18	---	--	169	0.6	3.2	bd	20.7	24.6
USGS-13R	0.1	0.23	0.101	---	----	---	157	0.6	3.1	bd	21.1	---
USGS-14	0.0	0.38	0.214	5.90	---	---	155	0.9	5.5	bd	9.4	25.6
KBA-11-37	0.0	0.32	0.400	5.88	---	----	547	3.6	12.7	bd	95.1	25.4

Table 2.--Redox parameters for NAS Kings Bay 1-11-02.

Sample	DO (mg/L)	Fe(II) (mg/L)	HS (mg/L)	pH (units)	H ₂ (nM)	CO (nM)	DIC (mg/L)	CH ₄ (mg/L)	Cl ⁻ (mg/L)	Br ⁻ (mg/L)	SO ₄ ⁼ (mg/L)	Temp (°C)
KBA-11-34	0.0	1.64	0.003	5.56	5.0	0.56	365	0.0	6.41	0.0	467	21.8
USGS-1	0.0	43	0.005	4.12	---	---						21.5
USGS-2	0.0	59.8	0.015	6.49	0.2	1.74	644	0.1	10.49	0.0	1,688	21.6
USGS-3	0.0	159	0.080	6.36	0.41	1.60	657	0.1	7.18	0.0	1,201	24.5
USGS-15	0.0	156	0.011	3.86	--	--						21.8
KBA-11-13A	0.0	64.5	0.069	6.97	0.35	3.71	645	0.7	8.20	0.0	989	21.7
USGS-4	0.0	0.74	0.485	5.92	---	---						24.3
USGS-5	0.20	0.37	1.575	8.03	1.27	4.55	734	4.6	10.07	0.0	39.37	21.8
USGS-6	0.0	0.73	1.525	5.28	1.32	2.83	711	2.6	7.7	0.0	216	22.0
USGS-7	0.0	0.05	0.579	5.90	---	---						21.8
USGS-8	0.0	0.04	5.025	5.76	---	---						21.1
USGS-9	0.0	0.01	0.261	5.62	---	---						21.5
USGS-10	0.1	0.06	1.125	5.29	0.51	1.44	665	4.4	1.69	0.0	0.67	23.1
USGS-11	0.0	0.08	0.566	5.27	0.51	1.53	706	3.8	13.47	0.0	9.21	23.3
USGS-12	0.0	0.02	0.328	5.52	---	---						22.0
USGS-13	0.1	0.22	0.107	5.18	---	--						21.1
USGS-13R	0.1	0.23	0.101	---	---	---						---
USGS-14	0.0	0.38	0.214	5.90	---	---						21.8
KBA-11-37	0.0	0.27	0.651	4.99	---	---	653	2.0	11.75	0.0	53.67	22.5

Table 3.--Redox parameters for NAS Kings Bay 4-04-02.

Sample	DO (mg/L)	Fe(II) (mg/L)	HS (mg/L)	pH (units)	H ₂ (nM)	CO (nM)	DIC (mg/L)	CH ₄ (mg/L)	Turb (ntu)	Cond (:S/cm)	SO ₄ ⁼ (mg/L)	Temp (°C)
KBA-11-34	1.0	0.37	0.008	---	---	---	217	0.4	11.2	987	486	24.3
USGS-1	0.00	25.25	0.255	---	---	---	511	0.4	2.9	510	195	21.9
USGS-2	0.00	160	0.016	---	0.23	1.21	571	0.5	0.9	1765	1462	21.7
USGS-3	0.00	298	0.015	---	0.11	1.12	538.9	0.6	10.2	1269	838	21.6
USGS-15	0.00	63.3	0.042	---	---	---	541	0.5	1.7	1161	787	21.7
KBA-11-13A	0.00	65.5	0.099	---	0.26	---	574	0.5	8.5	1422	835	21.7
USGS-4	---	0.08	0.467	---	---	---	604	6.5	4.8	453	22.8	21.9
USGS-5	0.00	0.24	0.700	---	1.43	2.51	640	4.4	18.2	524	61.1	21.9
USGS-6	0.00	1.05	0.725	---	0.24	3.69	645.8	3.2	9.3	853	265	21.8
USGS-7	0.00	0.49	2.20	---	---	---	633	5.5	6.1	552	4.9	21.6
USGS-8	0.00	0.09	5.25	---	---	---	564	2.5	14.8	335	6.7	20.2
USGS-9	0.00	0.08	0.35	---	---	---	469	0.7	8.0	219	7.2	21.2
USGS-10	0.00	0.09	0.425	---	0.28	1.69	585	5.1	5.4	277	4.7	22.2
USGS-11	0.00	0.04	0.275	---	0.67	2.57	593	3.8	2.7	206	10.1	21.9
USGS-12	0.00	0.02	0.175	---	---	---	500	2.8	7.9	220	8.9	21.6
USGS-13	0.00	0.18	1.25	---	---	---	167	0.5	3.5	195	20.0	21.4
USGS-14	0.00	1.25	0.55	---	---	---	590	5.9	8.7	193	14.1	20.5
KBA-11-37	0.00	0.4	0.600	---	---	---	568	3.0	0.9	530	89.4	23.3

Table 4.--Redox parameters for NAS Kings Bay 8-22-02.

Sample	DO (mg/L)	Fe(II) (mg/L)	HS (mg/L)	pH (units)	H ₂ (nM)	CO (nM)	DIC (mg/L)	CH ₄ (mg/L)	Turb (ntu)	Cond (:S/cm)	SO ₄ ⁼ (mg/L)	Temp (°C)
KBA-11-34	0.0	51.5	0.300	3.23	0.36	3.78	537	0.7	2.7	642	302	28.5
USGS-1	0.00	20.8	0.466	3.97	---	---	548	0.4	1.7	511	181	19.0
USGS-2	0.00	64	0.05	3.36	---	---	624	0.6	1.5	12.65	944	19.0
USGS-3	0.00	69.8	0.054	3.30	0.64	1.20	563	1.4	10.5	719	532	19.7
USGS-15	0.00	1.98	0.379	3.25	---	---	534	0.7	6.8	756	428	25.8
KBA-11-13A	0.00	1.60	0.188	4.18	0.60	1.73	603	1.0	5.7	984	711	26.8
USGS-4	0.00	0.05	0.650	5.05	---	---	601	5.2	19.3	461	8.94	26.2
USGS-5	0.00	0.30	1.325	5.49	1.65	1.65	691	3.9	19.2	600	105	25.8
USGS-6	0.00	0.86	1.175	4.64	1.43	1.18	643	3.1	5.6	550	303	26.2
USGS-7	0.00	0.96	0.672	3.70	---	---	675	4.1	5.9	812	245	18.9
USGS-8	0.00	0.07	0.613	5.30	---	---	570	2.9	1.82	287	6.6	16.3
USGS-9	0.00	0.08	0.318	5.52	---	---	499	1.0	3.61	224	7.86	23.4
USGS-10	0.00	0.26	1.025	5.07	1.40	1.10	602	4.3	5.59	256	3.3	16.6
USGS-11	0.00	0.05	0.506	5.56	0.86	0.63	601	3.7	2.71	240	10.4	23.8
USGS-12	0.00	0.01	0.348	6.24	---	---	505	2.0	5.72	1965	7.43	24.4
USGS-13	0.00	0.13	0.043	5.91	---	---	172	0.6	1.7	92.1	18.5	17.8
USGS-14	0.05	0.11	0.155	5.70	---	---	581	5.1	7.4	145	14.3	18.3
KBA-11-37	0.00	0.34	0.598	5.78	---	---	562	2.7	1.2	431	57.4	19.0

Table 5.-Chlorinated ethenes at Kings Bay, August 14, 2001.

Well no	PCE	TCE	cis-DCE	VC
KBA-11-34	43.1	<5	<5	<5
USGS-1	<5	<5	<5	<5
USGS-2	8.6	6.4	7.1	<5
USGS-3	4.6	<5	16	<5
USGS-15	26.3	<5	<5	<5
KBA-11-13A	<5	35.7	68.1	<5
USGS-4	<5	8.5	276	108
USGS-5	<5	<5	22.5	62.9
USGS-6	<5	<5	13.0	22.6
USGS-7	<5	<5	6.5	7.2
USGS-8	<5	<5	<5	<5
USGS-9	<5	<5	<5	<5
USGS-10	<5	<5	27.3	26.5
USGS-11	<5	<5	144	50.7
USGS-12	<5	<5	66.6	16.7
USGS-13	<5	<5	7.6	<5
USGS-14	<5	<5	<5	<5
KBA-11-37	<5	<5	15.6	<5

Table 6.-Chlorinated ethenes at Kings Bay, January 9, 2002.

well no	PCE	TCE	cis-DCE	VC
KBA-11-34	35.4	<5	<5	<5
USGS-1	<5	<5	<5	<5
USGS-2	12.4	<5	<5	<5
USGS-3	6.4	<5	<5	<5
USGS-15	17.3	<5	<5	<5
KBA-11-13A	<5	16.0	31.8	<5
USGS-4	<5	9.2	298	126
USGS-5	<5	<5	18.0	59.3
USGS-6	<5	<5	12.4	6.2
USGS-7	<5	<5	7.5	<5
USGS-8	7.0	<5	<5	<5
USGS-9	<5	<5	<5	<5
USGS-10	<5	<5	27.6	29.4
USGS-10R	<5	<5	---	39.0
USGS-11	<5	<5	111	50.7
USGS-12	<5	<5	18.9	6.9
USGS-13	<5	<5	<5	<5
USGS-14	<5	<5	<5	<5
KBA-11-37	<5	<5	5.9	<5

Table 7.—Chlorinated ethenes at Kings Bay, March 5, 2002.

well no	PCE	TCE	cis-DCE	VC
KBA-11-34	34.9	<5	<5	<5
USGS-1	<5	<5	<5	<5
USGS-2	11.9	<5	<5	<5
USGS-3	21.0	<5	<5	<5
USGS-15	19.0	<5	<5	<5
KBA-11-13A	<5	13.2	25.1	<5
USGS-4	<5	12.2	394	154
USGS-5	<5	<5	25.9	65.4
USGS-6	<5	<5	17.0	<5
USGS-7	<5	<5	10.2	<5
USGS-8	<5	<5	<5	<5
USGS-9	<5	<5	<5	<5
USGS-10	<5	<5	33.6	33.6
USGS-11	<5	<5	95.2	51.3
USGS-12	<5	<5	71.3	18.1
USGS-13	<5	<5	<5	<5
USGS-14	<5	<5	5.3	<5
USGS-14R	<5	<5	<5	<5
KBA-11-37	<5	<5	5.9	<5

Table 8.—Chlorinated ethenes at Kings Bay, August 22, 2002.

well no	PCE	TCE	cis-DCE	VC
KBA-11-34	79.7	5.6	<5	<5
KBA-11-34R	71.7	5.2	<5	<5
USGS-1	<5	7.7	<5	<5
USGS-2	7.5	<5	<5	<5
USGS-3	28.3	<5	<5	<5
USGS-15	14.6	<5	<5	<5
KBA-11-13A	<5	13.2	20.3	<5
USGS-4	<5	13.9	483	188
USGS-5	<5	<5	36.4	43.5
USGS-6	<5	<5	38.7	<5
USGS-7	<5	<5	41.6	<5
USGS-8	<5	<5	5.3	<5
USGS-9	<5	<5	<5	<5
USGS-10	<5	<5	49.3	30.1
USGS-11	<5	<5	107	47.6
USGS-12	<5	<5	34.4	<5
USGS-13	<5	<5	<5	<5
USGS-14	<5	<5	<5	<5
KBA-11-37	5.9	<5	<5	<5

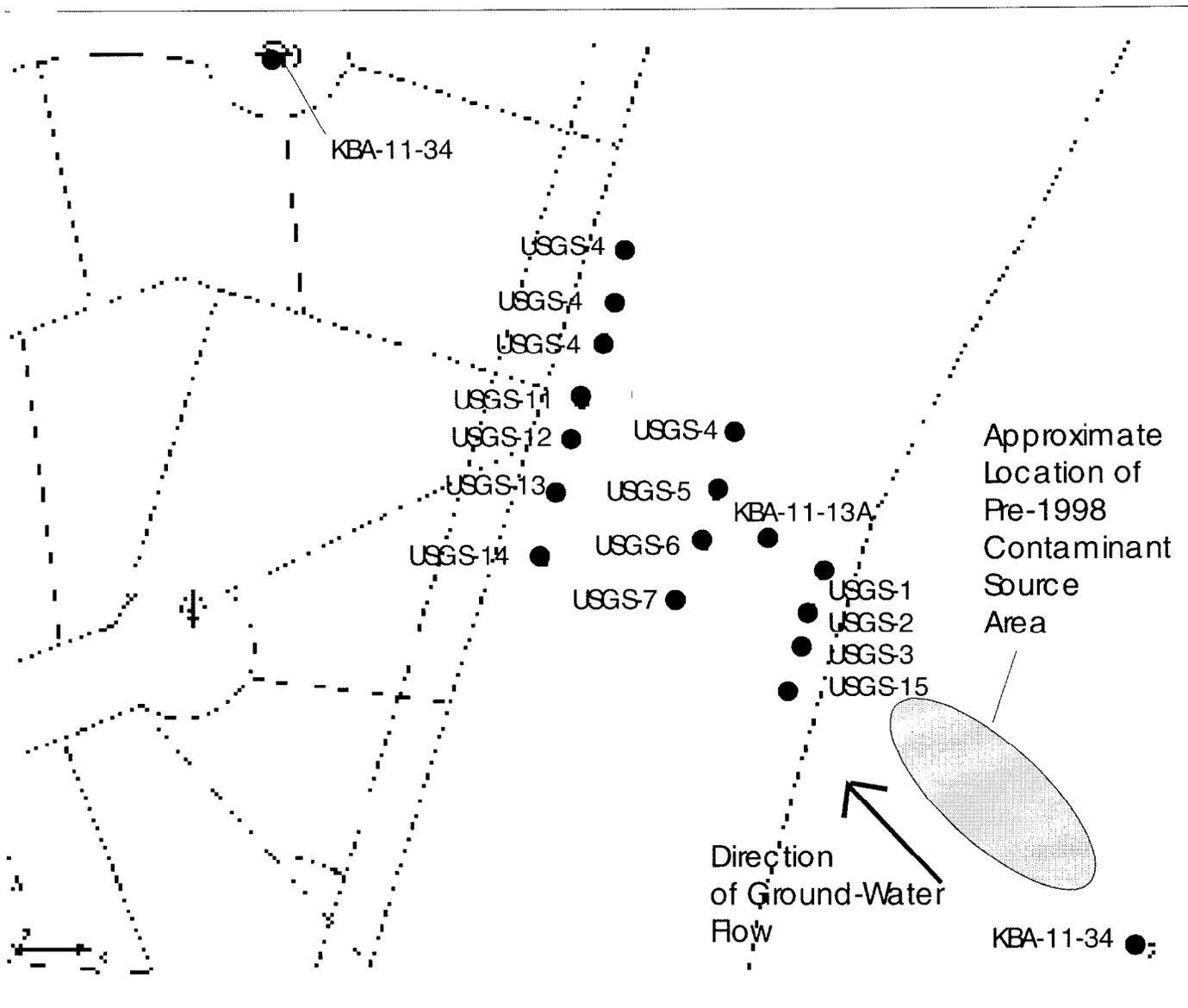


Figure 1.-Locations of USGS monitoring wells relative to the contaminant source area, Old Camden County Landfill, Kings Bay, Georgia.

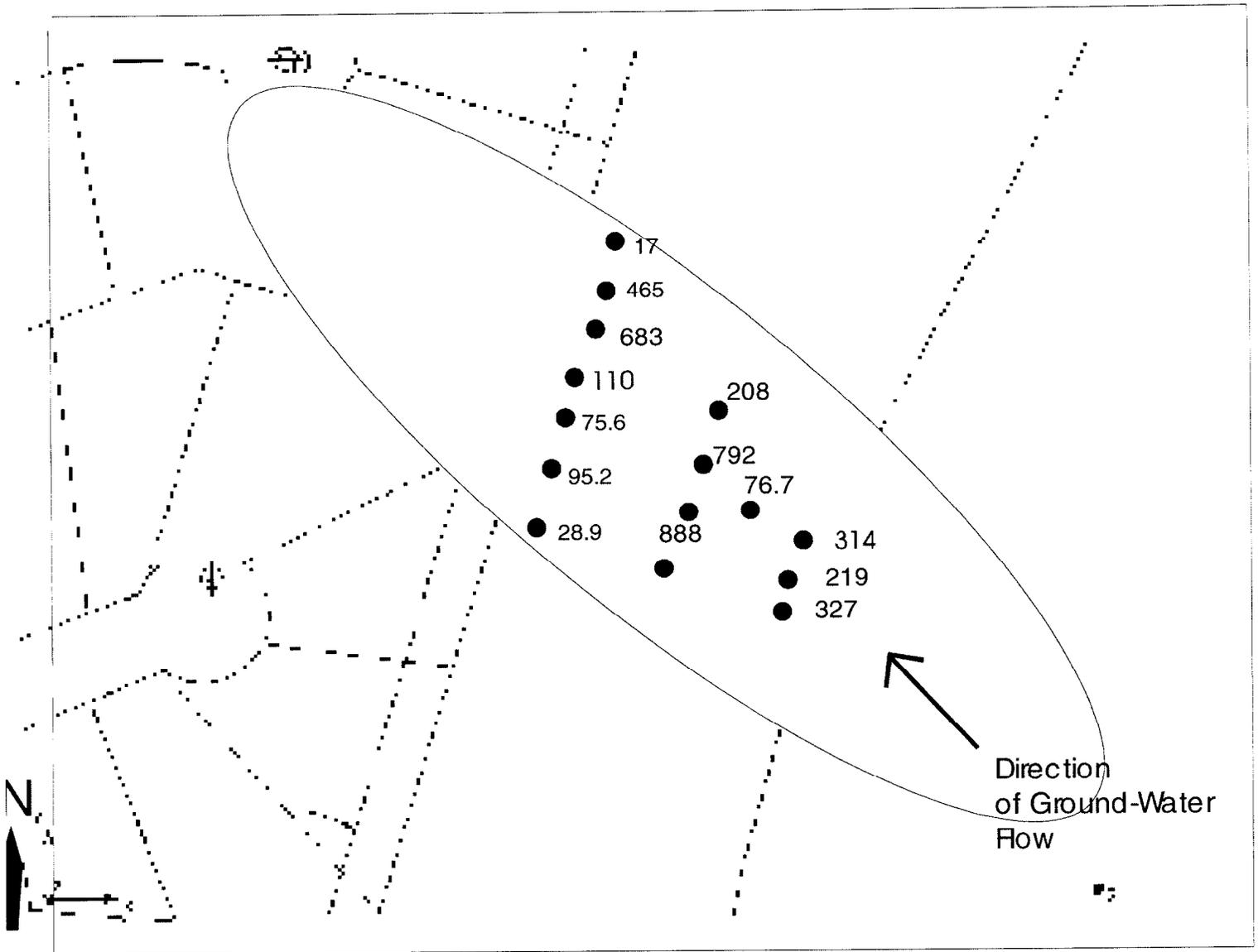


Figure 2.-Concentrations of vinyl chloride, August, 1998, Old Camden County Landfill, Kings Bay, Georgia, prior to in-situ oxidation..

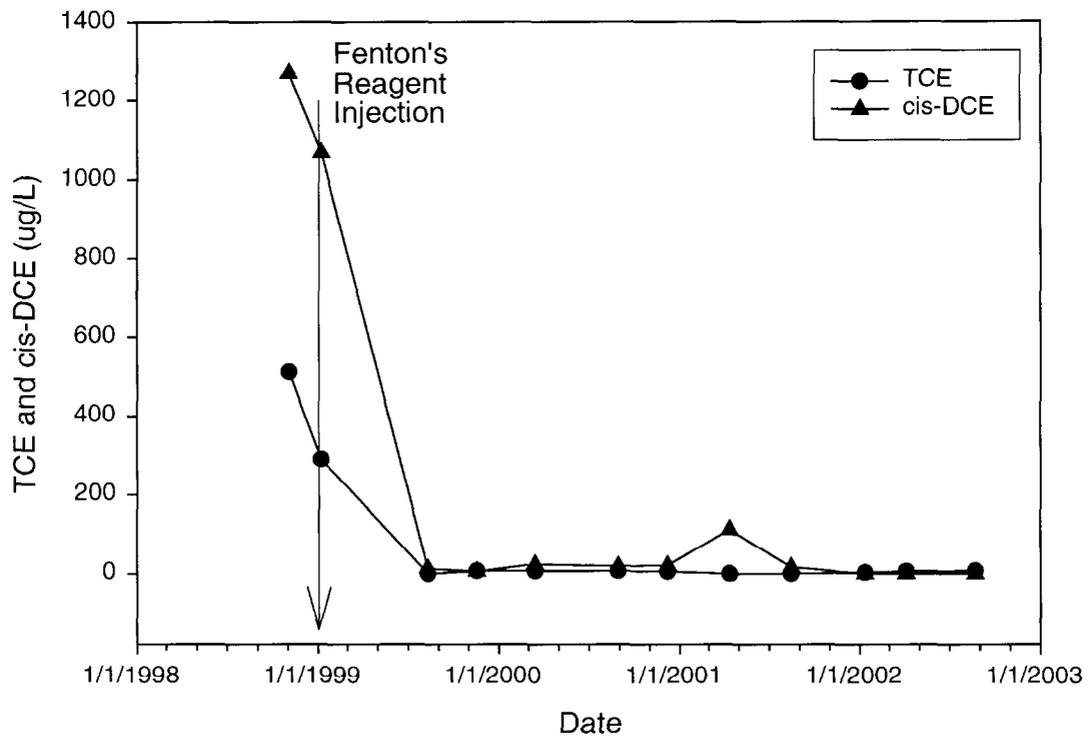
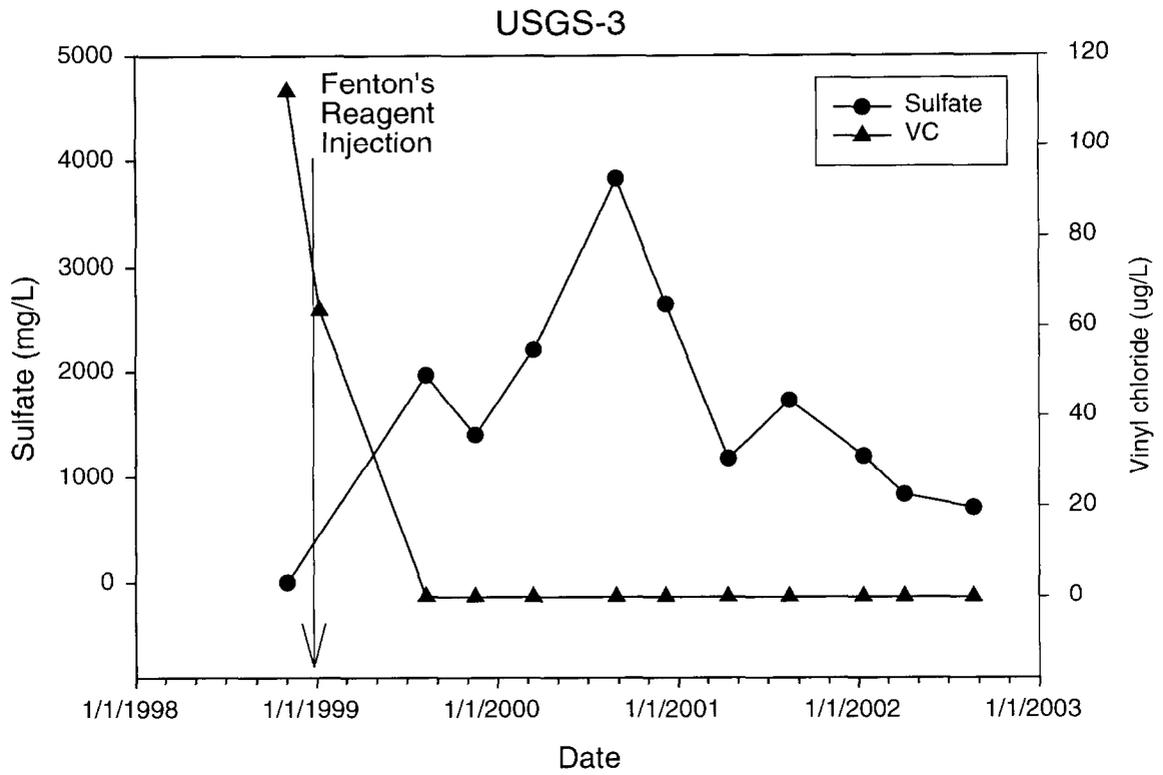


Figure 4--. Concentrations of sulfate and chlorinated ethenes versus time at well USGS-3 following in-situ oxidation.

KBA-11-13A

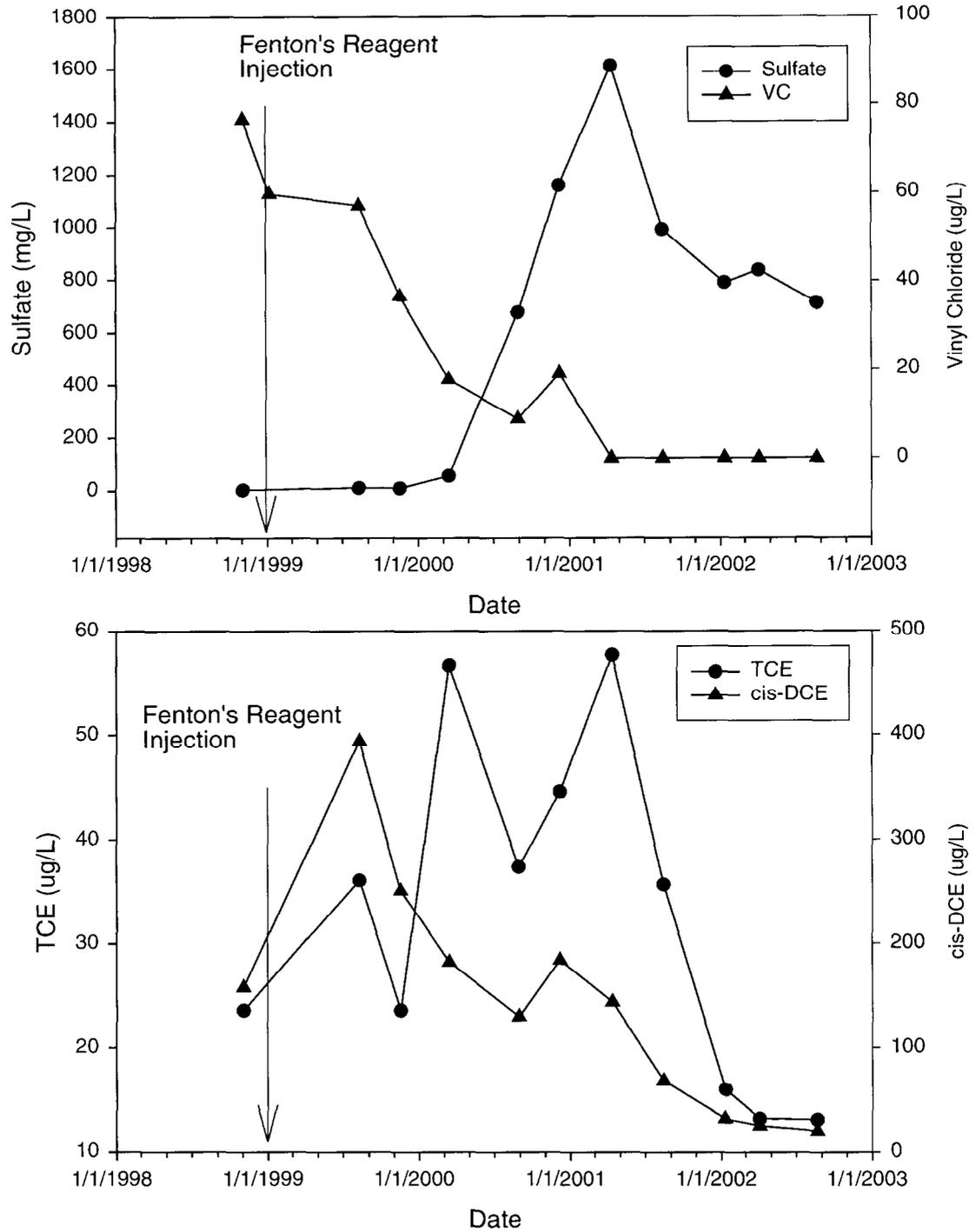


Figure 5--. Concentrations of sulfate and chlorinated ethenes versus time at well KBA-13A following in-situ oxidation.

USGS-5

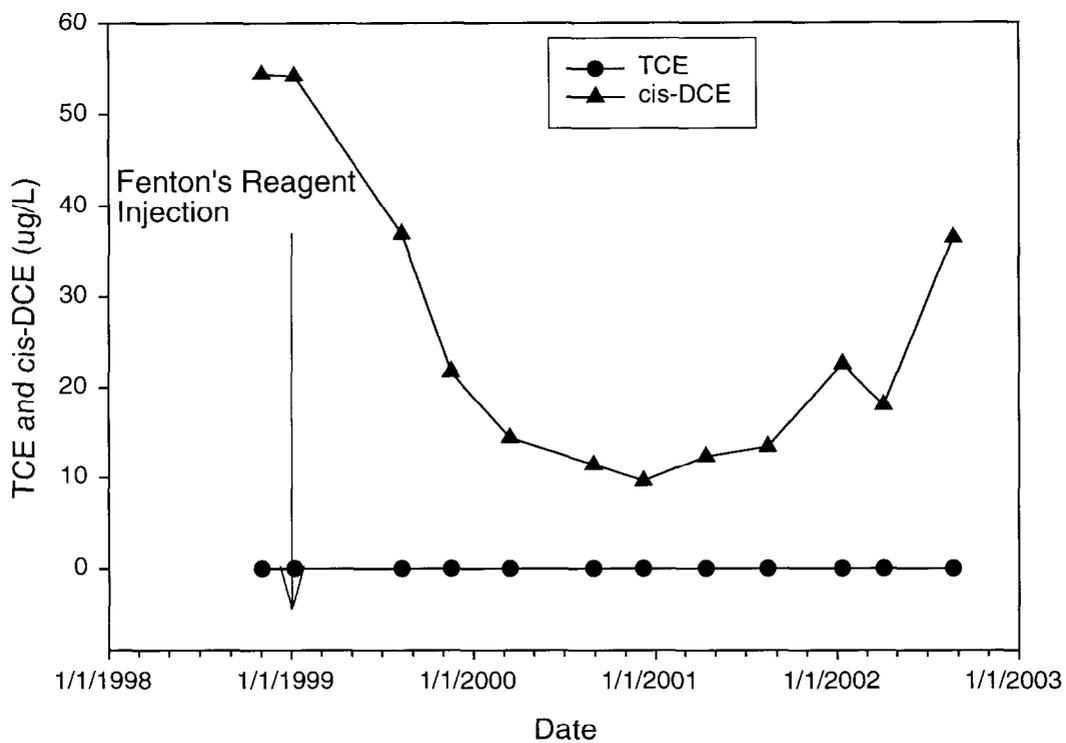
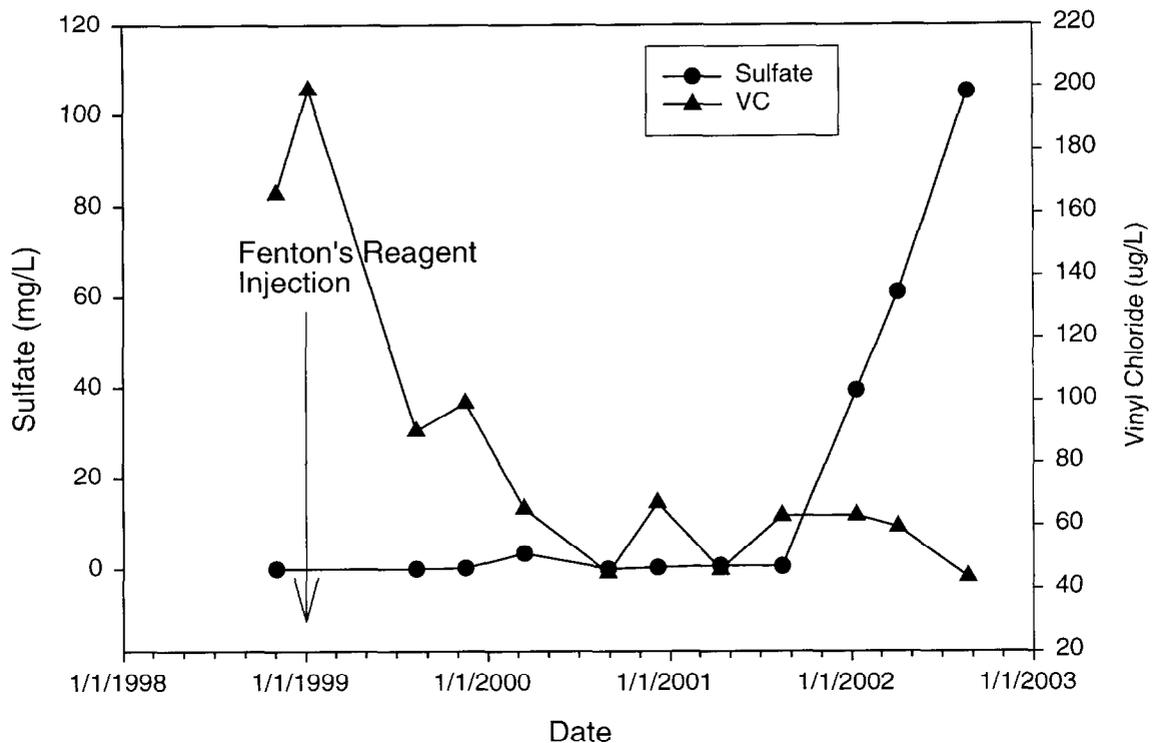


Figure 6--. Concentrations of sulfate and chlorinated ethenes versus time at well USGS-5 following in-situ oxidation.

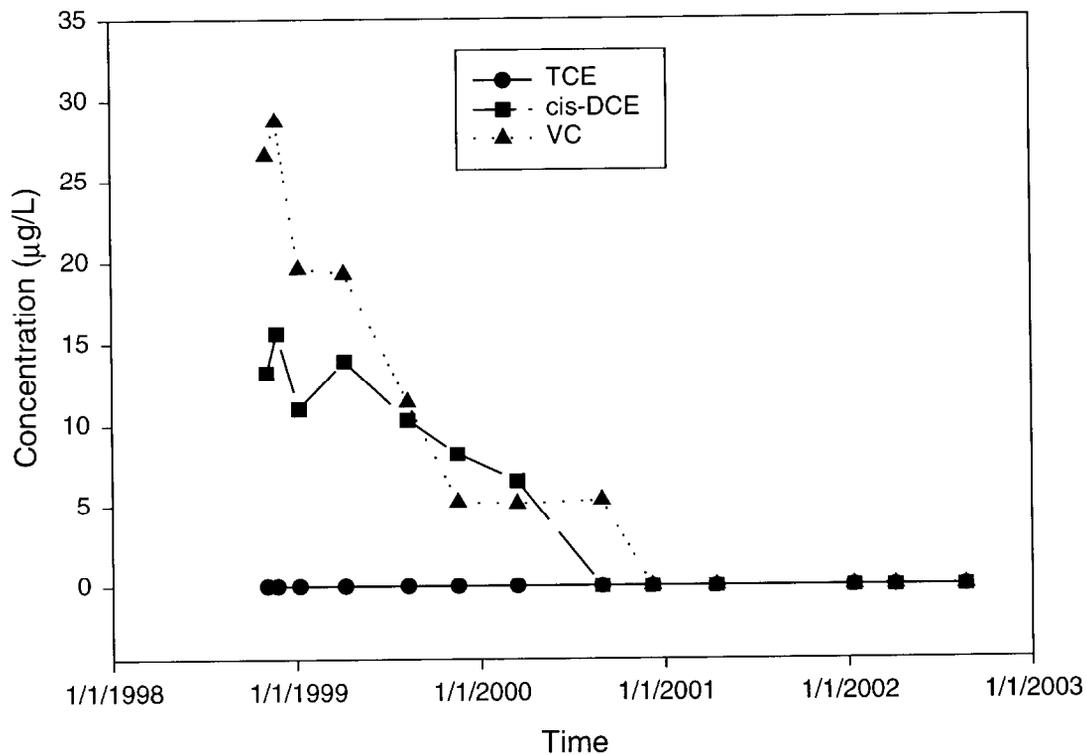


Figure 7.--Changes in concentrations of chlorinated ethenes versus time at well USGS-9 following in-situ oxidation.

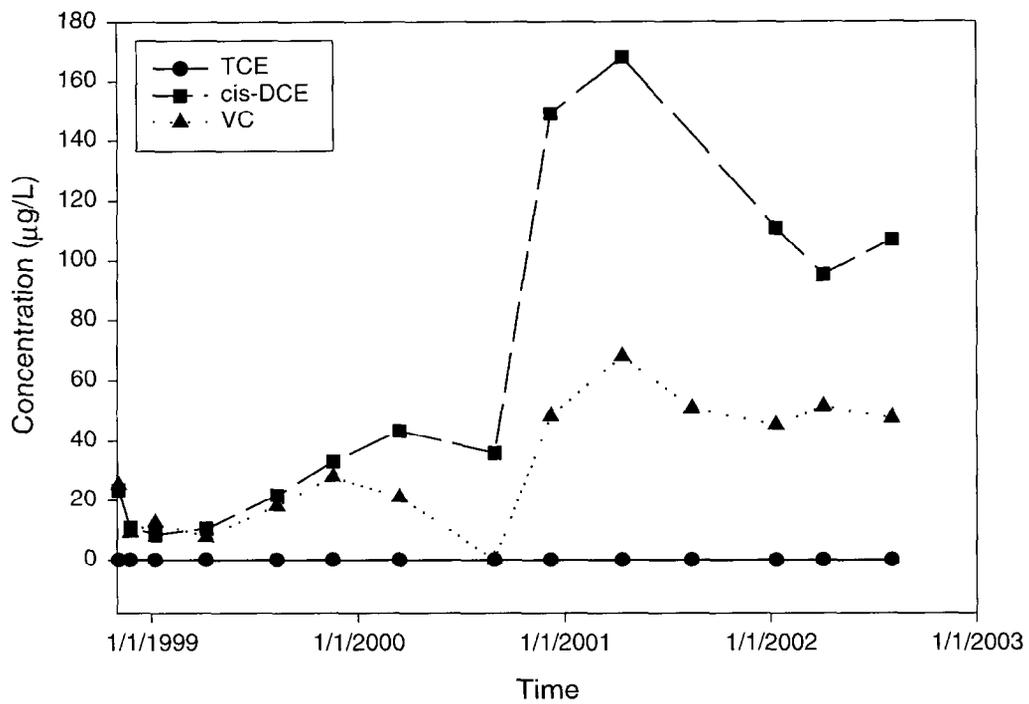


Figure 8.--Concentrations of chlorinated ethenes versus time at well USGS-9 following in-situ oxidation.

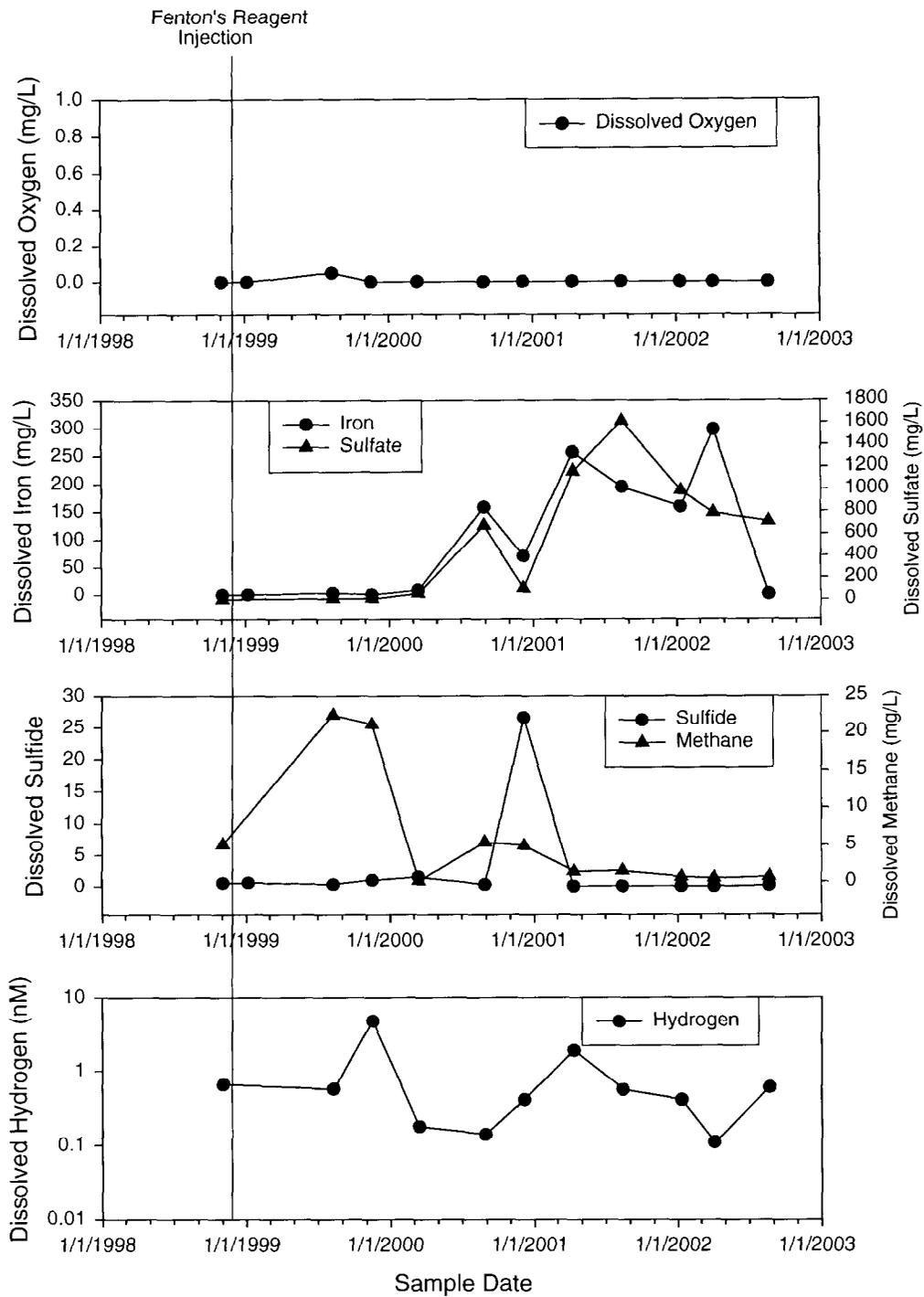


Figure 9.--Concentrations of dissolved redox-sensitive parameters at well KBA-11-13A versus time following in-situ oxidation.