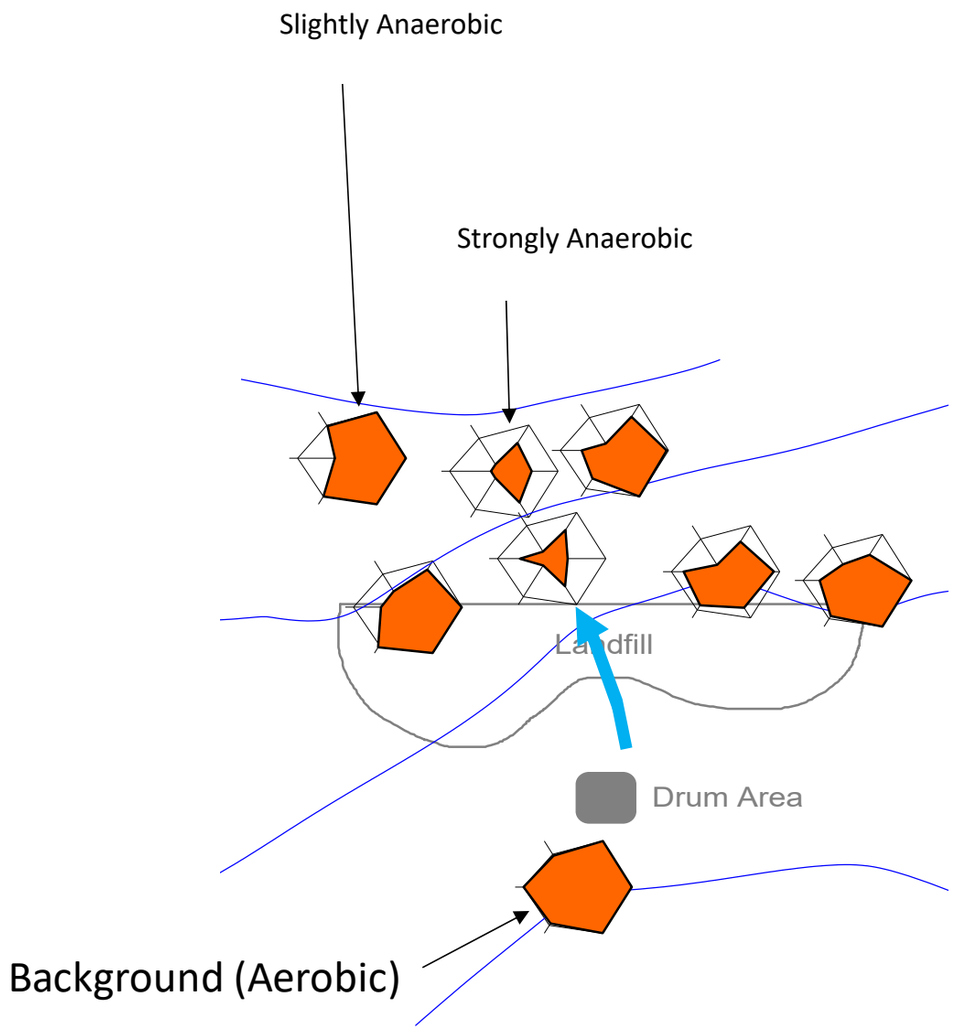
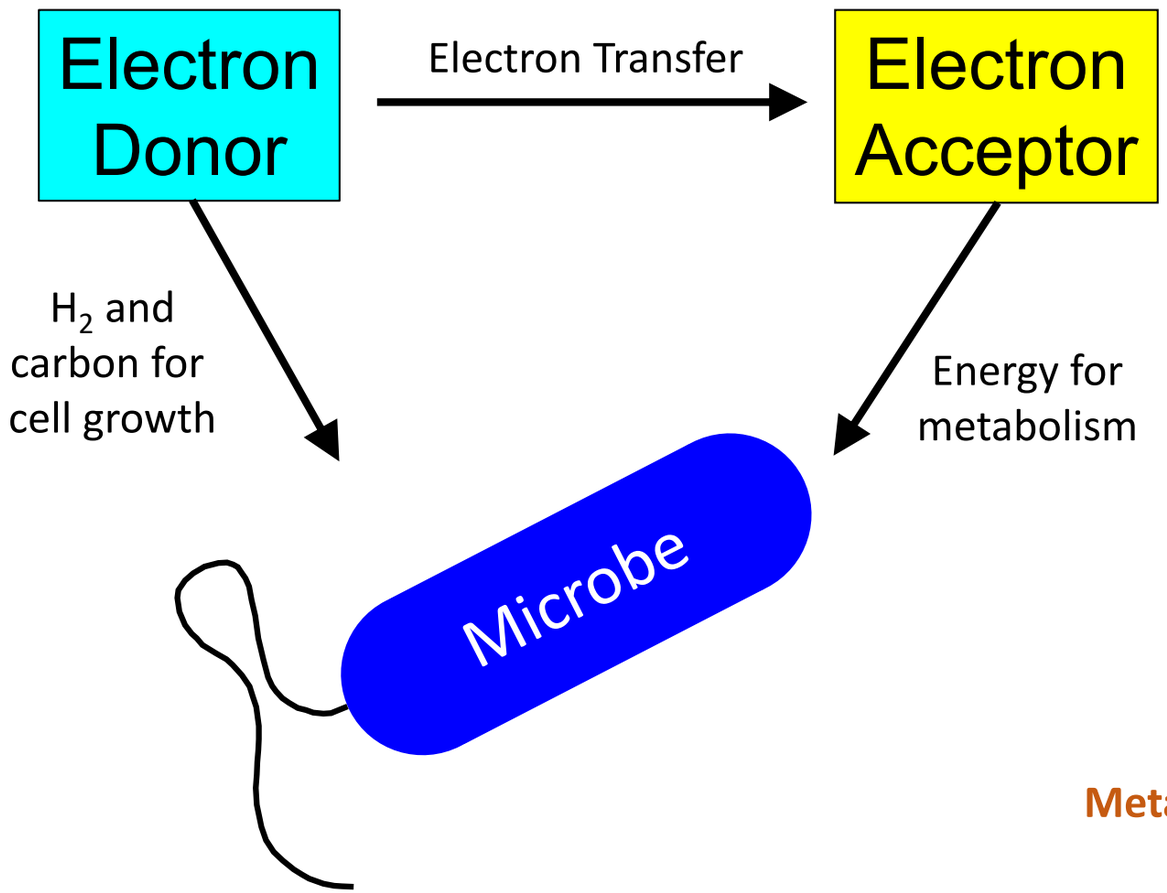
Visualizing Biodegradation Zones

By Grant R. Carey, Ph.D.

Porewater Solutions
Expertise • Experience • Innovation



Biogeochemical Processes

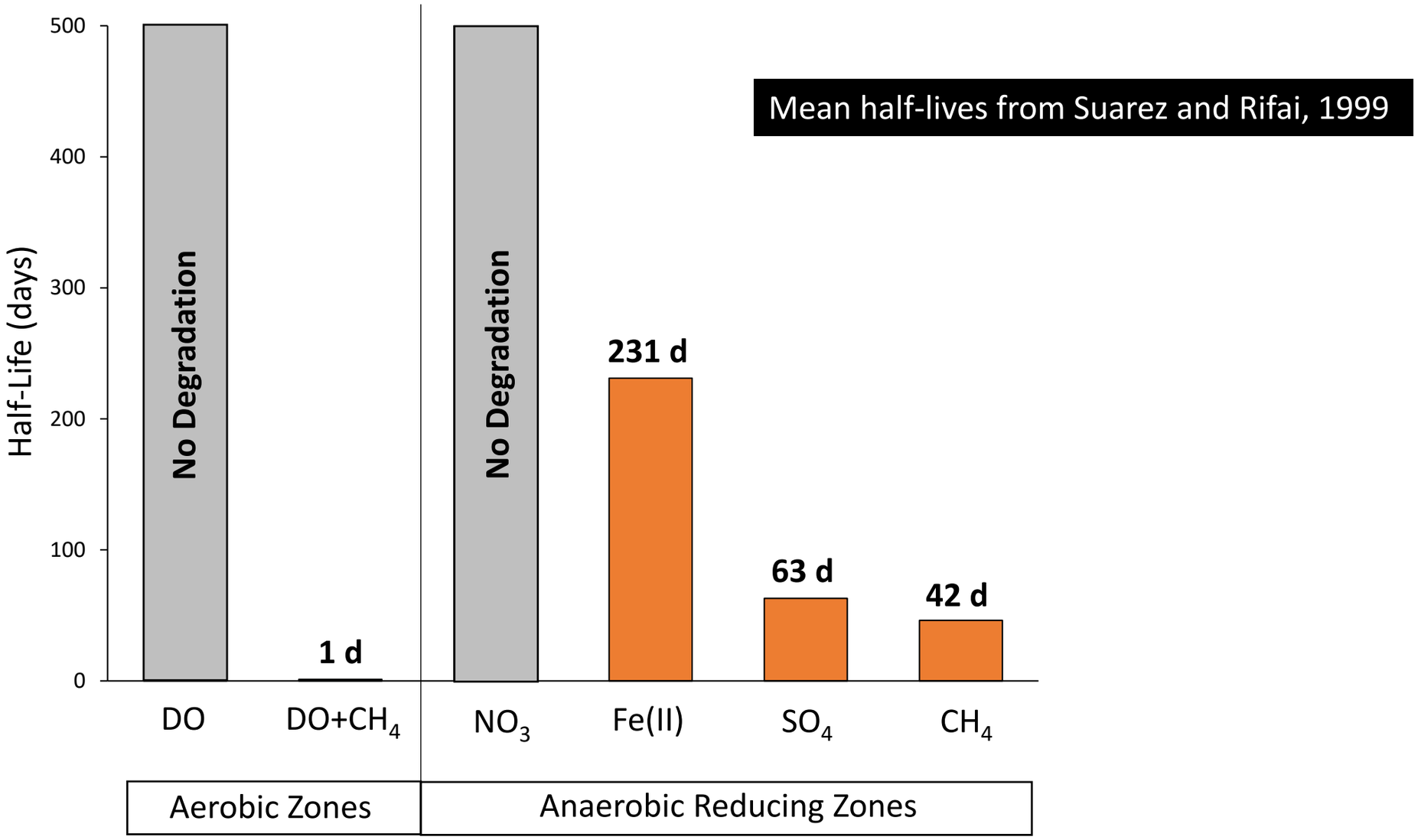


Inorganic Electron Acceptors:

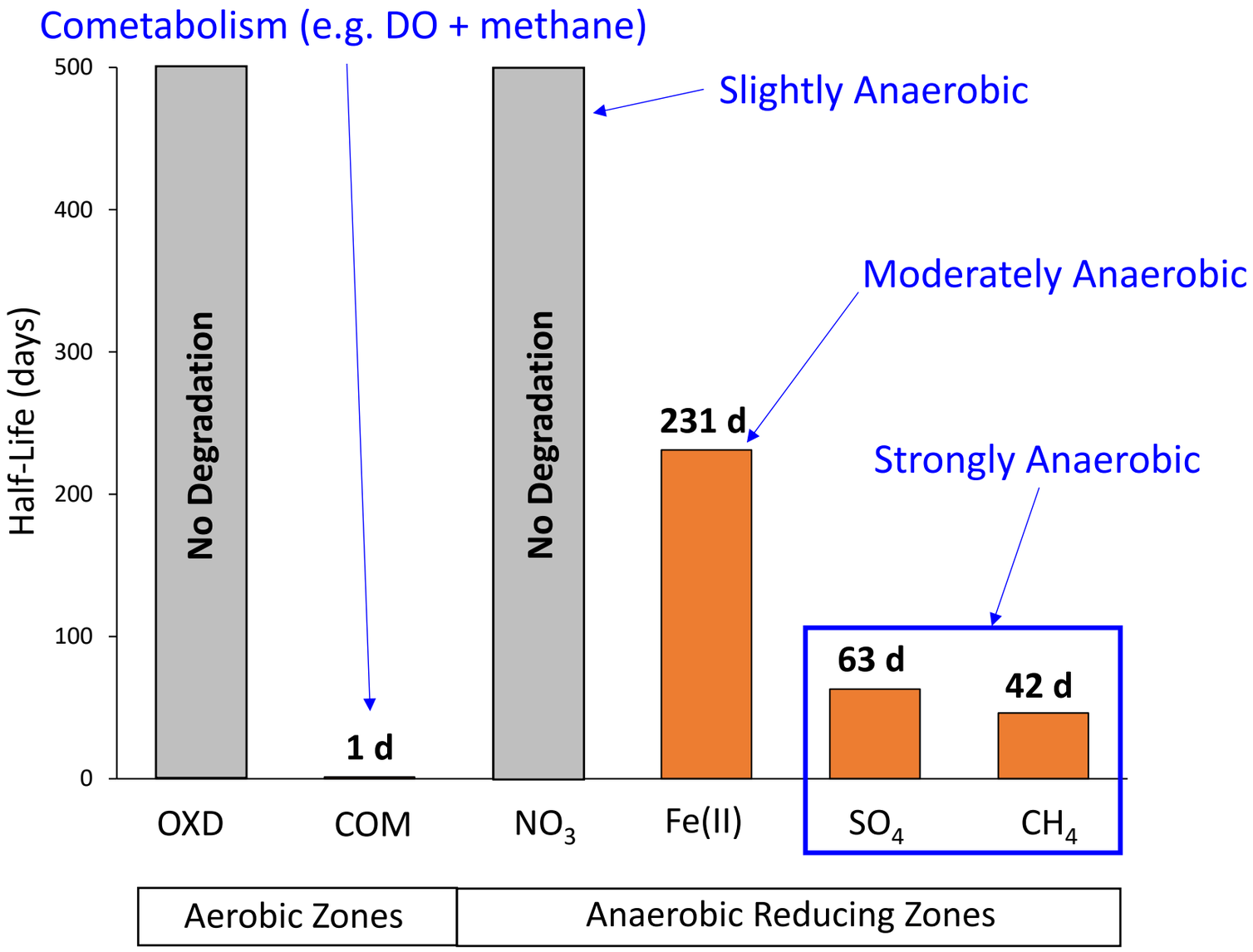
- O_2
- NO_3
- $Mn_{(s)} \rightarrow Mn^{2+}$
- $Fe_{(s)} \rightarrow Fe^{2+}$
- SO_4
- $CO_2 \rightarrow CH_4$

Metabolic Byproducts

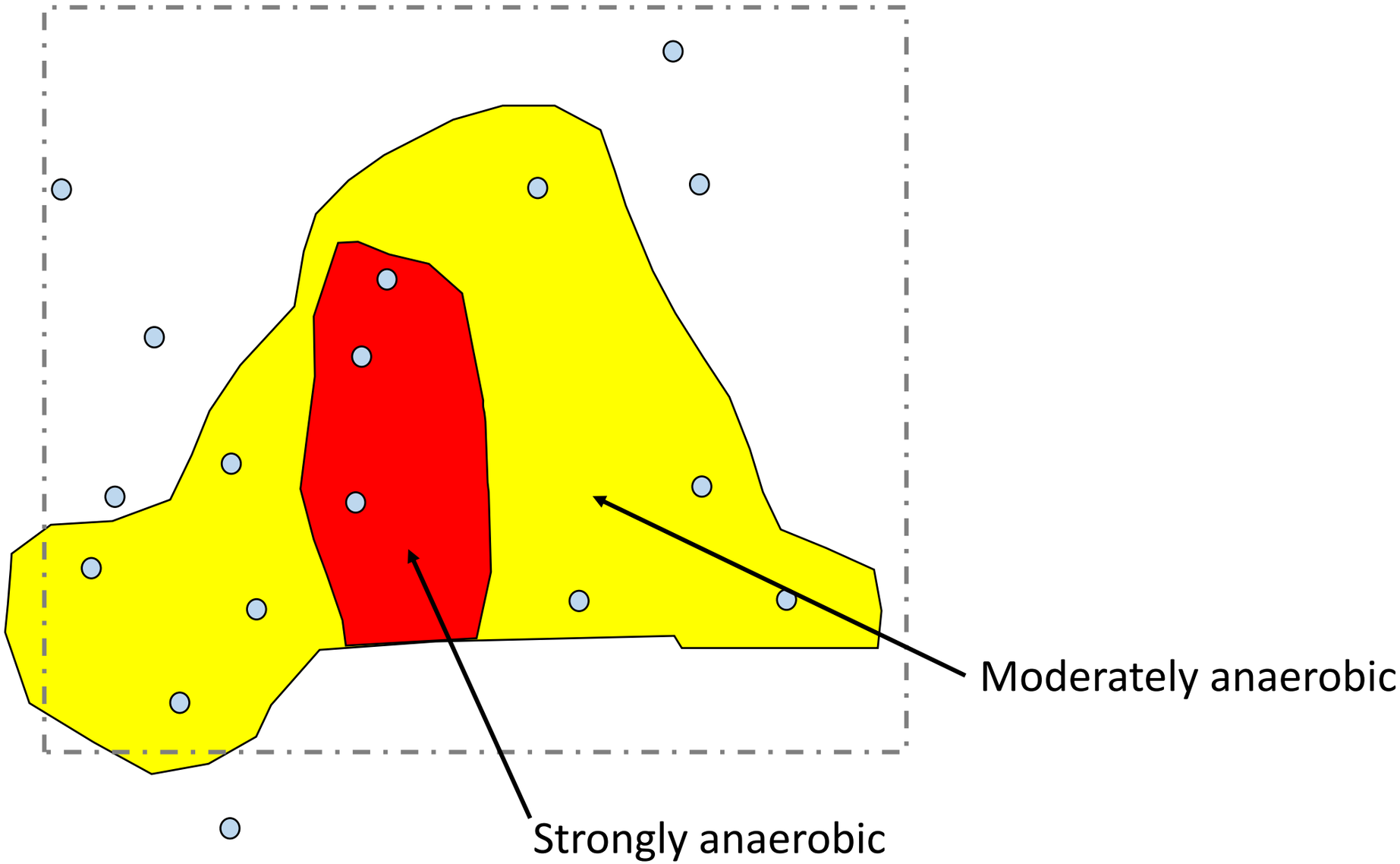
TCE Degradation by Redox Zone



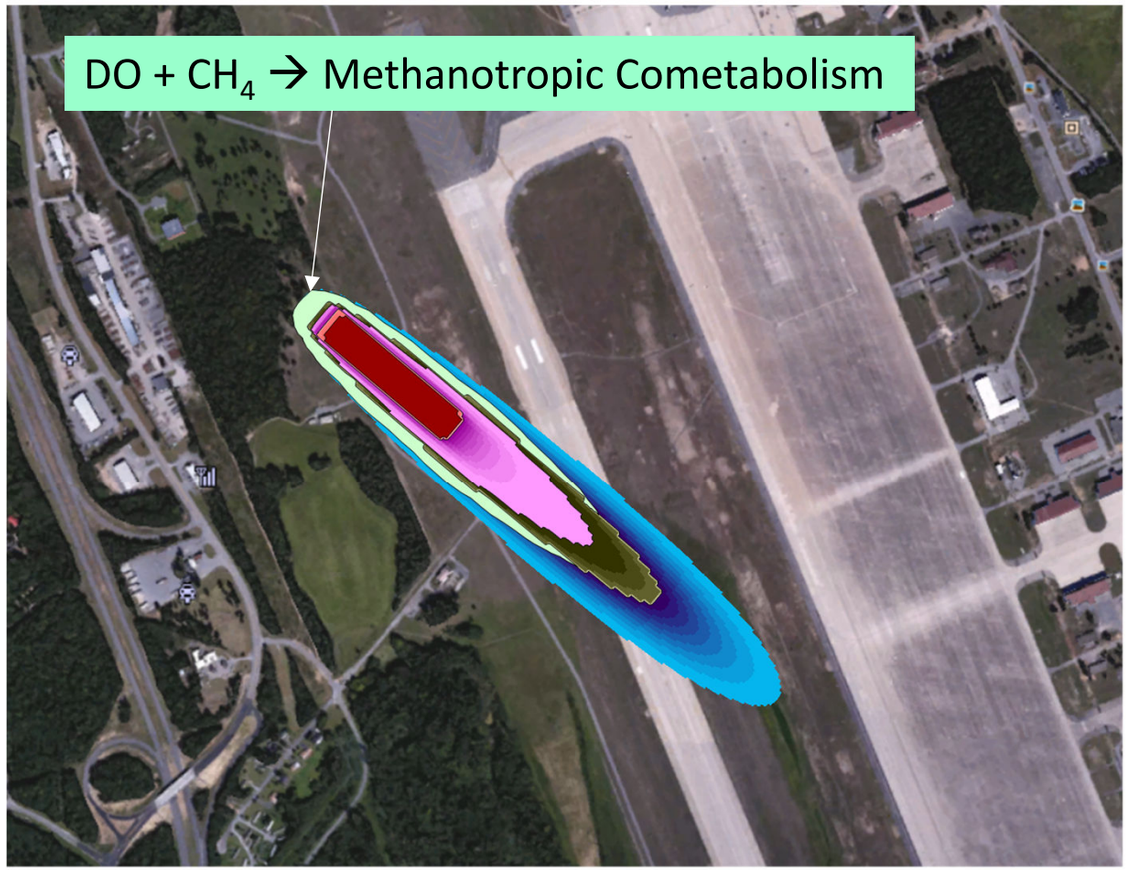
TCE Degradation by Redox Zone



Example of Redox Zone Delineation



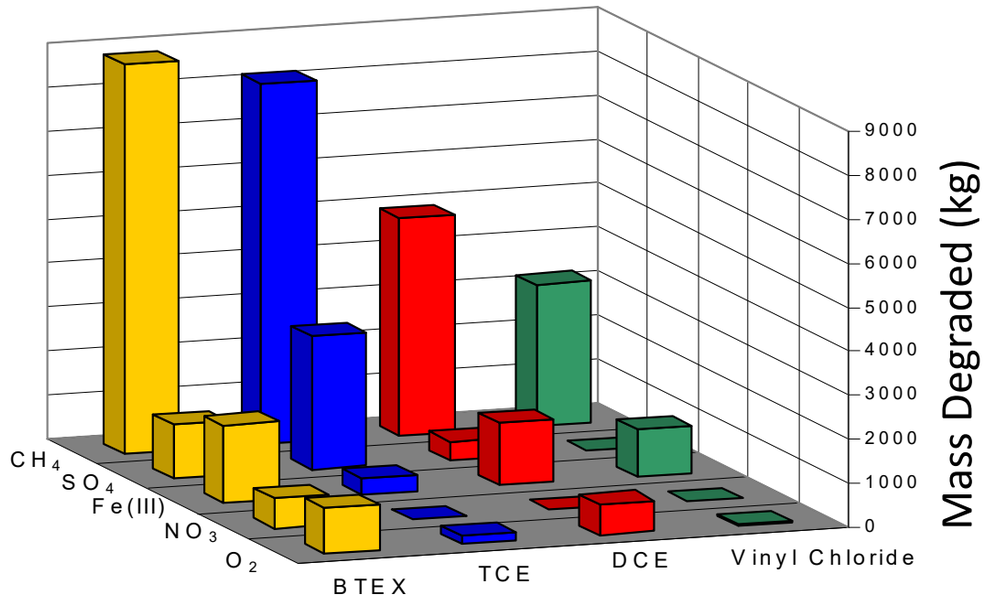
Redox Zone Mass Balance at Plattsburgh Air Force Base



Oxygen | Nitrate | Iron | Sulfate | CO_2 → CH_4

Modeled using In-Situ Remediation (ISR-MT3DMS)

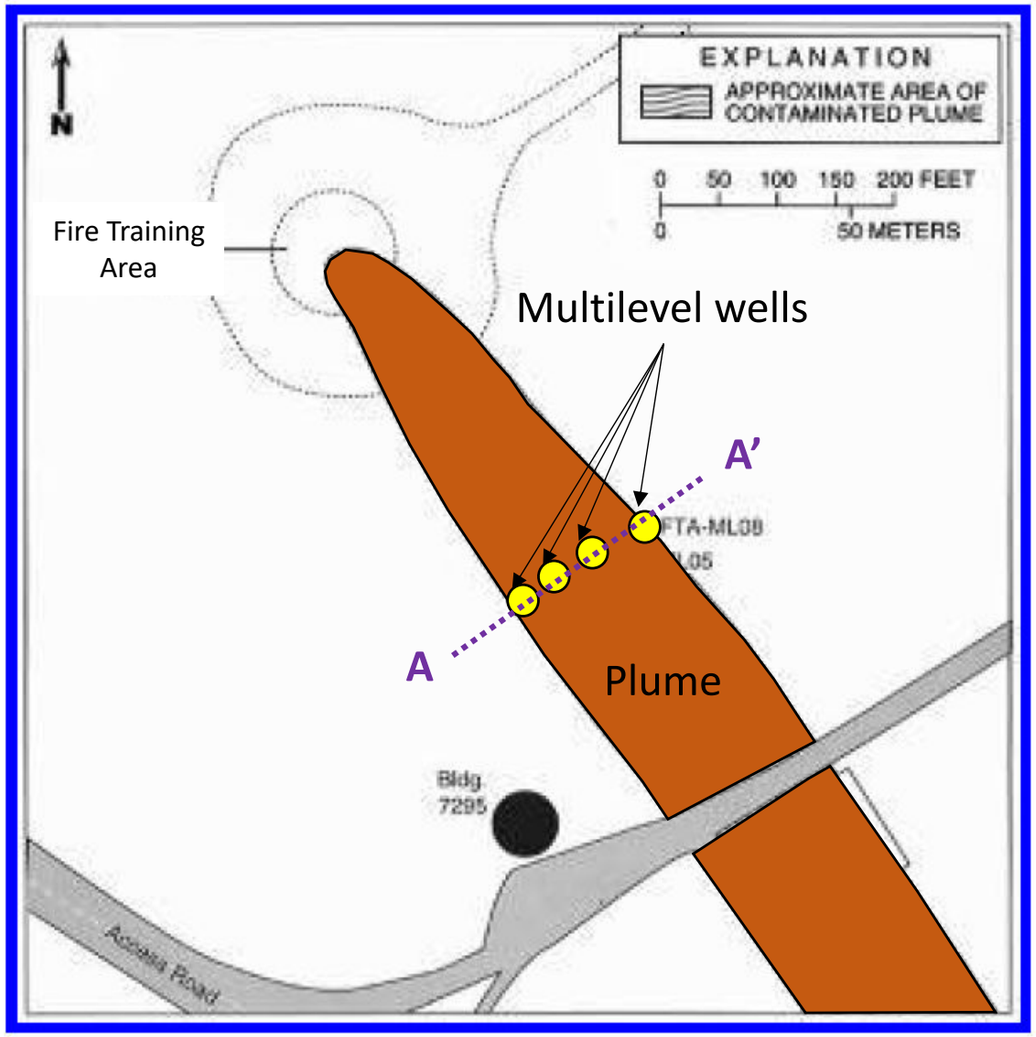
Modeled Mass Balance by Redox Zone (t = 40 years)



	CH_4	SO_4	Fe/Mn	NO_3	O_2
PCE					
TCE					
cis-DCE					
Vinyl Chloride					

- Oxidation (rapid, NO Daughters)
- Reductive Dechlorination (moderate, Daughters, need ED)
- Reductive Dechlorination (slow, Daughters, need ED)
- Cometabolism (rapid if substrate present, NO Daughters)

Wurtsmith Air Force Base, Michigan



Redox Indicators

- 20 wells
- 5 indicators

→ 100 data points

ES&T, 1996, 30: 3565-3569

Comparison of E_h and H_2 Measurements for Delineating Redox Processes in a Contaminated Aquifer

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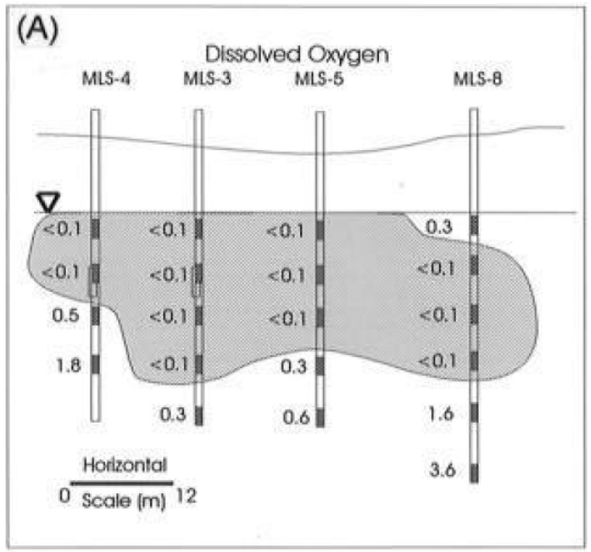
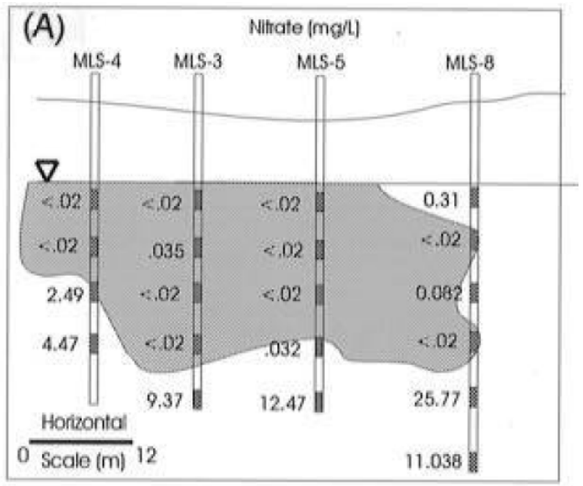
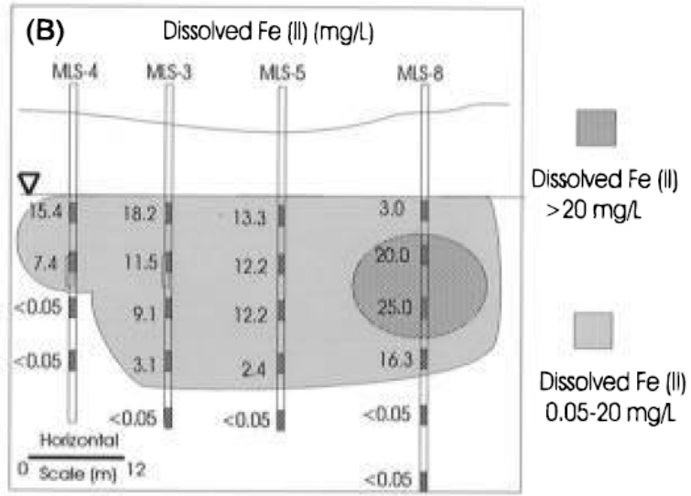
Presentation Method #1 – The TABLE

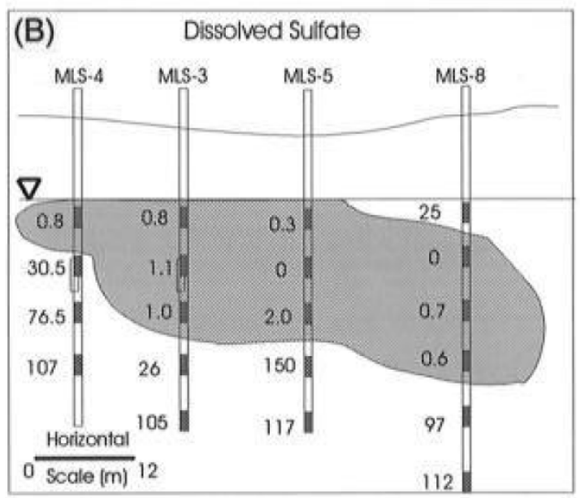
Well	Dissolved Oxygen (mg/L)	Nitrate (mg/L)	Dissolved Iron (mg/L)	Sulfate (mg/L)	Methane (mg/L)
MLS-3A	<0.1	<0.02	18.2	0.8	16.9
MLS-3B	<0.1	0.035	11.5	1.1	6.5
MLS-3C	<0.1	<0.02	9.1	1	3
MLS-3D	<0.1	<0.02	3.1	26	2.2
MLS-3E	0.3	9.37	<0.05	105	0.2
MLS-4A	<0.1	<0.02	15.4	0.8	12.1
MLS-4B	<0.1	<0.02	7.4	30.5	2.5
MLS-4C	0.5	2.49	<0.05	76.5	3.8
MLS-4D	1.8	4.47	<0.05	107	0.4
MLS-5A	<0.1	<0.02	13.3	0.3	13.1
MLS-5B	<0.1	<0.02	12.2	<0.5	4.3
MLS-5C	<0.1	<0.02	12.2	2	7
MLS-5D	0.3	0.032	2.4	150	0.4
MLS-5E	0.6	12.47	<0.05	117	<0.1
MLS-8A	0.3	0.31	3	25	1.7
MLS-8B	0.3	<0.02	20	<0.5	11.7
MLS-8C	0.3	0.082	25	0.7	14.2
MLS-8D	0.3	<0.02	16.3	0.6	16.6
MLS-8E	1.6	25.77	<0.05	97	<0.1
MLS-8F	3.6	11.038	<0.05	112	0.1

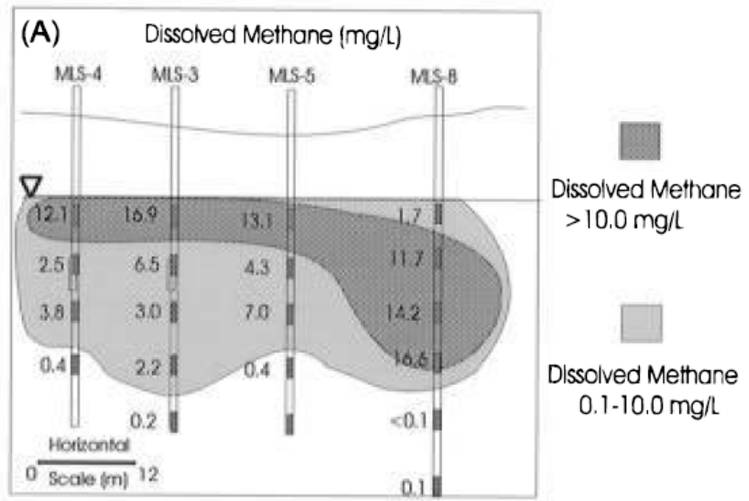
Presentation Method #2 – Individual Contour Maps





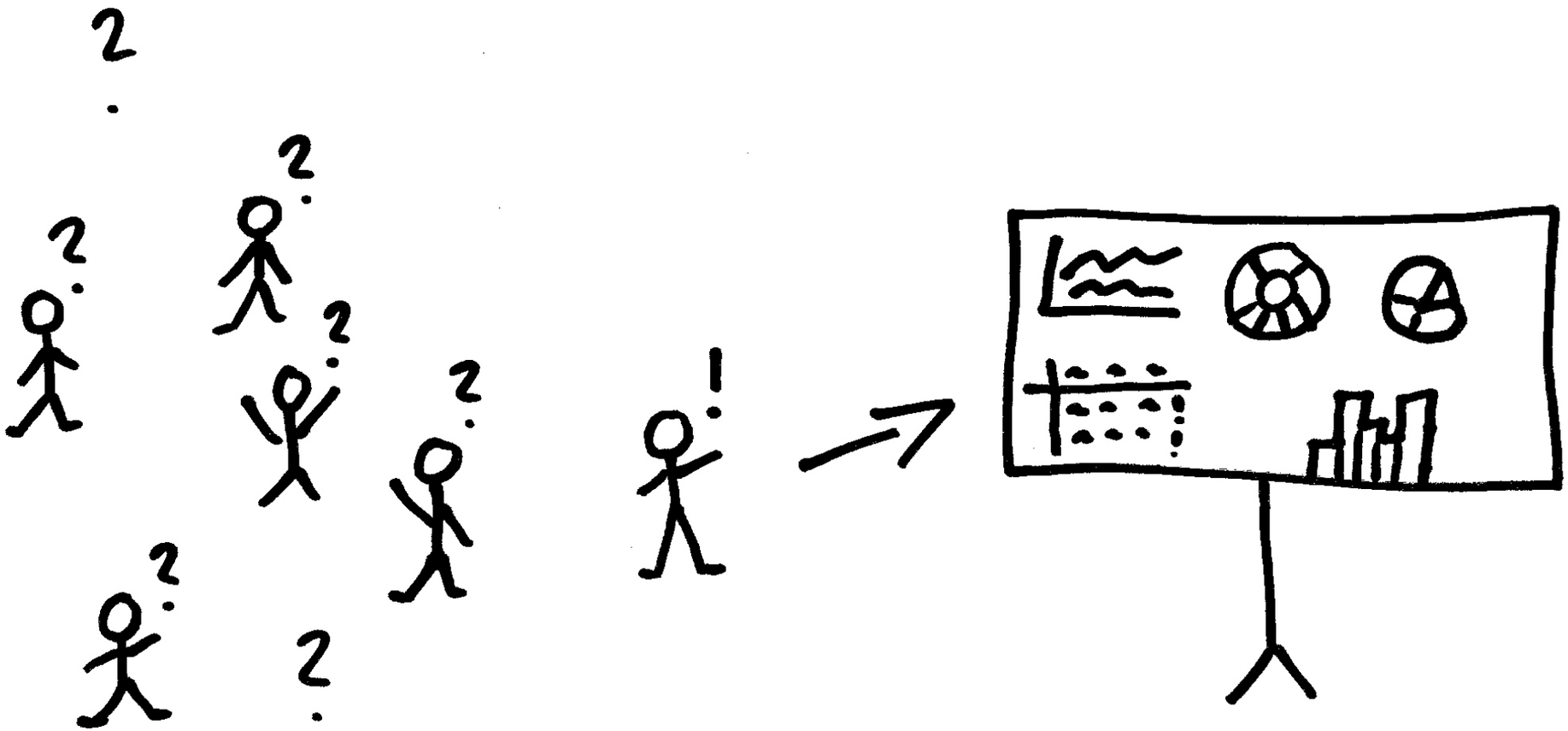




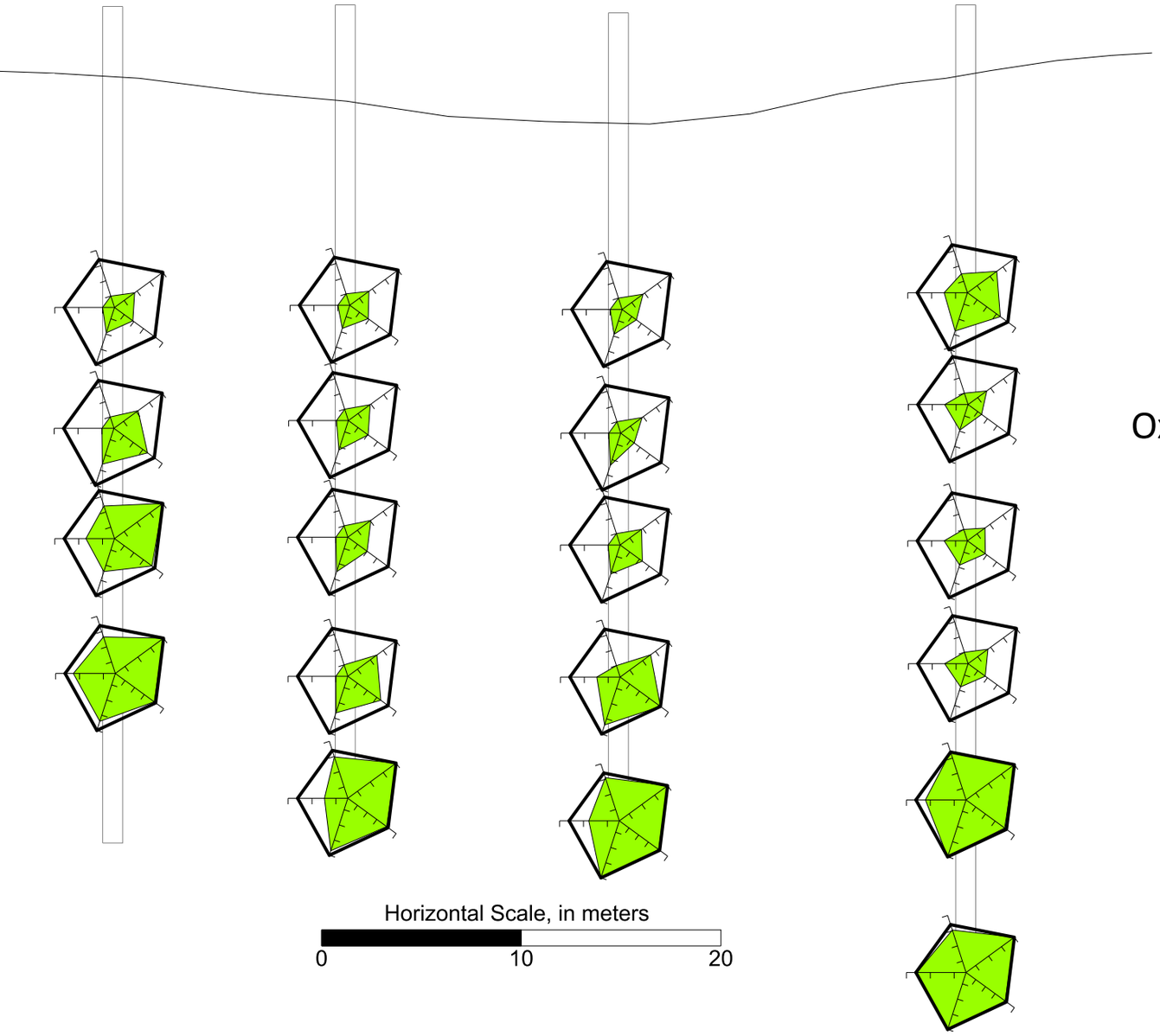


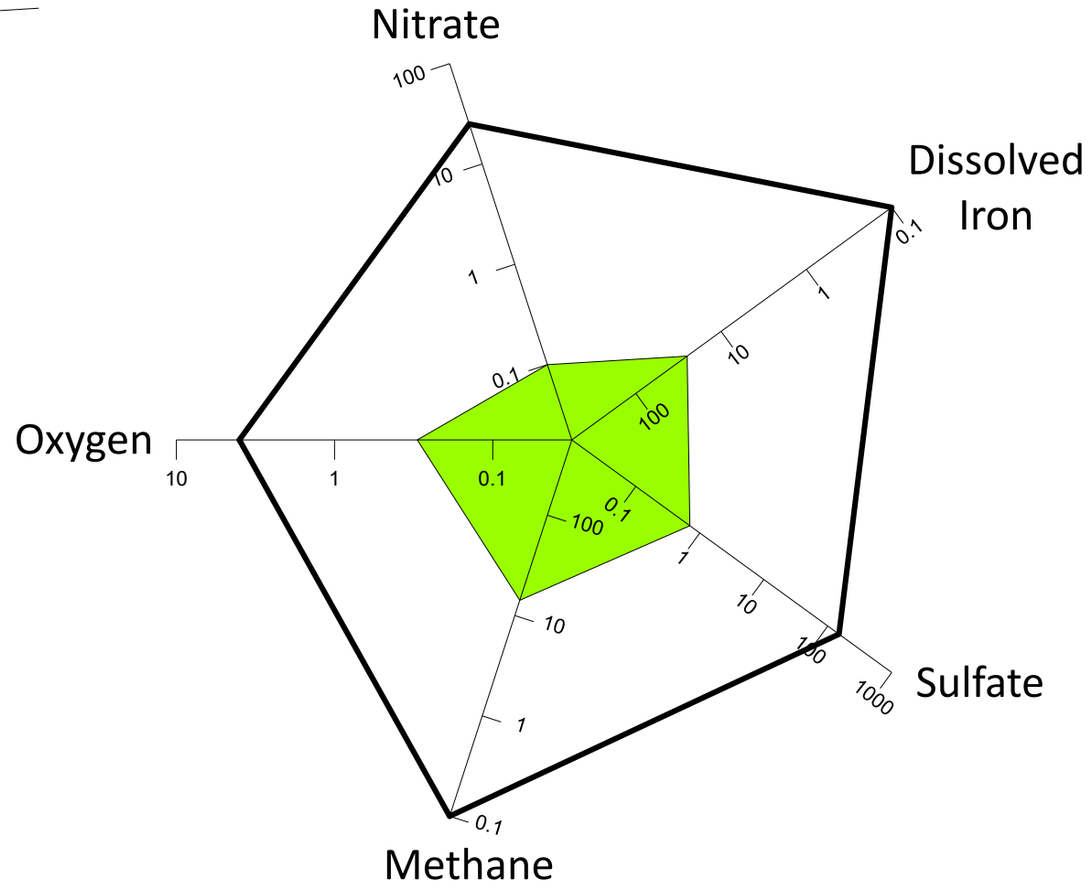
Main Challenge with MNA and EISB

How do we communicate results??



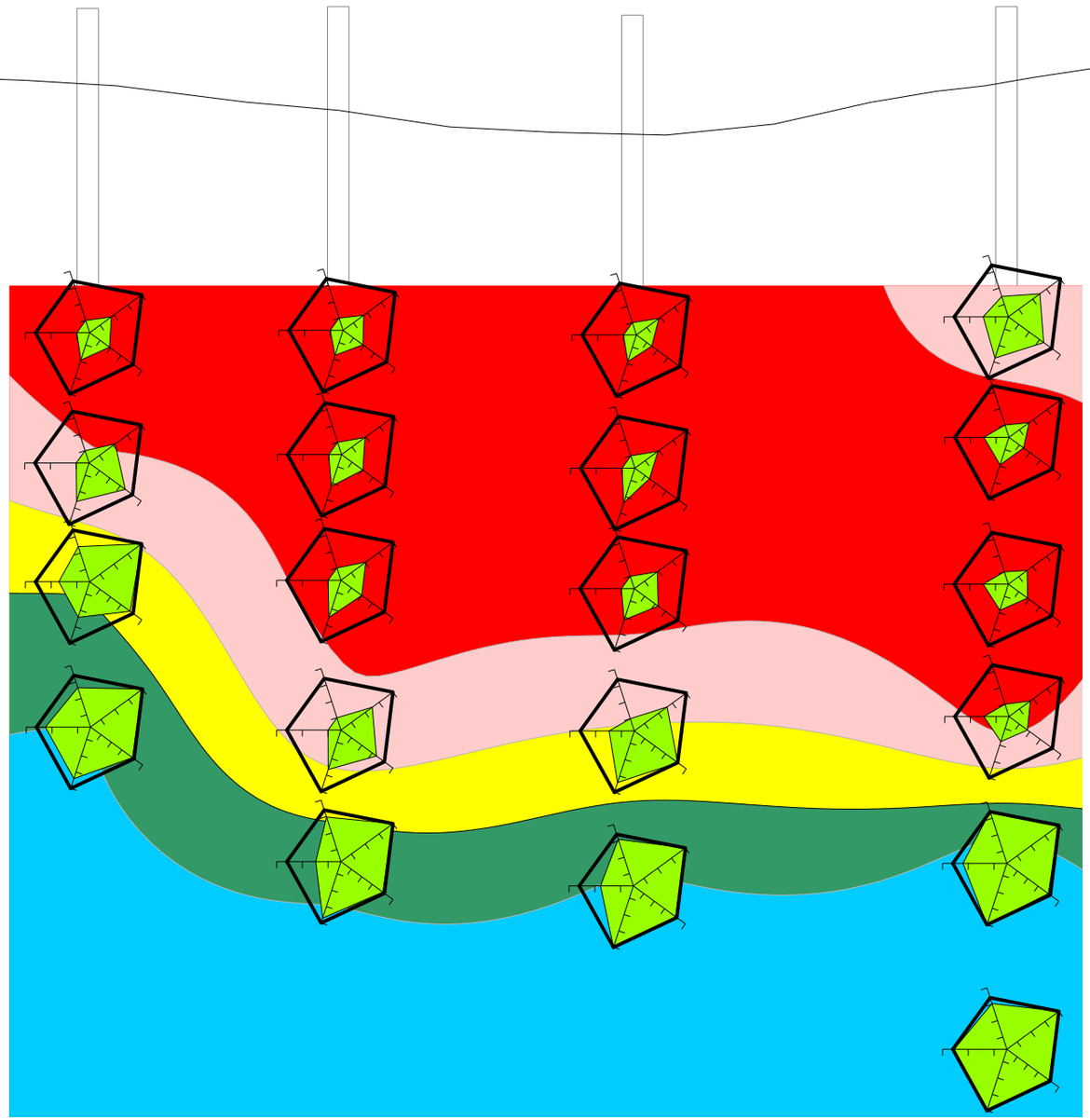
Redox Radial Diagrams





All concentrations in mg/L.

Relative Redox Area Contours



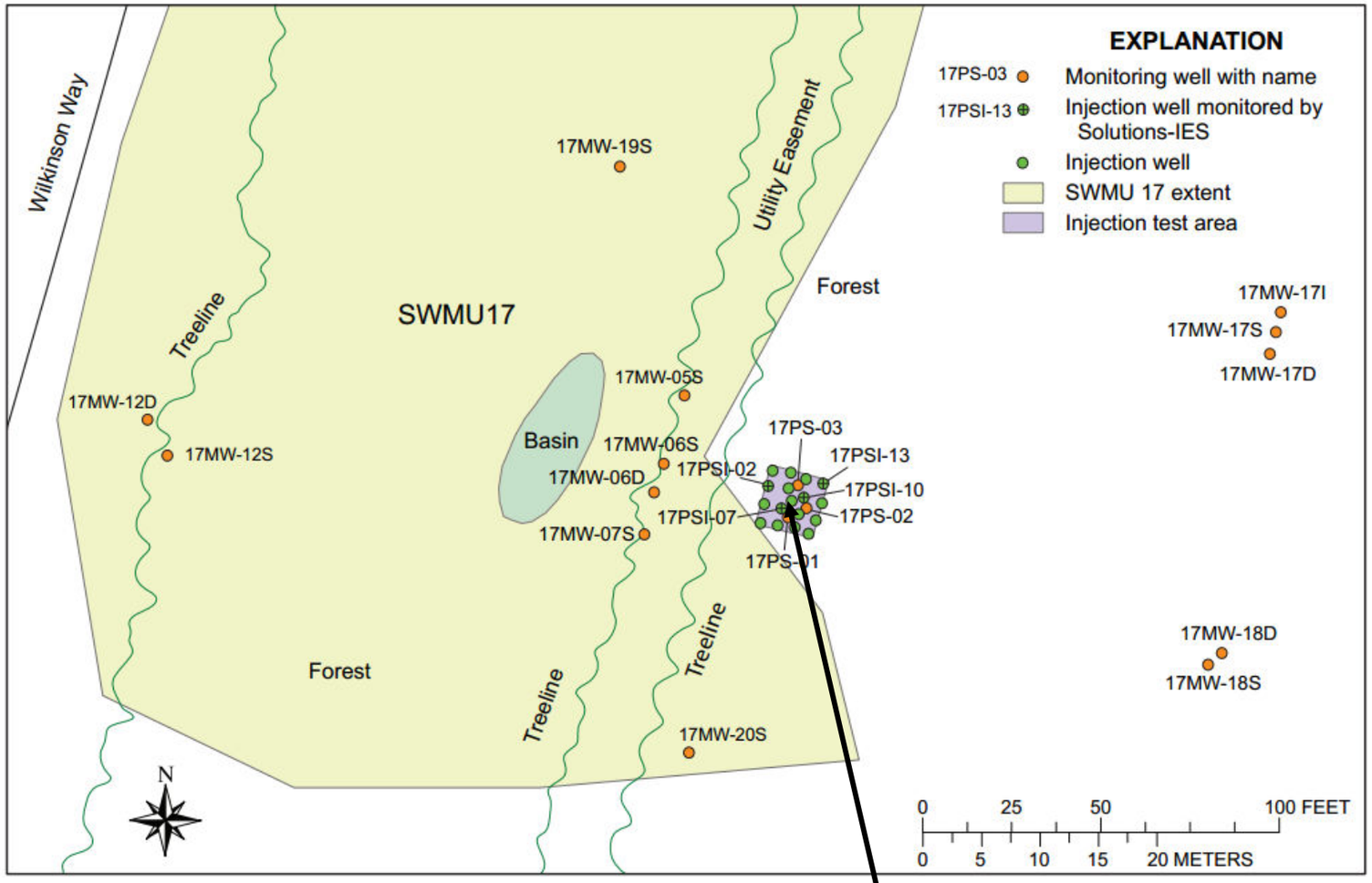
Sulfate-reducing

Methanogenic

Sulfate-reducing
Iron-reducing
Nitrate-reducing

Aerobic

Charleston Naval Weapons Station, South Carolina



USGS, 2009

Emulsified Oil Pilot Test Area

Redox Indicators

- 7 wells
- 6 indicators
- 12 events

→ 500 data points

Charleston Naval Weapons Station

Location	Days Since Injection 5/13/2004	Sample Date	Dissolved Oxygen (mg/L)	Nitrate (mg/L)	Manganese (mg/L)	Dissolved Iron (mg/L)	Sulfate (mg/L)	Methane (µg/L)
17PSI-02	-43	3/31/04	1.48	<0.5	0.390	33	91.5	53.2
17PSI-02	20	6/2/04	0.39	<0.5	0.570	150	18.0	47.4
17PSI-02	111	9/1/04	0.42	<0.5	0.510	160	<0.5	42.6
17PSI-02	188	11/17/04	0.14	<0.5	0.530	210	<0.5	256.3
17PSI-02	271	2/8/05	0.44	1.0/1.0	0.550	210	0.95	429.6
17PSI-02	377	5/25/05	0.19	< 0.5	0.660	210	< 0.5	1135
17PSI-02	468	8/24/05	0.35	< 0.5	0.630	180	< 0.5	812.8
17PSI-02	684	3/28/06	0.68	<0.5	0.590	210	<0.5	1933.2
17PSI-02	865	9/25/06	0.62	<0.5	0.530	60	<0.5	1366.9
17PSI-02	951	12/20/06	NM	<0.5	0.100	6.9	28.3	2135.8
17PSI-02	1062	4/10/07	0.36	<0.5	0.300	0.6	32.8/35.8	9433.9
17PSI-02	1252	10/17/07	0.80	<0.5	0.230	1.5	<0.5	5269.8
17PSI-07	-43	3/31/04	3.93	<0.5	0.370	24	102.5	40.7
17PSI-07	20	6/2/04	0.60	<0.5	0.710	180	1.8	53.7
17PSI-07	111	9/1/04	0.13	<0.5	0.820	300	0.5	26.6
17PSI-07	188	11/17/04	0.09	<0.5	0.740	240	<0.5	156.3
17PSI-07	271	2/8/05	0.48	<0.5	0.790	320	<0.5	151.7
17PSI-07	377	5/25/05	0.26	< 0.5	0.810	310	< 0.5	1469.4
17PSI-07	468	8/24/05	0.39	< 0.5	0.710	260	< 0.5	1816.0
17PSI-07	684	3/28/06	0.61	<0.5	0.530	420	<0.5	2121.1
17PSI-07	865	9/25/06	1.81	<0.5	0.620	320	<0.5	2684.9
17PSI-07	951	12/20/06	0.62	<0.5	0.750	220	<0.5/0.7	5509.0
17PSI-07	1062	4/10/07	0.98	<0.5	0.700	250	<0.5	4086.0
17PSI-07	1252	10/17/07	1.00	<0.5	0.720	120	<0.5	5377.2
17PSI-10	-43	3/31/04	4.05	<0.5	0.400	29	58.7	35.5
17PSI-10	20	6/2/04	0.47	<0.5	0.920	150	53.5/52.6	16.9
17PSI-10	111	9/1/04	0.26	<0.5	0.700	130	0.7	20.1
17PSI-10	188	11/17/04	0.14	<0.5	0.940	190	<0.5	27.2
17PSI-10	271	2/8/05	0.41	<0.5	0.830	220	<0.5	851.9
17PSI-10	377	5/25/05	0.32	< 0.5	0.800	220	< 0.5	2626.4
17PSI-10	468	8/24/05	0.45	< 0.5	1.200	190	< 0.5	1884.3
17PSI-10	684	3/28/06	0.56	<0.5	0.640	240	<0.5	2152.8
17PSI-10	866	9/26/06	0.52	<0.5	0.720	210	<0.5	4147.0
17PSI-10	951	12/20/06	0.74	<0.5	0.590	170	0.7	5972.8
17PSI-10	1062	4/10/07	0.51	<0.5	0.750	200	<0.5	9990.4
17PSI-10	1252	10/17/07	0.80	<0.5	0.510	40	<0.5/0.6	6651.4
17PSI-13	-43	3/31/04	4.66	<0.5	0.610	53	102.6	13.4
17PSI-13	20	6/2/04	0.74	<0.5	0.920	120	82.6	17.5
17PSI-13	111	9/1/04	0.19	<0.5	0.840	200	<0.5	14.3
17PSI-13	187	11/16/04	0.10	<0.5/<0.5	0.920	210	<0.5/<0.5	78.7
17PSI-13	271	2/8/05	0.39	<0.5	0.880	190	<0.5	534.5
17PSI-13	376	5/24/05	0.29	<0.5/<0.5	0.800	160	<0.5/<0.5	3441.6
17PSI-13	468	8/24/05	0.35	< 0.5	0.990	160	< 0.5	2550.7
17PSI-13	684	3/28/06	NA	<0.5	0.880	260	<0.5	1105.7
17PSI-13	866	9/26/06	0.56	<0.5	0.830	180	<0.5	5069.7
17PSI-13	951	12/20/06	0.81	<0.5	0.850	260	1.1	5540.8
17PSI-13	1062	4/10/07	0.46	<0.5	0.840	280	<0.5	7879.1
17PSI-13	1252	10/17/07	0.60	<0.5	0.570	90	<0.5	9099.5
17PS-01	-42	4/1/04	0.67	<0.5	0.630	78	65.5	27.2
17PS-01	20	6/2/04	1.14	<0.5	0.720	120	44.1/44.6	25.8
17PS-01	111	9/1/04	0.15	<0.5	0.540	110	15.3	37.7
17PS-01	187	11/16/04	0.17	<0.5	0.780	130	23.4	33.1
17PS-01	271	2/8/05	0.23	<0.5	0.680	150	27.9	145.0
17PS-01	377	5/25/05	0.34	< 0.5	0.690	130	20.3	231.9
17PS-01	468	8/24/05	0.33	< 0.5	0.570	190	21.6	92.2
17PS-01	685	3/29/06	0.49	<0.5	0.490	210	30.9	261.2
17PS-01	866	9/26/06	0.81	<0.5	0.690	110	<0.5	1232.6
17PS-01	951	12/20/06	NA	<0.5	0.190	7.2	1.4	7415.3
17PS-01	1062	4/10/07	0.72	<0.5	0.050	1.0	<0.5	11308.5
17PS-01	1252	10/17/07	0.20	1.3	0.230	2.1	0.5	7759.2
17PS-02	-42	4/1/04	1.50	<0.5	0.560	50	58	30.8
17PS-02	20	6/2/04	3.36	<0.5	0.740	81	5.4	30.6
17PS-02	111	9/1/04	0.14	<0.5	0.570	170	15.0	36.7
17PS-02	187	11/16/04	0.16	<0.5	0.590	150	2.8	66.0
17PS-02	271	2/8/05	0.20	<0.5/<0.5	0.520	120	10.0	1144.8
17PS-02	377	5/25/05	0.47	< 0.5	0.660	92	6.7	1176.5
17PS-02	468	8/24/05	0.32	< 0.5	0.540	150	20.8	1681.8
17PS-02	685	3/29/06	0.50	<0.5	0.550	130	14	3639.3
17PS-02	866	9/26/06	0.48	<0.5	0.620	170	2.8	2133.3
17PS-02	951	12/20/06	NA	<0.5	0.180	1.10	9.6	9880.6
17PS-02	1062	4/10/07	0.75	<0.5	0.260	12.0	<0.5/0.57	8896.9
17PS-02	1252	10/17/07	0.40	1.1	0.075	0.41	<0.5	9148.4
17PS-03	-42	4/1/04	0.40	<0.5	0.680	69	77.5	36.0
17PS-03	20	6/2/04	1.22	<0.5	0.810	110	10.0	50.7
17PS-03	111	9/1/04	0.14	<0.5	0.460	130	<0.5	173.3
17PS-03	187	11/16/04	0.18	<0.5/<0.5	0.800	200	0.5/<0.5	2062.5
17PS-03	271	2/8/05	0.25	<0.5	0.570	180	<0.5	7737.5
17PS-03	377	5/25/05	0.31	< 0.5	0.700	180	< 0.5	4425.3
17PS-03	468	8/24/05	0.37	< 0.5	0.470	190	2.10	3136.5
17PS-03	685	3/29/06	0.44	<0.5	0.430	370	1.6	3522.2
17PS-03	866	9/26/06	0.57	<0.5	0.580	96	1.9	4852.4
17PS-03	951	12/20/06	NA	<0.5	0.170	1.1	9.6/9.5	9839.1
17PS-03	1062	4/10/07	0.68	<0.5	0.055	0.38	5.0	4281.3
17PS-03	1252	10/17/07	0.40	1.3	0.120	0.58	<0.5	10127.1

Redox Indicators

- 7 wells
- 6 indicators
- 12 events

→ 500 data points

Charleston Naval Weapons Station

Location	Days Since Injection 5/13/2004	Sample Date	Dissolved Oxygen (mg/L)	Nitrate (mg/L)	Manganese (mg/L)	Dissolved Iron (mg/L)	Sulfate (mg/L)	Methane (µg/L)
17PSI-02	-43	3/31/04	1.48	<0.5	0.390	33	91.5	53.2
17PSI-02	20	6/2/04	0.39	<0.5	0.570	150	18.0	47.4
17PSI-02	111	9/1/04	0.42	<0.5	0.510	160	<0.5	42.6
17PSI-02	188	11/17/04	0.14	<0.5	0.530	210	<0.5	256.3
17PSI-02	271	2/8/05	0.44	1.0/1.0	0.550	210	0.95	429.6
17PSI-02	377	5/25/05	0.19	< 0.5	0.660	210	< 0.5	1135
17PSI-02	468	8/24/05	0.35	< 0.5	0.630	180	< 0.5	812.8
17PSI-02	684	3/28/06	0.68	<0.5	0.590	210	<0.5	1933.2
17PSI-02	865	9/25/06	0.62	<0.5	0.530	60	<0.5	1366.9
17PSI-02	951	12/20/06	NM	<0.5	0.100	6.9	28.3	2135.8
17PSI-02	1062	4/10/07	0.36	<0.5	0.300	0.6	32.8/35.8	9433.9
17PSI-02	1252	10/17/07	0.80	<0.5	0.230	1.5	<0.5	5269.8
17PSI-07	-43	3/31/04	3.93	<0.5	0.370	24	102.5	40.7
17PSI-07	20	6/2/04	0.60	<0.5	0.710	180	1.8	53.7
17PSI-07	111	9/1/04	0.13	<0.5	0.820	300	0.5	26.6
17PSI-07	188	11/17/04	0.09	<0.5	0.740	240	<0.5	156.3
17PSI-07	271	2/8/05	0.48	<0.5	0.790	320	<0.5	151.7
17PSI-07	377	5/25/05	0.26	< 0.5	0.810	310	< 0.5	1469.4
17PSI-07	468	8/24/05	0.39	< 0.5	0.710	260	< 0.5	1816.0
17PSI-07	684	3/28/06	0.61	<0.5	0.530	420	<0.5	2121.1
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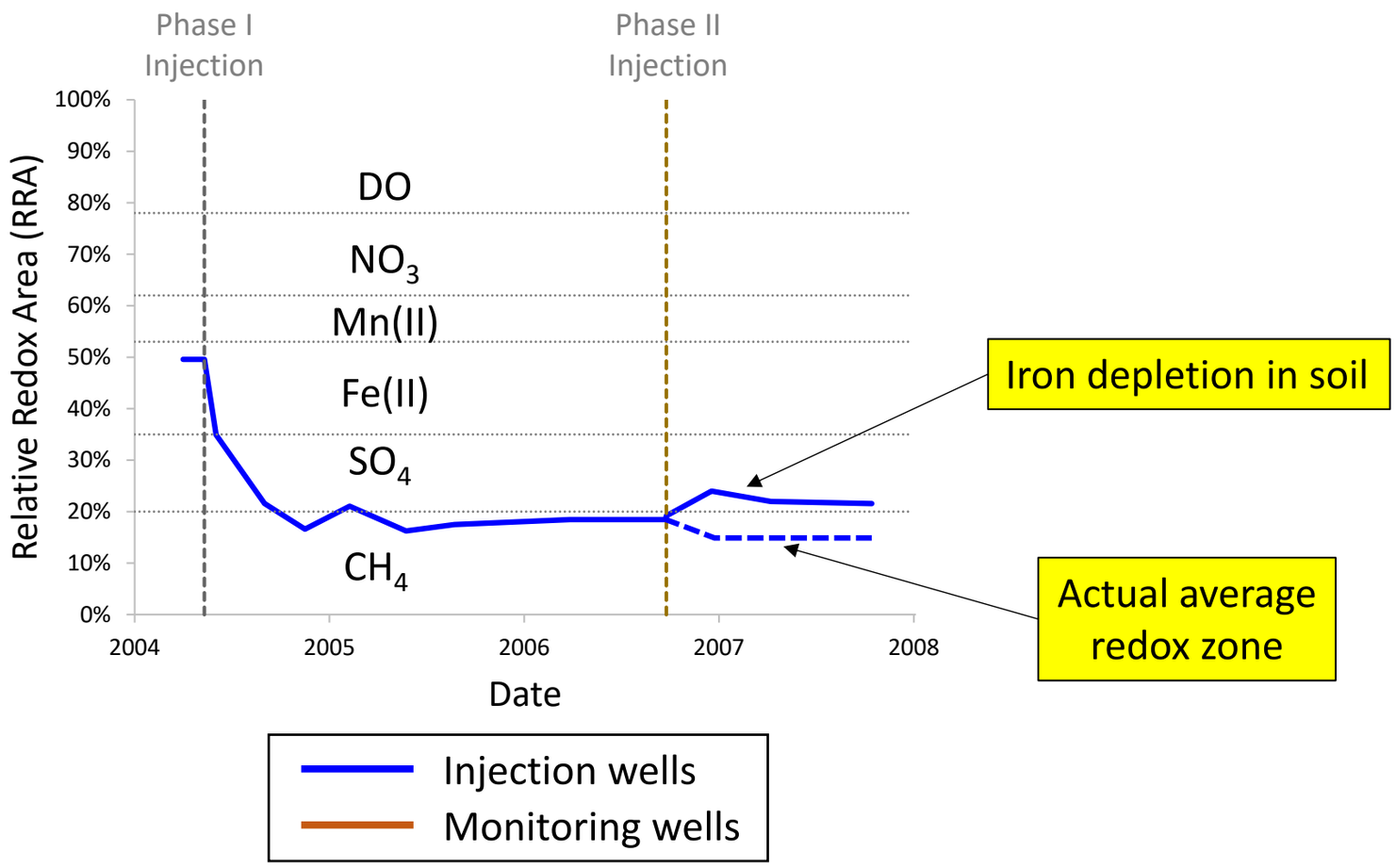
17PSI-07	951	12/20/06	0.62	<0.5	0.750	220	<0.5/0.7	5509.0
17PSI-07	1062	4/10/07	0.98	<0.5	0.700	250	<0.5	4086.0
17PSI-07	1252	10/17/07	1.00	<0.5	0.720	120	<0.5	5377.2
17PSI-10	-43	3/31/04	4.05	<0.5	0.400	29	58.7	35.5
17PSI-10	20	6/2/04	0.47	<0.5	0.920	150	53.5/52.6	16.9
17PSI-10	111	9/1/04	0.26	<0.5	0.700	130	0.7	20.1
17PSI-10	188	11/17/04	0.14	<0.5	0.940	190	<0.5	27.2
17PSI-10	271	2/8/05	0.41	<0.5	0.830	220	<0.5	851.9
17PSI-10	377	5/25/05	0.32	< 0.5	0.800	220	< 0.5	2626.4
17PSI-10	468	8/24/05	0.45	< 0.5	1.200	190	< 0.5	1884.3
17PSI-10	684	3/28/06	0.56	<0.5	0.640	240	<0.5	2152.8
17PSI-10	866	9/26/06	0.52	<0.5	0.720	210	<0.5	4147.0
17PSI-10	951	12/20/06	0.74	<0.5	0.590	170	0.7	5972.8
17PSI-10	1062	4/10/07	0.51	<0.5	0.750	200	<0.5	9990.4
17PSI-10	1252	10/17/07	0.80	<0.5	0.510	40	<0.5/0.6	6651.4
17PSI-13	-43	3/31/04	4.66	<0.5	0.610	53	102.6	13.4
17PSI-13	20	6/2/04	0.74	<0.5	0.920	120	82.6	17.5
17PSI-13	111	9/1/04	0.19	<0.5	0.840	200	<0.5	14.3
17PSI-13	187	11/16/04	0.10	<0.5/<0.5	0.920	210	<0.5/<0.5	78.7
17PSI-13	271	2/8/05	0.39	<0.5	0.880	190	<0.5	534.5
17PSI-13	376	5/24/05	0.29	<0.5/<0.5	0.800	160	<0.5/<0.5	3441.6
17PSI-13	468	8/24/05	0.35	< 0.5	0.990	160	< 0.5	2550.7
17PSI-13	684	3/28/06	NA	<0.5	0.880	260	<0.5	1105.7
17PSI-13	866	9/26/06	0.56	<0.5	0.830	180	<0.5	5069.7
17PSI-13	951	12/20/06	0.81	<0.5	0.850	260	1.1	5540.8
17PSI-13	1062	4/10/07	0.46	<0.5	0.840	280	<0.5	7879.1
17PSI-13	1252	10/17/07	0.60	<0.5	0.570	90	<0.5	9099.5
17PS-01	-42	4/1/04	0.67	<0.5	0.630	78	65.5	27.2
17PS-01	20	6/2/04	1.14	<0.5	0.720	120	44.1/44.6	25.8
17PS-01	111	9/1/04	0.15	<0.5	0.540	110	15.3	37.7
17PS-01	187	11/16/04	0.17	<0.5	0.780	130	23.4	33.1
17PS-01	271	2/8/05	0.23	<0.5	0.680	150	27.9	145.0
17PS-01	377	5/25/05	0.34	< 0.5	0.690	130	20.3	231.9
17PS-01	468	8/24/05	0.33	< 0.5	0.570	190	21.6	92.2
17PS-01	685	3/29/06	0.49	<0.5	0.490	210	30.9	261.2
17PS-01	866	9/26/06	0.81	<0.5	0.690	110	<0.5	1232.6
17PS-01	951	12/20/06	NA	<0.5	0.190	7.2	1.4	7415.3
17PS-01	1062	4/10/07	0.72	<0.5	0.050	1.0	<0.5	11308.5
17PS-01	1252	10/17/07	0.20	1.3	0.230	2.1	0.5	7759.2
17PS-02	-42	4/1/04	1.50	<0.5	0.560	50	58	30.8
17PS-02	20	6/2/04	3.36	<0.5	0.740	81	5.4	30.6
17PS-02	111	9/1/04	0.14	<0.5	0.570	170	15.0	36.7
17PS-02	187	11/16/04	0.16	<0.5	0.590	150	2.8	66.0
17PS-02	271	2/8/05	0.20	<0.5/<0.5	0.520	120	10.0	1144.8
17PS-02	377	5/25/05	0.47	< 0.5	0.660	92	6.7	1176.5
17PS-02	468	8/24/05	0.32	< 0.5	0.540	150	20.8	1681.8
17PS-02	685	3/29/06	0.50	<0.5	0.550	130	14	3639.3
17PS-02	866	9/26/06	0.48	<0.5	0.620	170	2.8	2133.3
17PS-02	951	12/20/06	NA	<0.5	0.180	1.10	9.6	9880.6
17PS-02	1062	4/10/07	0.75	<0.5	0.260	12.0	<0.5/0.57	8896.9
17PS-02	1252	10/17/07	0.40	1.1	0.075	0.41	<0.5	9148.4
17PS-03	-42	4/1/04	0.40	<0.5	0.680	69	77.5	36.0
17PS-03	20	6/2/04	1.22	<0.5	0.810	110	10.0	50.7
17PS-03	111	9/1/04	0.14	<0.5	0.460	130	<0.5	173.3
17PS-03	187	11/16/04	0.18	<0.5/<0.5	0.800	200	0.5/<0.5	2062.5
17PS-03	271	2/8/05	0.25	<0.5	0.570	180	<0.5	7737.5
17PS-03	377	5/25/05	0.31	< 0.5	0.700	180	< 0.5	4425.3
17PS-03	468	8/24/05	0.37	< 0.5	0.470	190	2.10	3136.5
17PS-03	685	3/29/06	0.44	<0.5	0.430	370	1.6	3522.2
17PS-03	866	9/26/06	0.57	<0.5	0.580	96	1.9	4852.4
17PS-03	951	12/20/06	NA	<0.5	0.170	1.1	9.6/9.5	9839.1
17PS-03	1062	4/10/07	0.68	<0.5	0.055	0.38	5.0	4281.3
17PS-03	1252	10/17/07	0.40	1.3	0.120	0.58	<0.5	10127.1

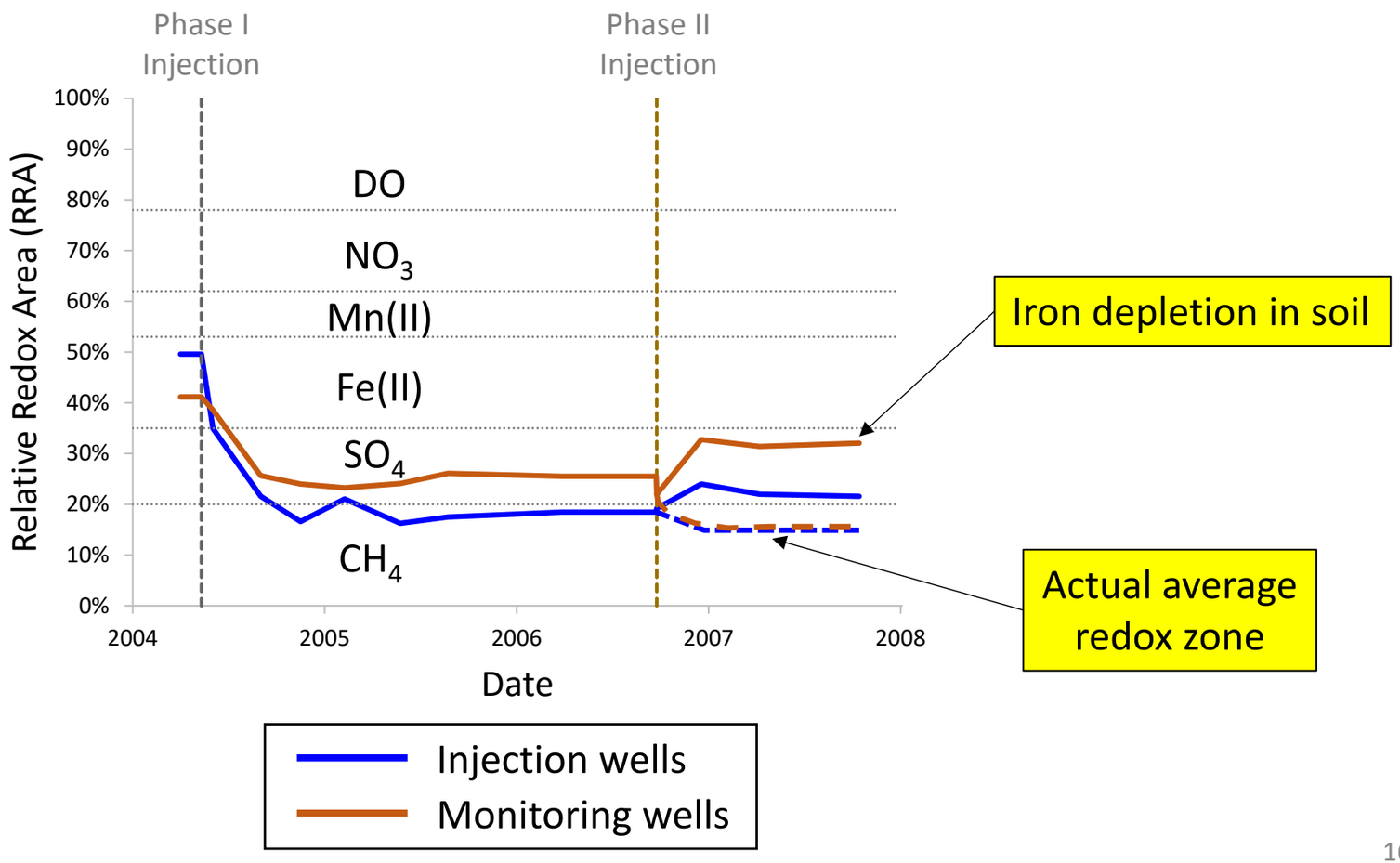
Average RRA versus time in Pilot Test Area (IWs)



Charleston Naval Weapons Station

Location	Days Since Injection 5/13/2004	Sample Date	Dissolved Oxygen (mg/L)	Nitrate (mg/L)	Manganese (mg/L)	Dissolved Iron (mg/L)	Sulfate (mg/L)	Methane (µg/L)
17PSI-02	-43	3/31/04	1.48	<0.5	0.390	33	91.5	53.2
17PSI-02	20	6/2/04	0.39	<0.5	0.570	150	18.0	47.4
17PSI-02	111	9/1/04	0.42	<0.5	0.510	160	<0.5	42.6
17PSI-02	188	11/17/04	0.14	<0.5	0.530	210	<0.5	256.3
17PSI-02	271	2/8/05	0.44	1.0/1.0	0.550	210	0.95	429.6
17PSI-02	377	5/25/05	0.19	< 0.5	0.660	210	< 0.5	1135
17PSI-02	468	8/24/05	0.35	< 0.5	0.630	180	< 0.5	812.8
17PSI-02	684	3/28/06	0.68	<0.5	0.590	210	<0.5	1933.2
17PSI-02	865	9/25/06	0.62	<0.5	0.530	60	<0.5	1366.9
17PSI-02	951	12/20/06	NM	<0.5	0.100	6.9	28.3	2135.8
17PSI-02	1062	4/10/07	0.36	<0.5	0.300	0.6	32.8/35.8	9433.9
17PSI-02	1252	10/17/07	0.80	<0.5	0.230	1.5	<0.5	5269.8
17PSI-07	-43	3/31/04	3.93	<0.5	0.370	24	102.5	40.7
17PSI-07	20	6/2/04	0.60	<0.5	0.710	180	1.8	53.7
17PSI-07	111	9/1/04	0.13	<0.5	0.820	300	0.5	26.6
17PSI-07	188	11/17/04	0.09	<0.5	0.740	240	<0.5	156.3
17PSI-07	271	2/8/05	0.48	<0.5	0.790	320	<0.5	151.7
17PSI-07	377	5/25/05	0.26	< 0.5	0.810	310	< 0.5	1469.4
17PSI-07	468	8/24/05	0.39	< 0.5	0.710	260	< 0.5	1816.0
17PSI-07	684	3/28/06	0.61	<0.5	0.530	420	<0.5	2121.1
17PSI-07	865	9/25/06	1.81	<0.5	0.620	320	<0.5	2684.9
17PSI-07	951	12/20/06	0.62	<0.5	0.750	220	<0.5/0.7	5509.0
17PSI-07	1062	4/10/07	0.98	<0.5	0.700	250	<0.5	4086.0
17PSI-07	1252	10/17/07	1.00	<0.5	0.720	120	<0.5	5377.2
17PSI-10	-43	3/31/04	4.05	<0.5	0.400	29	58.7	35.5
17PSI-10	20	6/2/04	0.47	<0.5	0.920	150	53.5/52.6	16.9
17PSI-10	111	9/1/04	0.26	<0.5	0.700	130	0.7	20.1
17PSI-10	188	11/17/04	0.14	<0.5	0.940	190	<0.5	27.2
17PSI-10	271	2/8/05	0.41	<0.5	0.830	220	<0.5	851.9
17PSI-10	377	5/25/05	0.32	< 0.5	0.800	220	< 0.5	2626.4
17PSI-10	468	8/24/05	0.45	< 0.5	1.200	190	< 0.5	1884.3
17PSI-10	684	3/28/06	0.56	<0.5	0.640	240	<0.5	2152.8
17PSI-10	866	9/26/06	0.52	<0.5	0.720	210	<0.5	4147.0
17PSI-10	951	12/20/06	0.74	<0.5	0.590	170	0.7	5972.8
17PSI-10	1062	4/10/07	0.51	<0.5	0.750	200	<0.5	9990.4
17PSI-10	1252	10/17/07	0.80	<0.5	0.510	40	<0.5/0.6	6651.4
17PSI-13	-43	3/31/04	4.66	<0.5	0.610	53	102.6	13.4
17PSI-13	20	6/2/04	0.74	<0.5	0.920	120	82.6	17.5
17PSI-13	111	9/1/04	0.19	<0.5	0.840	200	<0.5	14.3
17PSI-13	187	11/16/04	0.10	<0.5/<0.5	0.920	210	<0.5/<0.5	78.7
17PSI-13	271	2/8/05	0.39	<0.5	0.880	190	<0.5	534.5
17PSI-13	376	5/24/05	0.29	<0.5/<0.5	0.800	160	<0.5/<0.5	3441.6
17PSI-13	468	8/24/05	0.35	< 0.5	0.990	160	< 0.5	2550.7
17PSI-13	684	3/28/06	NA	<0.5	0.880	260	<0.5	1105.7
17PSI-13	866	9/26/06	0.56	<0.5	0.830	180	<0.5	5069.7
17PSI-13	951	12/20/06	0.81	<0.5	0.850	260	1.1	5540.8
17PSI-13	1062	4/10/07	0.46	<0.5	0.840	280	<0.5	7879.1
17PSI-13	1252	10/17/07	0.60	<0.5	0.570	90	<0.5	9099.5
17PS-01	-42	4/1/04	0.67	<0.5	0.630	78	65.5	27.2
17PS-01	20	6/2/04	1.14	<0.5	0.720	120	44.1/44.6	25.8
17PS-01	111	9/1/04	0.15	<0.5	0.540	110	15.3	37.7
17PS-01	187	11/16/04	0.17	<0.5	0.780	130	23.4	33.1
17PS-01	271	2/8/05	0.23	<0.5	0.680	150	27.9	145.0
17PS-01	377	5/25/05	0.34	< 0.5	0.690	130	20.3	231.9
17PS-01	468	8/24/05	0.33	< 0.5	0.570	190	21.6	92.2
17PS-01	685	3/29/06	0.49	<0.5	0.490	210	30.9	261.2
17PS-01	866	9/26/06	0.81	<0.5	0.690	110	<0.5	1232.6
17PS-01	951	12/20/06	NA	<0.5	0.190	7.2	1.4	7415.3
17PS-01	1062	4/10/07	0.72	<0.5	0.050	1.0	<0.5	11308.5
17PS-01	1252	10/17/07	0.20	1.3	0.230	2.1	0.5	7759.2
17PS-02	-42	4/1/04	1.50	<0.5	0.560	50	58	30.8
17PS-02	20	6/2/04	3.36	<0.5	0.740	81	5.4	30.6
17PS-02	111	9/1/04	0.14	<0.5	0.570	170	15.0	36.7
17PS-02	187	11/16/04	0.16	<0.5	0.590	150	2.8	66.0
17PS-02	271	2/8/05	0.20	<0.5/<0.5	0.520	120	10.0	1144.8
17PS-02	377	5/25/05	0.47	< 0.5	0.660	92	6.7	1176.5
17PS-02	468	8/24/05	0.32	< 0.5	0.540	150	20.8	1681.8
17PS-02	685	3/29/06	0.50	<0.5	0.550	130	14	3639.3
17PS-02	866	9/26/06	0.48	<0.5	0.620	170	2.8	2133.3
17PS-02	951	12/20/06	NA	<0.5	0.180	1.10	9.6	9880.6
17PS-02	1062	4/10/07	0.75	<0.5	0.260	12.0	<0.5/0.57	8896.9
17PS-02	1252	10/17/07	0.40	1.1	0.075	0.41	<0.5	9148.4
17PS-03	-42	4/1/04	0.40	<0.5	0.680	69	77.5	36.0
17PS-03	20	6/2/04	1.22	<0.5	0.810	110	10.0	50.7
17PS-03	111	9/1/04	0.14	<0.5	0.460	130	<0.5	173.3
17PS-03	187	11/16/04	0.18	<0.5/<0.5	0.800	200	0.5/<0.5	2062.5
17PS-03	271	2/8/05	0.25	<0.5	0.570	180	<0.5	7737.5
17PS-03	377	5/25/05	0.31	< 0.5	0.700	180	< 0.5	4425.3
17PS-03	468	8/24/05	0.37	< 0.5	0.470	190	2.10	3136.5
17PS-03	685	3/29/06	0.44	<0.5	0.430	370	1.6	3522.2
17PS-03	866	9/26/06	0.57	<0.5	0.580	96	1.9	4852.4
17PS-03	951	12/20/06	NA	<0.5	0.170	1.1	9.6/9.5	9839.1
17PS-03	1062	4/10/07	0.68	<0.5	0.055	0.38	5.0	4281.3
17PS-03	1252	10/17/07	0.40	1.3	0.120	0.58	<0.5	10127.1

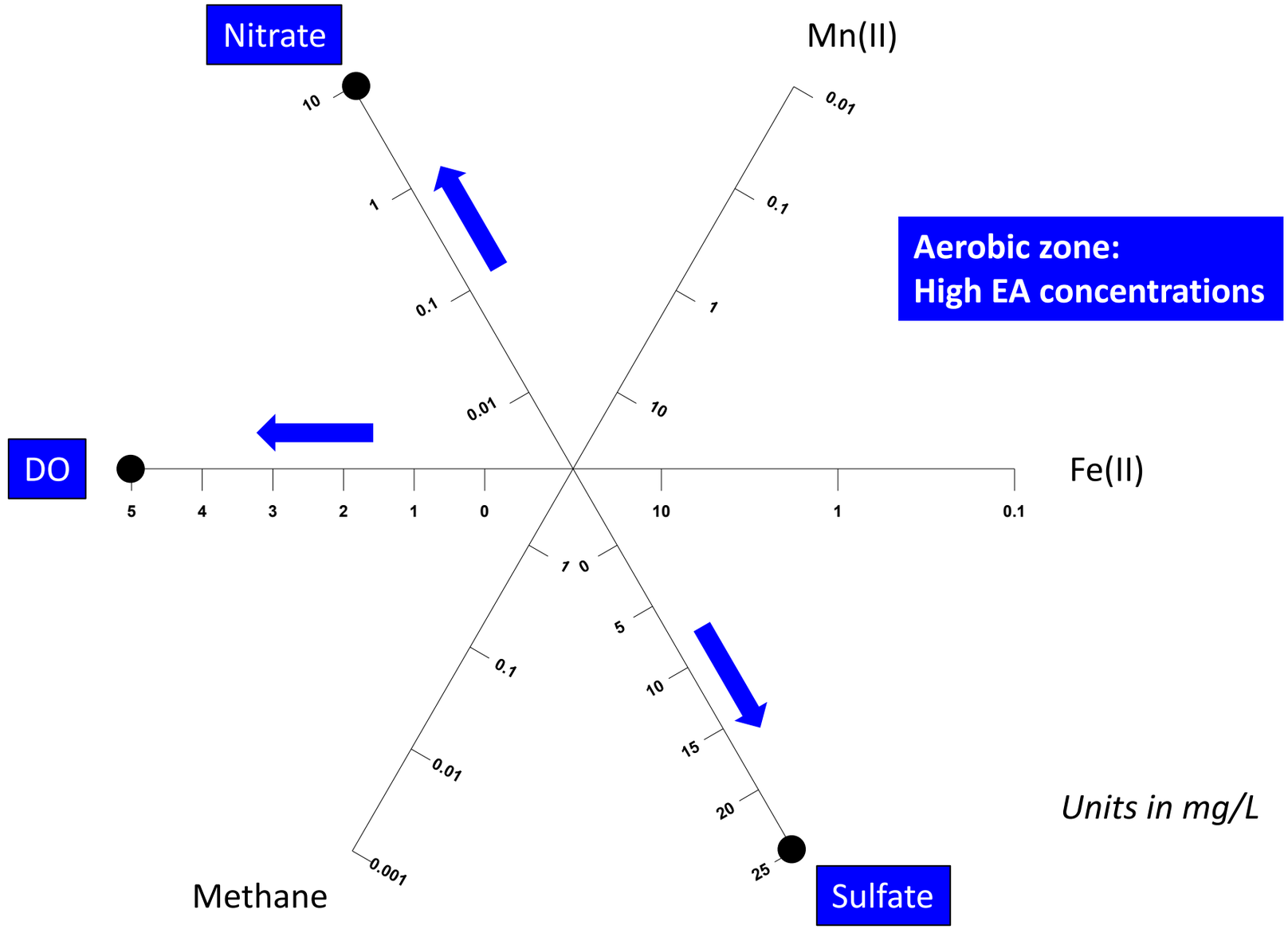
Average RRA versus time in Pilot Test Area (IWs)



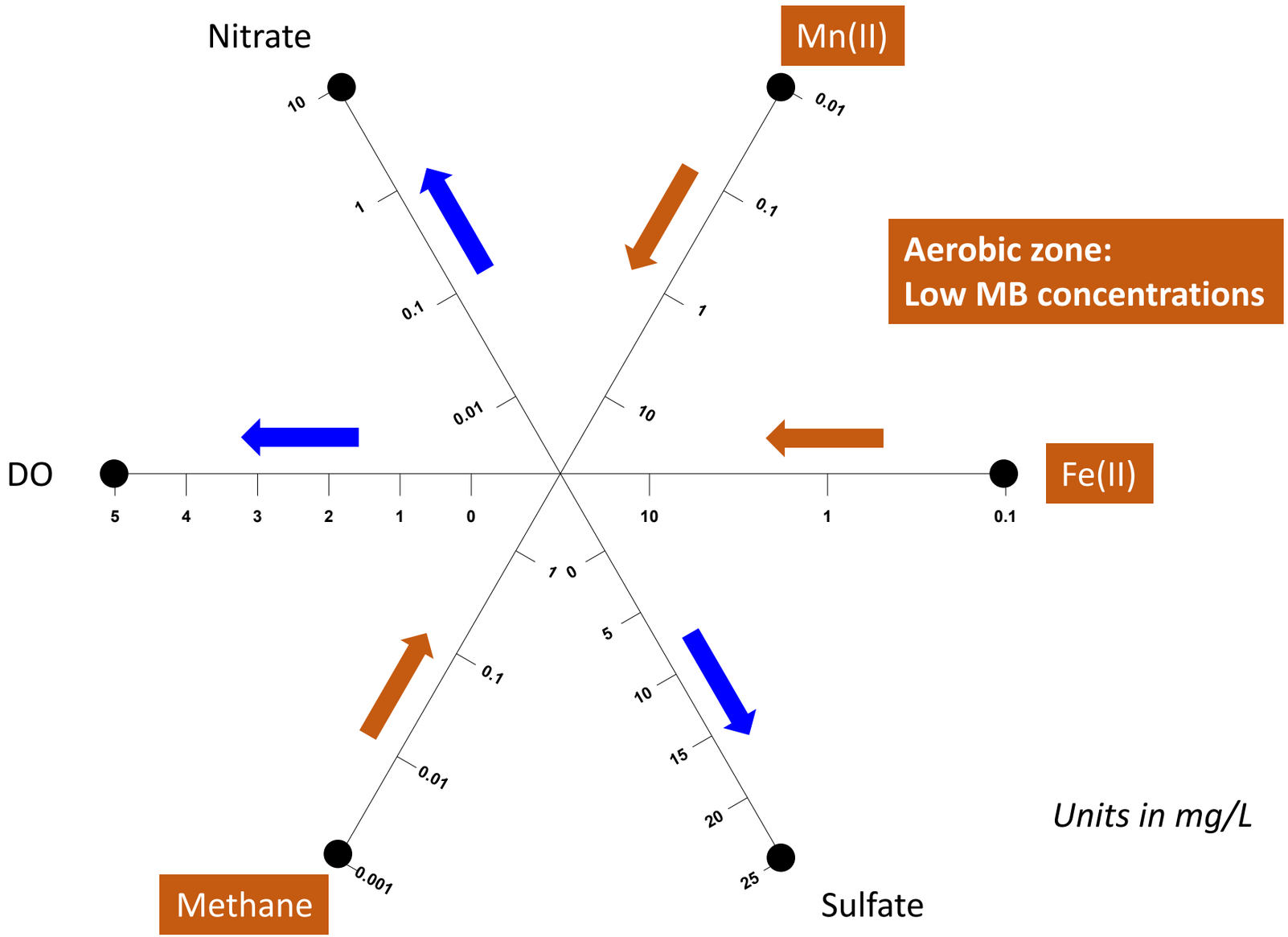
Redox Radial Diagrams

Section 2.1

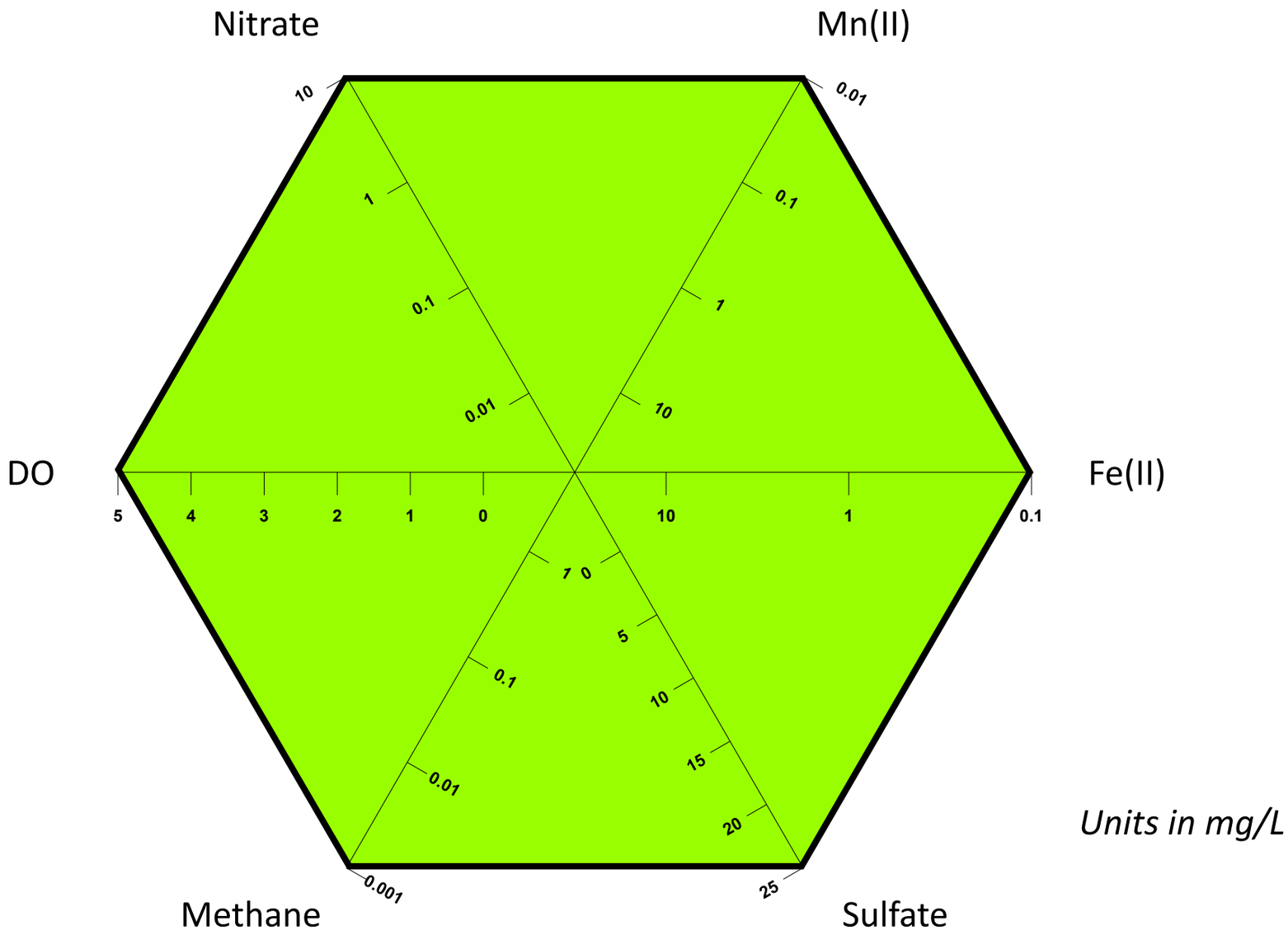
Redox Diagram: Electron Acceptors (EA)



Redox Diagram: Metabolic By-Products (MB)

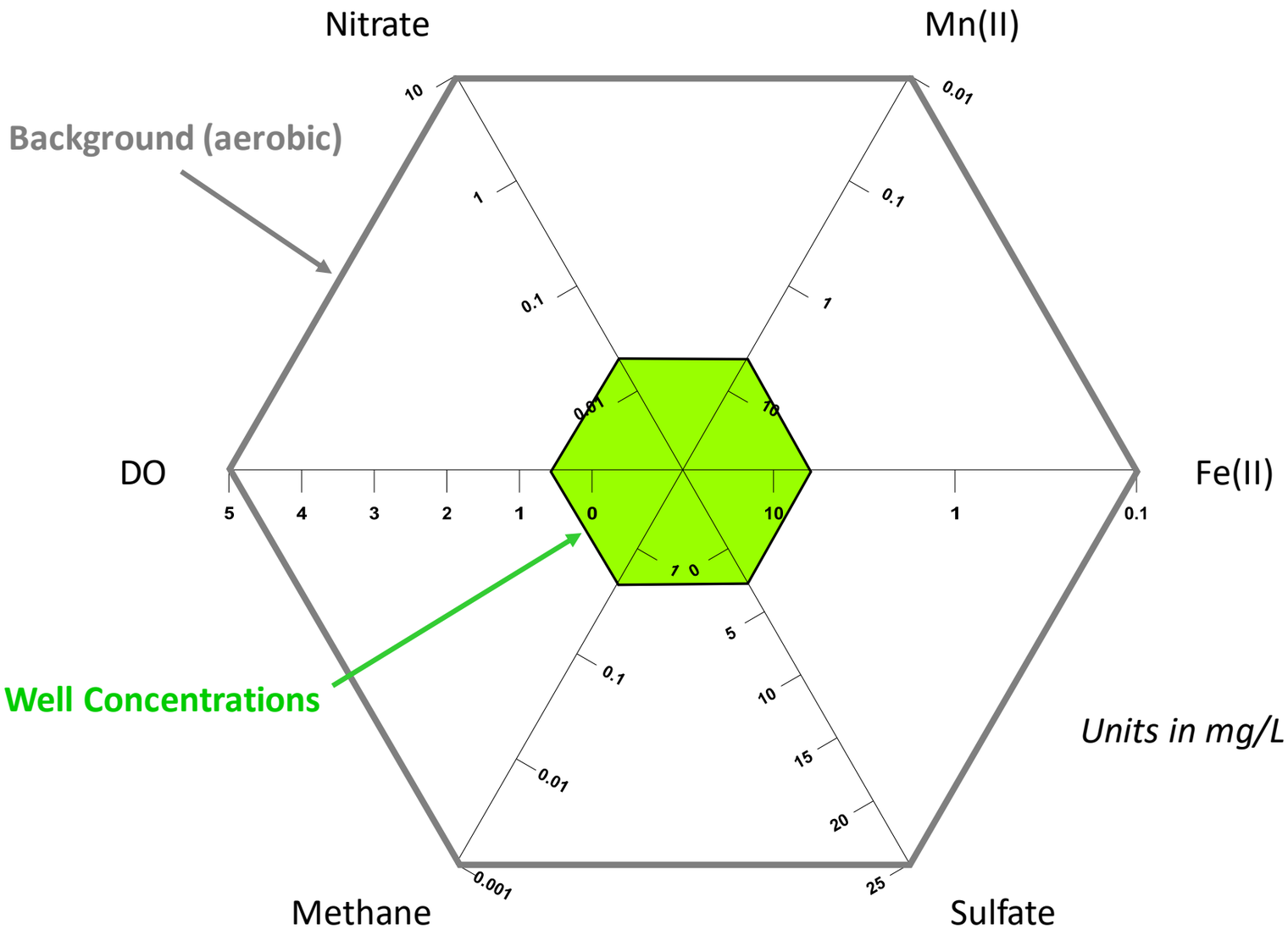


Redox Diagram: Aerobic (Background)

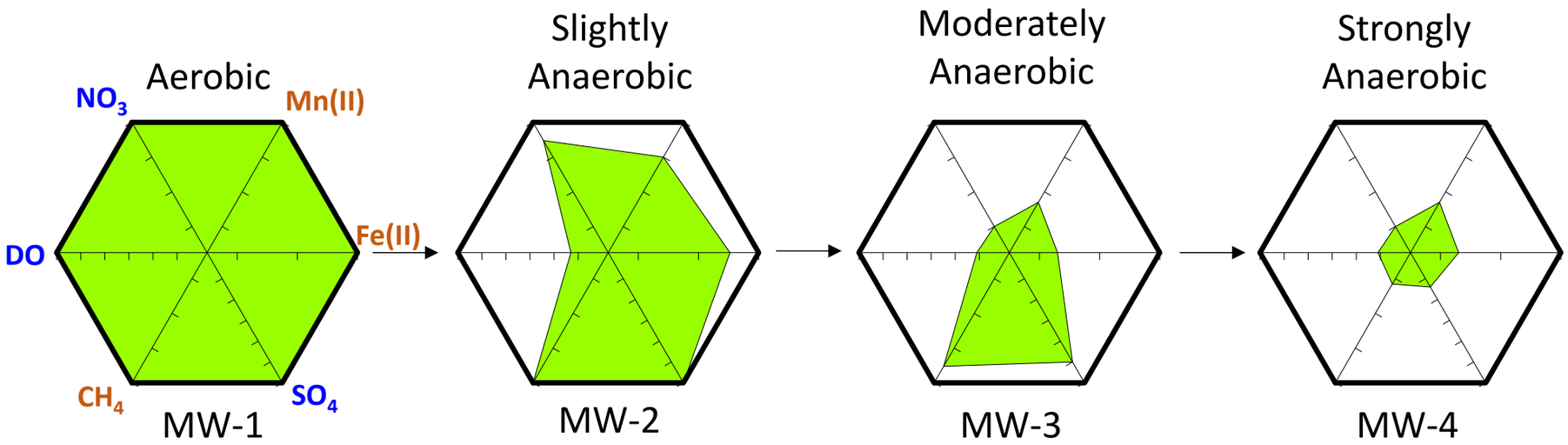


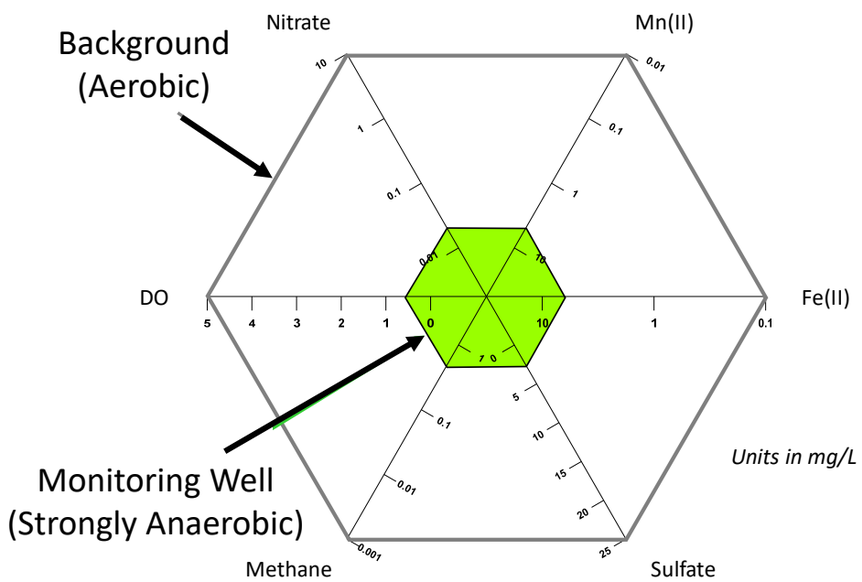
Units in mg/L

Redox Diagram: Strongly Anaerobic at Well



Redox Zone Transition

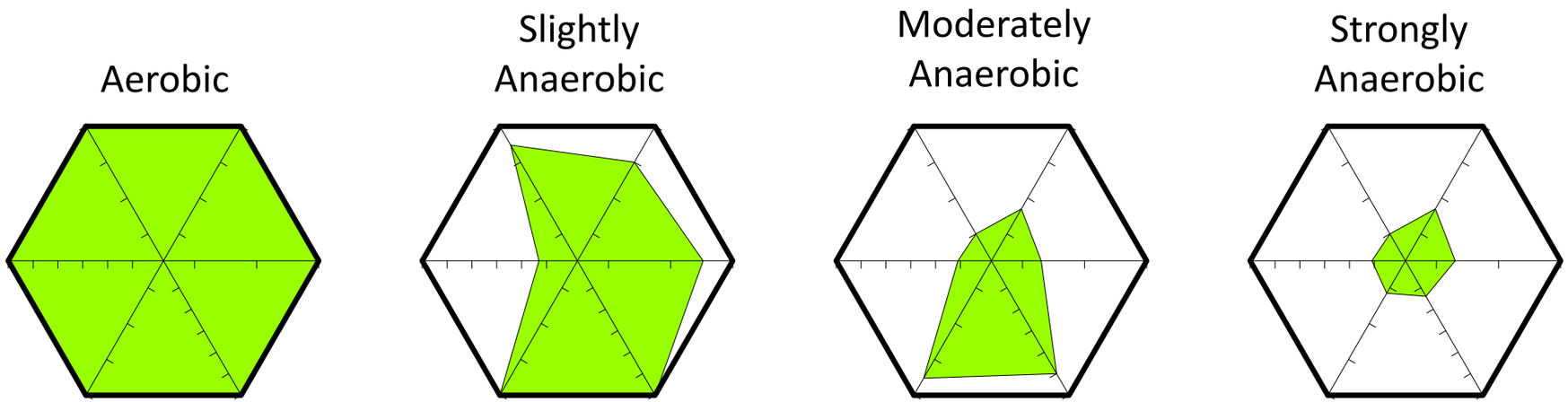




Redox Zone Transition

Location	DO (mg/L)	Nitrate (mg/L)	Mn(II) (mg/L)	Fe(II) (mg/L)	Sulfate (mg/L)	Methane (mg/L)
Aerobic	5	10	<0.01	<0.1	25	<0.001
Slightly Anaerobic	0.3	3	0.1	0.3	25	<0.001
Moderately Anaerobic	0.1	<0.01	2	5	18	0.01
Strongly Anaerobic	0.1	<0.01	2	5	2	0.7

Redox Zone Transition

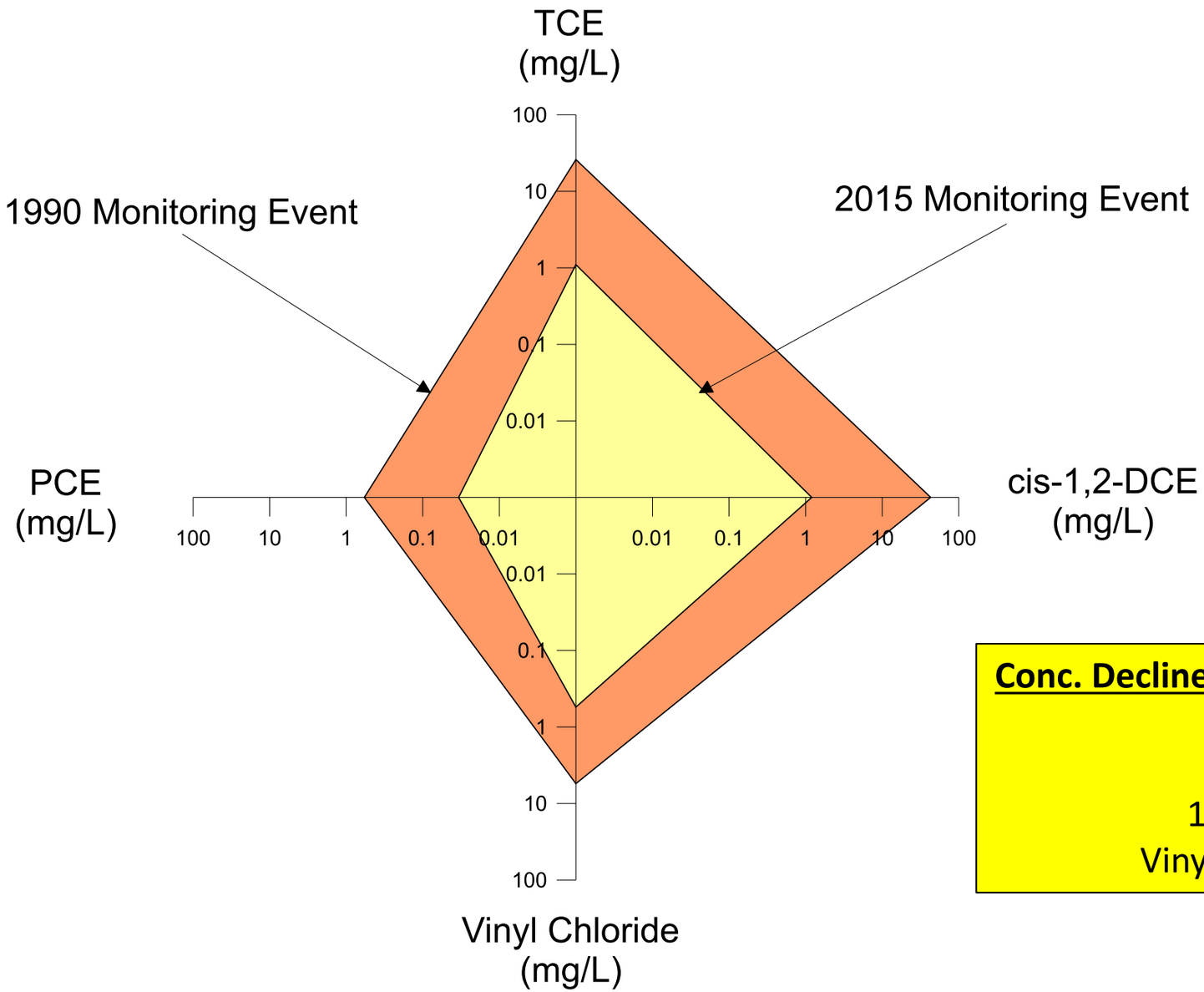


Radial diagrams are ideal for plotting relationships between redox indicators at each monitoring well.

Location	DO (mg/L)	Nitrate (mg/L)	Mn(II) (mg/L)	Fe(II) (mg/L)	Sulfate (mg/L)	Methane (mg/L)
Aerobic	5	10	<0.01	<0.1	25	<0.001
Slightly Anaerobic	0.3	3	0.1	0.3	25	<0.001
Moderately Anaerobic	0.1	<0.01	2	5	18	0.01
Strongly Anaerobic	0.1	<0.01	2	5	2	0.7

VOC Radial Diagrams

VOC Radial Diagram: Source Depletion



Conc. Declines at Well (1990 to 2015)

PCE: 10x

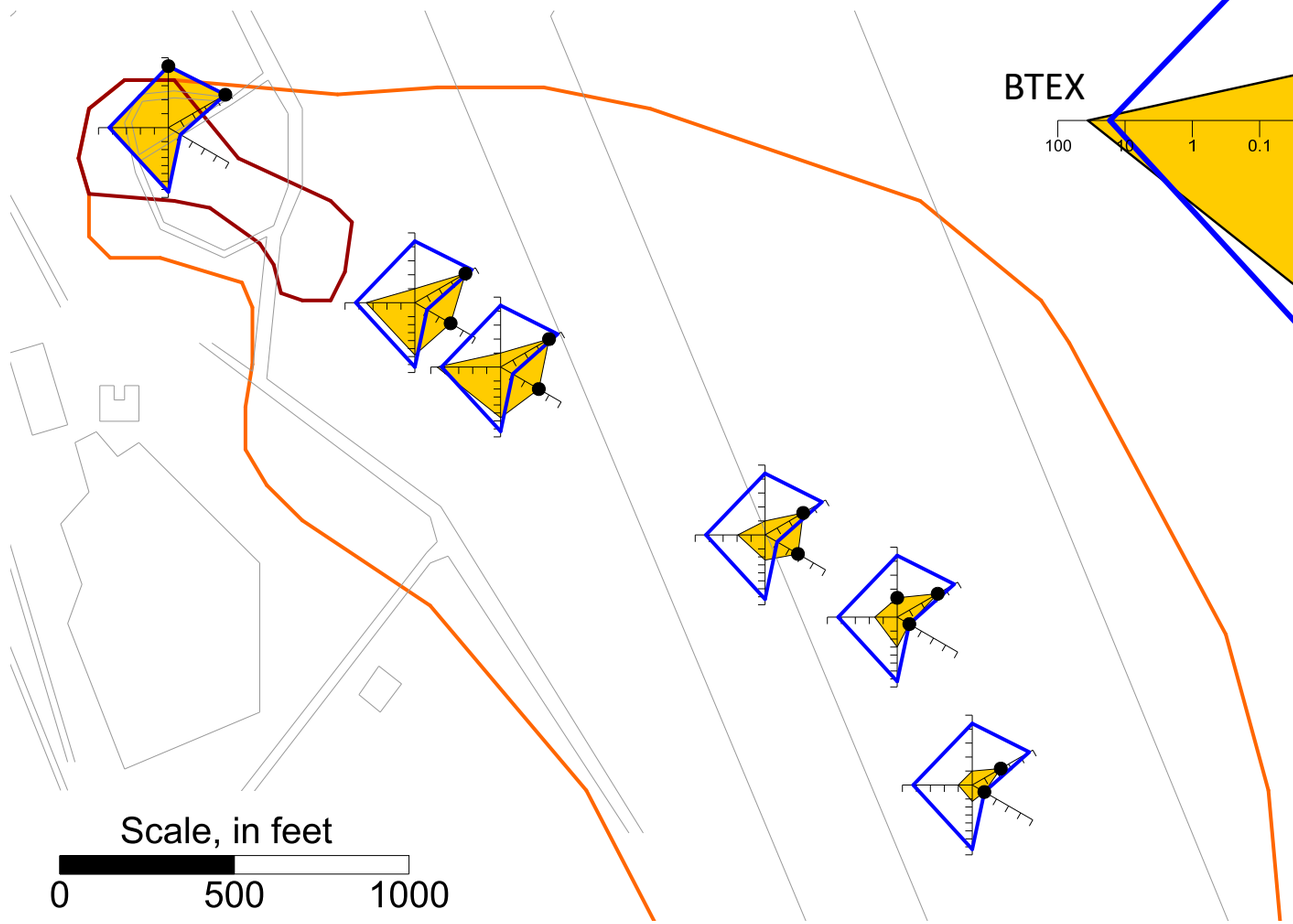
TCE: 30x

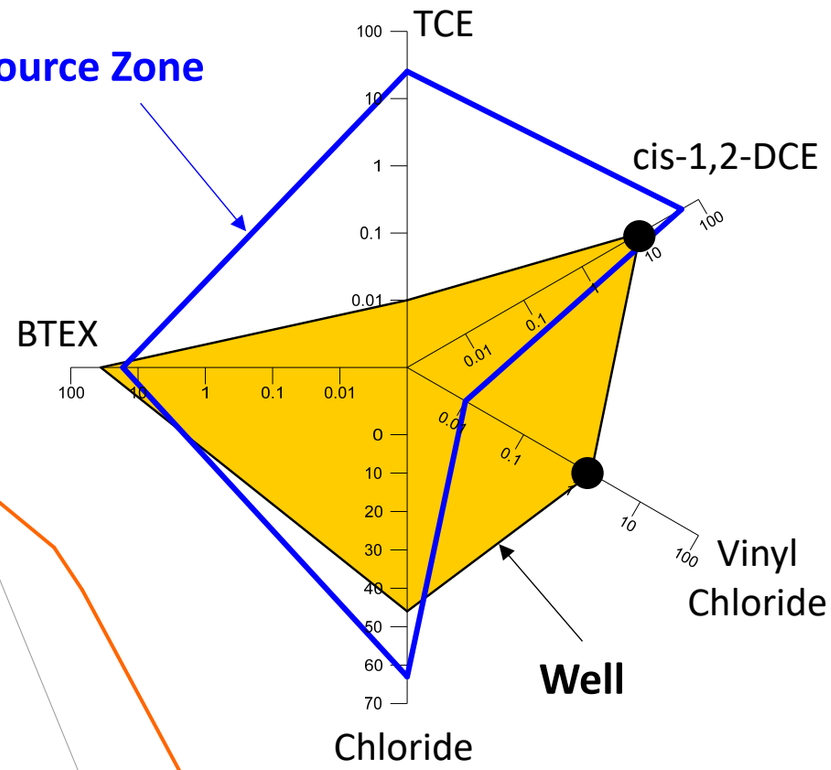
1,2-DCE: 30x

Vinyl Chloride: 10x

Plattsburgh Air Force Base: Plume Attenuation

Carey et al. (2003)





Concentrations in mg/L.

● MCL Exceedance

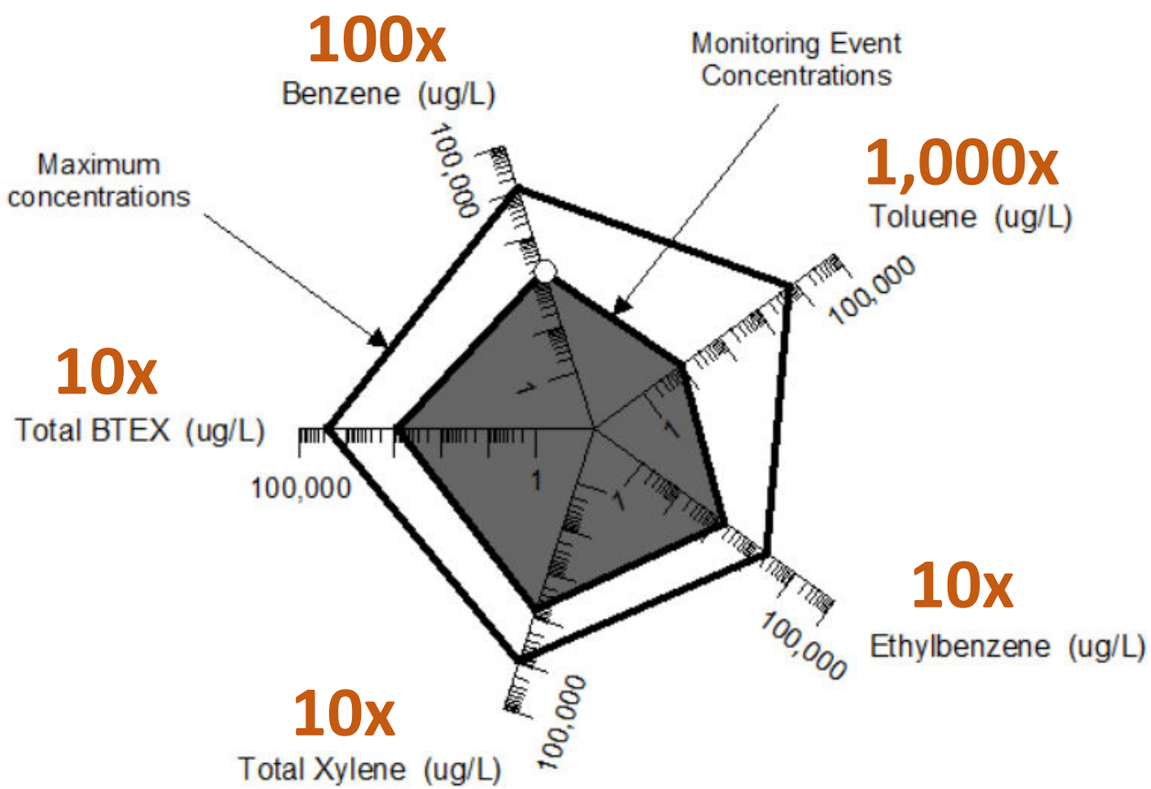
Hill Air Force Base: Plume Attenuation

Carey et al. (1999)

LEGEND

○ Measured analyte concentration exceeds Federal MCL

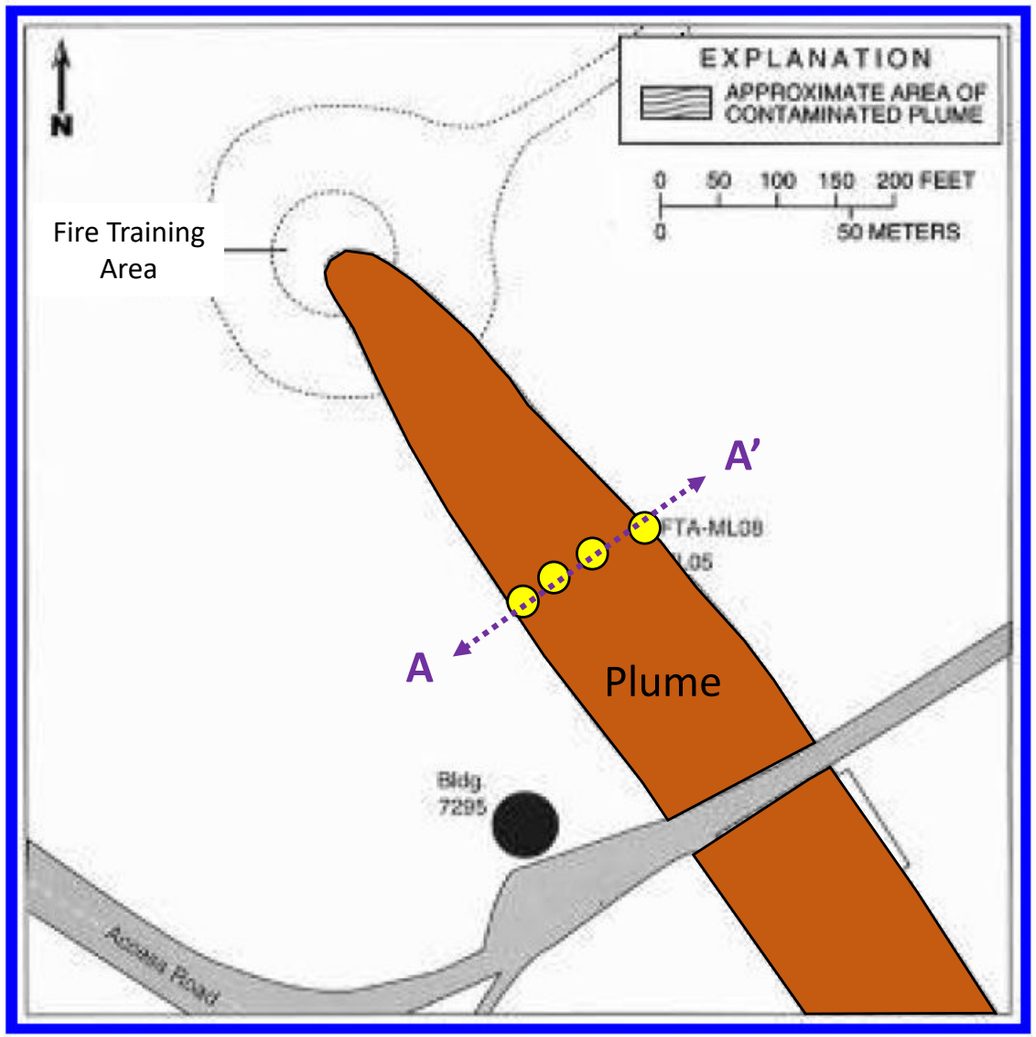
NOTE: All axes range in concentration from 1 ug/L to 100,000 ug/L and use a log scale.



Wurtsmith Air Force Base Case Study

Section 3.3

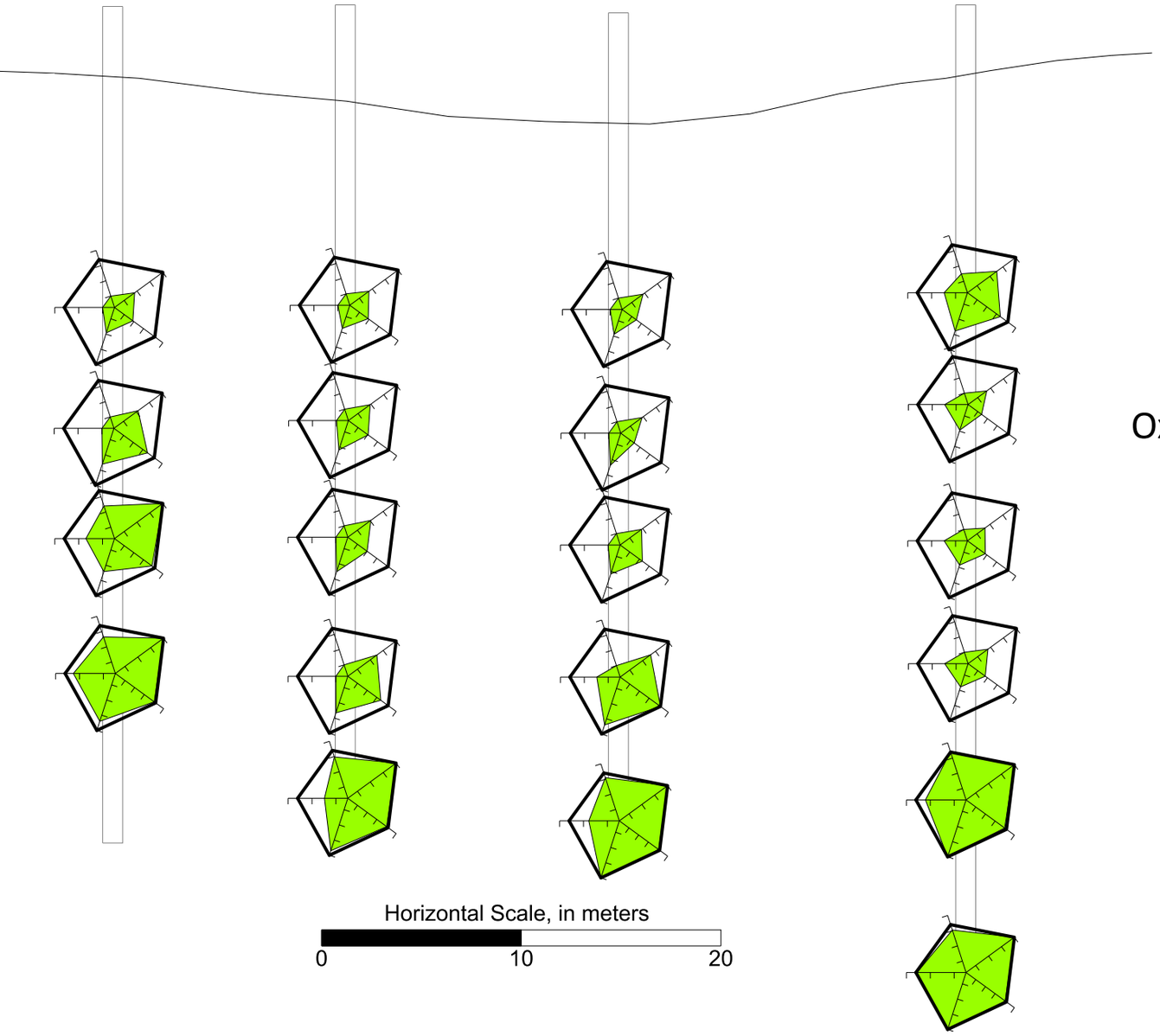
Wurtsmith Air Force Base, Michigan

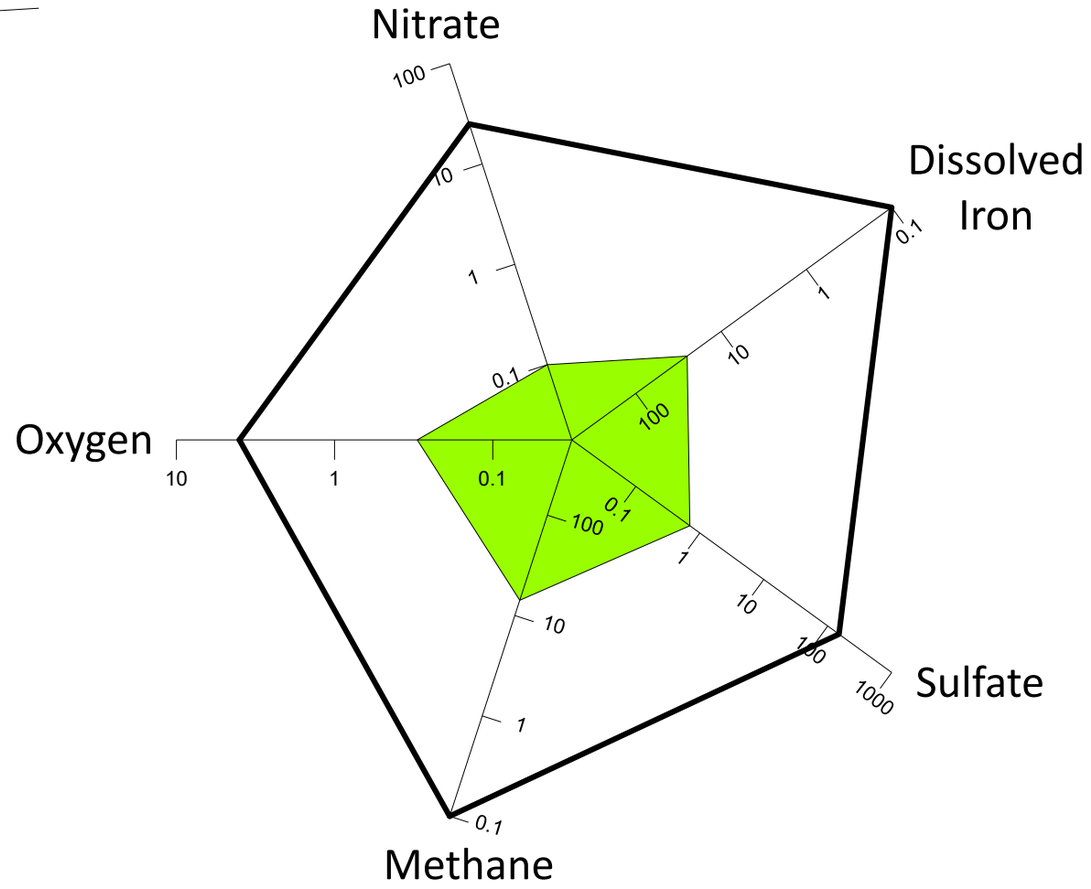


Chapelle et al. (Env. Sci. & Tech., 1996)

- Chlorinated solvents and petroleum hydrocarbons used to start fires (1952-86)
- Contaminants seeped to underlying water table (5-8 m bgs)
- Permeable sands and gravels
- Four multilevel wells
  - 1” diameter
  - 0.3 m screens, separated by 0.2 to 0.5 m

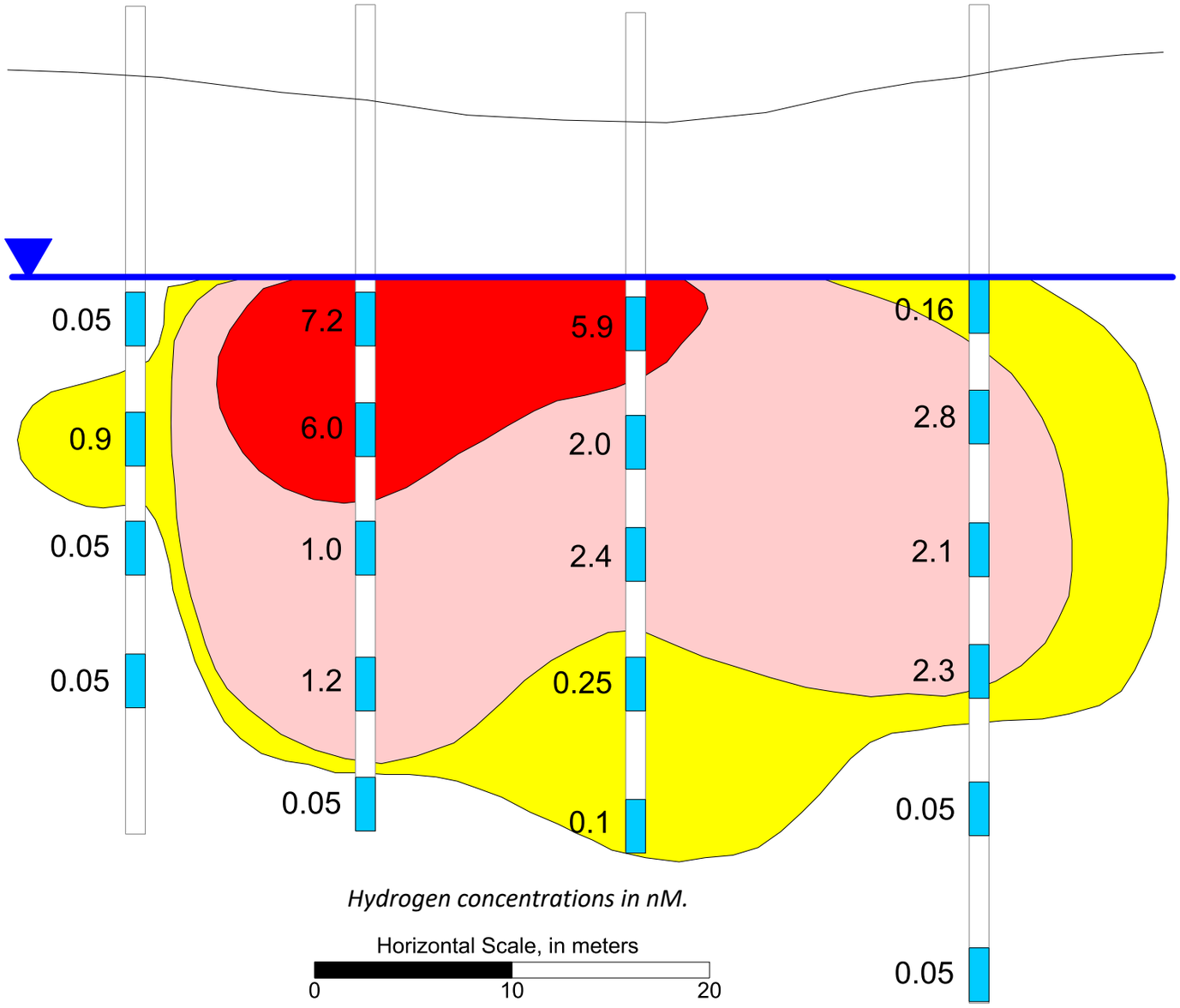
Redox Radial Diagrams



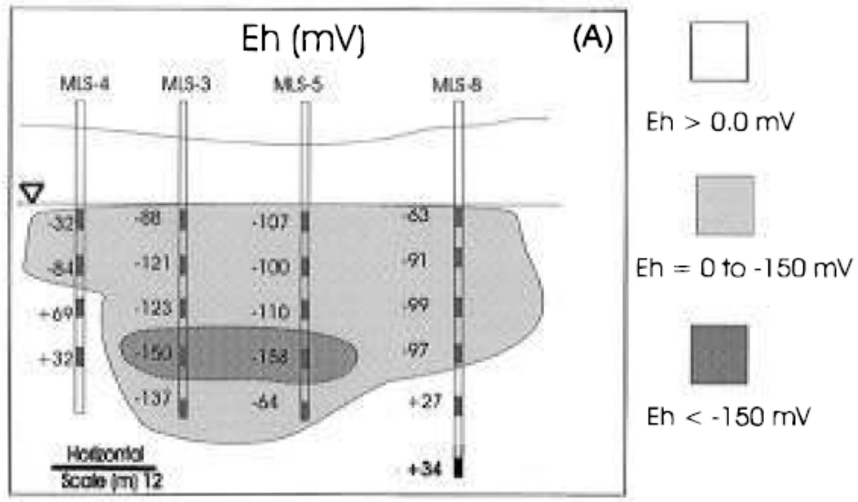


All concentrations in mg/L.

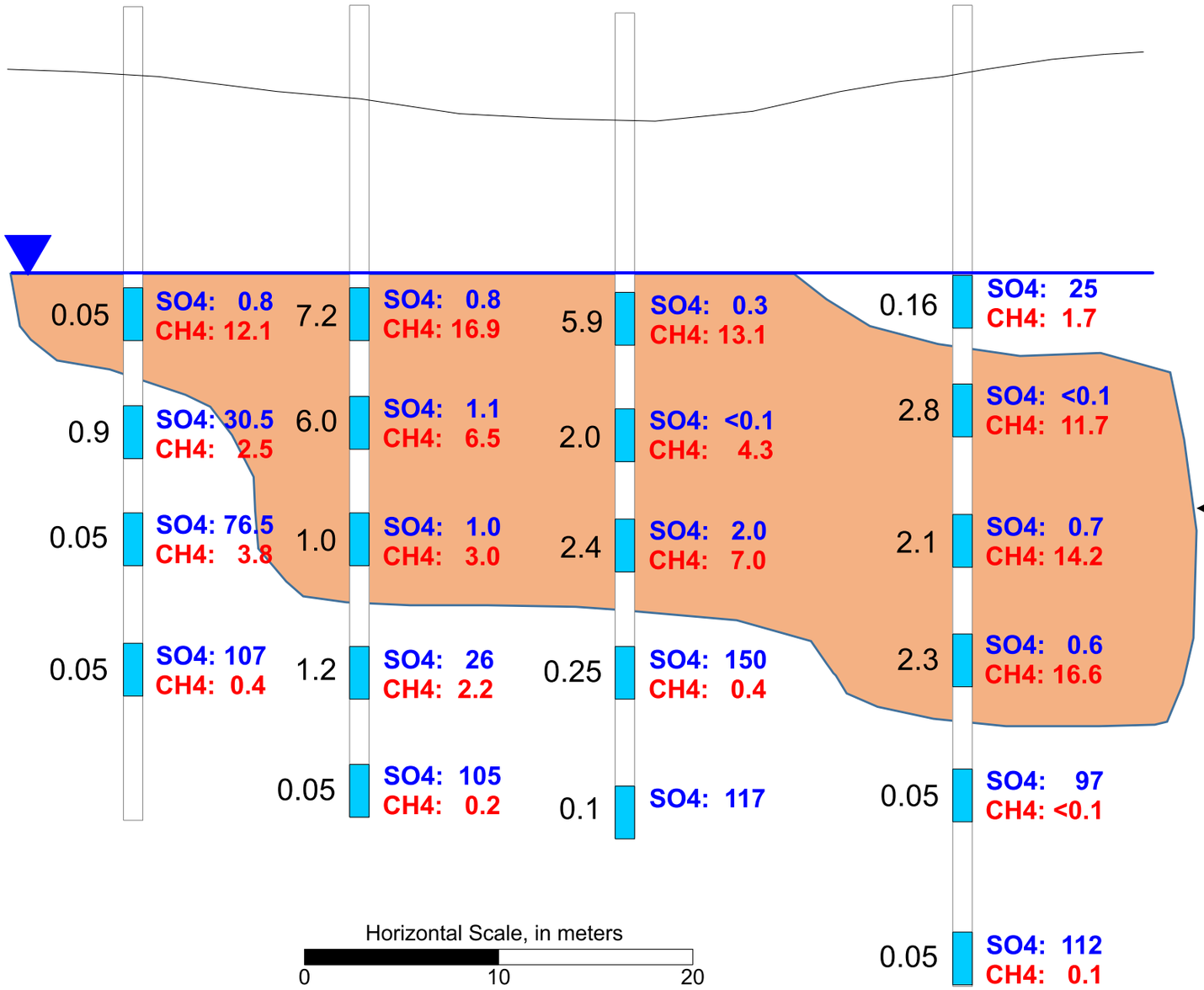
Hydrogen Concentrations (Chapelle et al., 1996)



	H_2 (nM)
Iron-reducers	**0.2 to 0.8**
Sulfate-reducers	**1 to 4**
Methanogens	**5 to 15**



Hydrogen Concentrations (Chapelle et al., 1996)

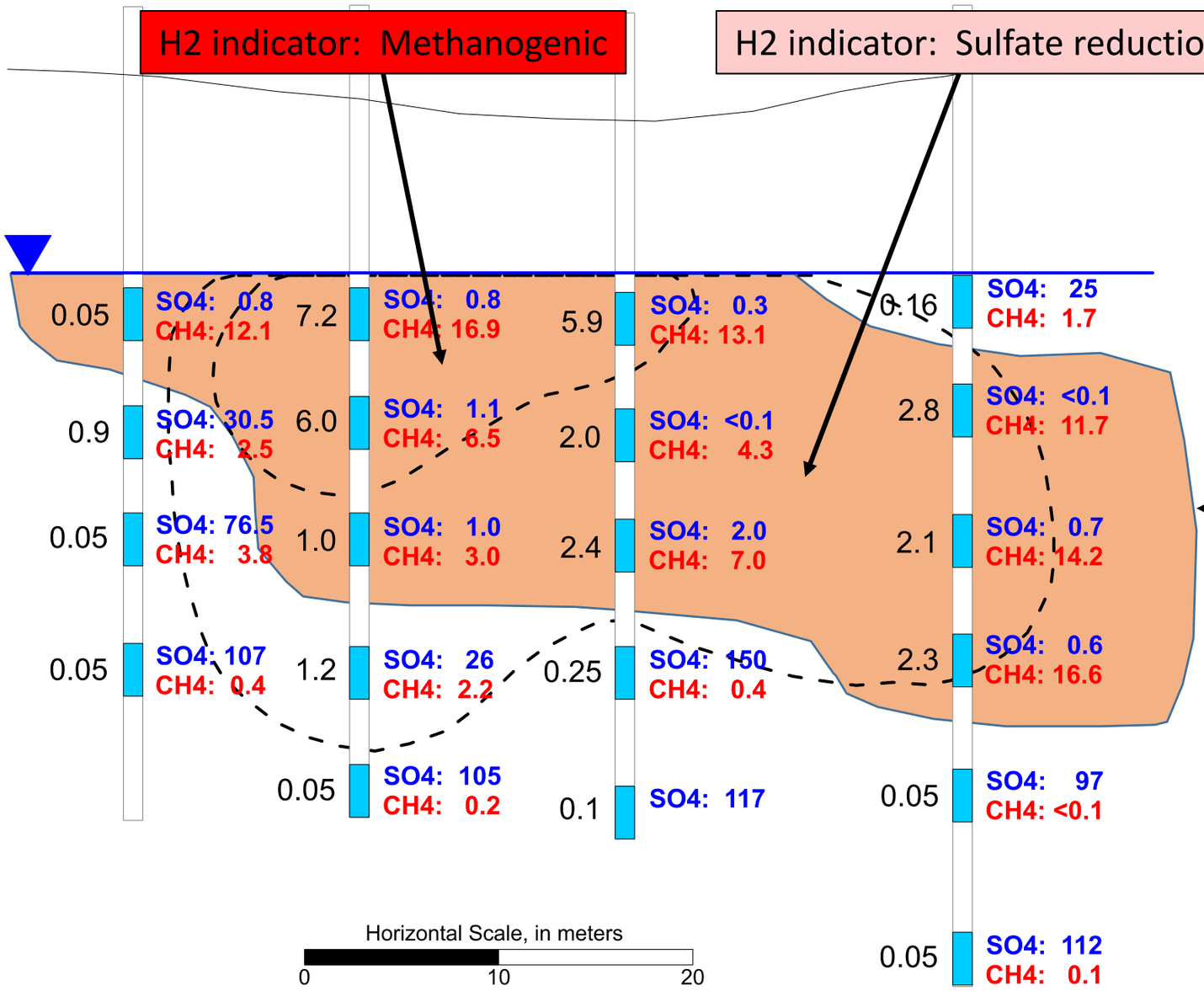


	H_2 (nM)
Iron-reducers	0.2 to 0.8
Sulfate-reducers	1 to 4
Methanogens	5 to 15

High methane and low sulfate (predominantly **Methanogenic**)

Note – concentrations in mg/L.

Hydrogen Concentrations (Chapelle et al., 1996)



	H_2 (nM)
Iron-reducers	0.2 to 0.8
Sulfate-reducers	1 to 4
Methanogens	5 to 15

High methane and low sulfate (predominantly **Methanogenic**)

Chapelle et al. (1996):

"Because of these complexities, using H_2 measurements as a sole indicator of redox processes is not appropriate."

Delineating Redox Zones Based on Indicator Concentrations

Redox Processes and Water Quality of Selected Principal Aquifer Systems

by P.B. McMahon[1] and F.H. Chapelle[2]

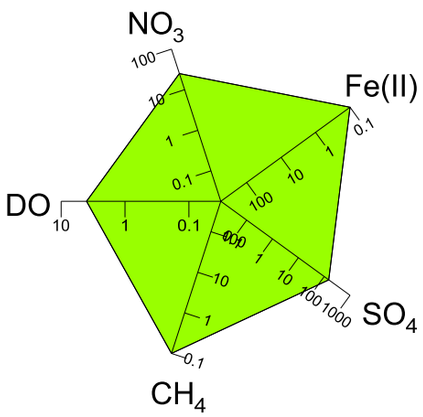
Ground Water, 2008, 46(2): 259-271

Redox Zone	Oxygen	Nitrate	Mn(II)	Fe(II)	SO4	Methane
Aerobic	≥0.5	--	<0.05	<0.1	--	--
Nitrate reduction	<0.5	≥0.5	<0.05	<0.1	--	--
Manganese reduction	<0.5	<0.5	≥0.5	<0.1	--	--
Iron / Sulfate reduction	<0.5	<0.5	<0.5	≥0.1	≥0.5	--
Methanogenesis	<0.5	<0.5	--	≥0.1	<0.5	--

Wurtsmith Relative Redox Area by Zone

- Threshold Areas in Visual Bio – define RRA for the initial transition to each redox zone.

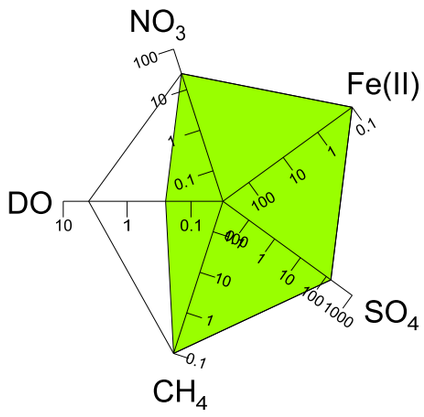
Aerobic



RRA=100%

DO = C_{max}

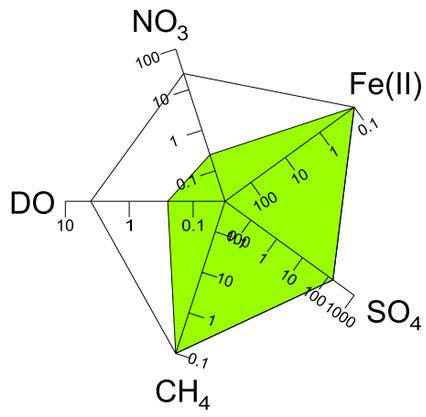
Nitrate reduction



RRA=78%

DO = C_{min}

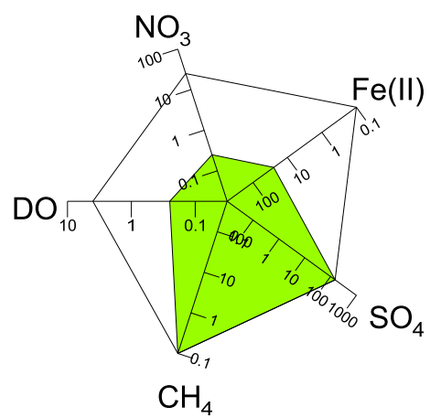
Iron reduction



RRA=60%

NO_3 = C_{min}

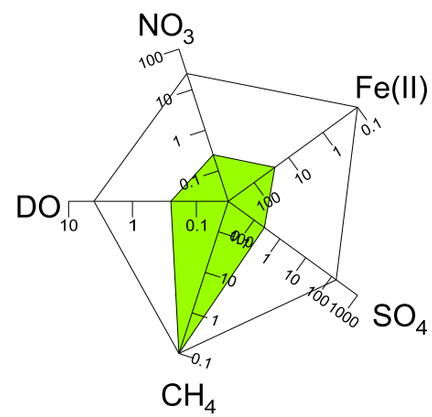
Sulfate reduction



RRA=42%

Fe(II) = C_{max}

Methanogenesis

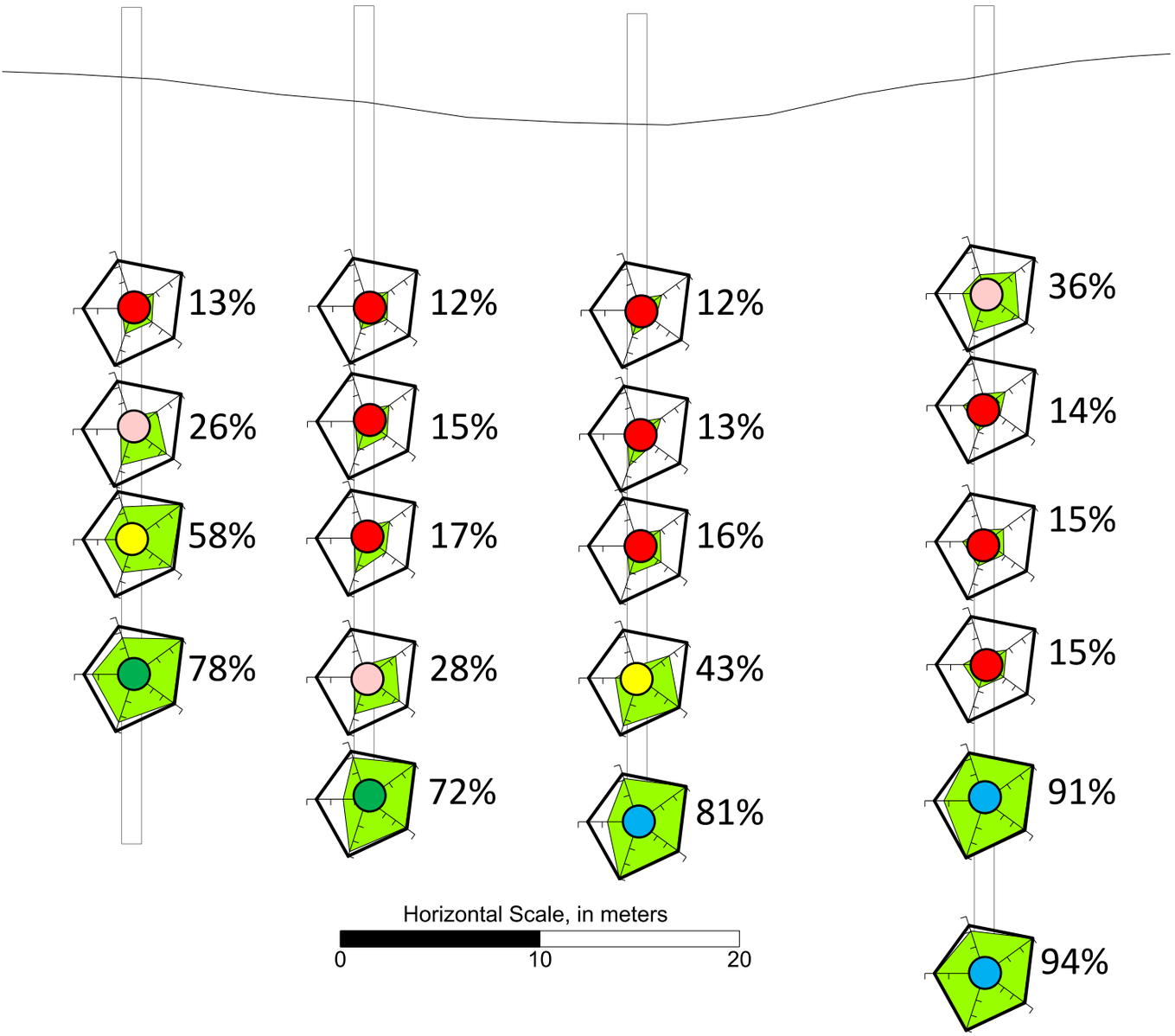


RRA=24%

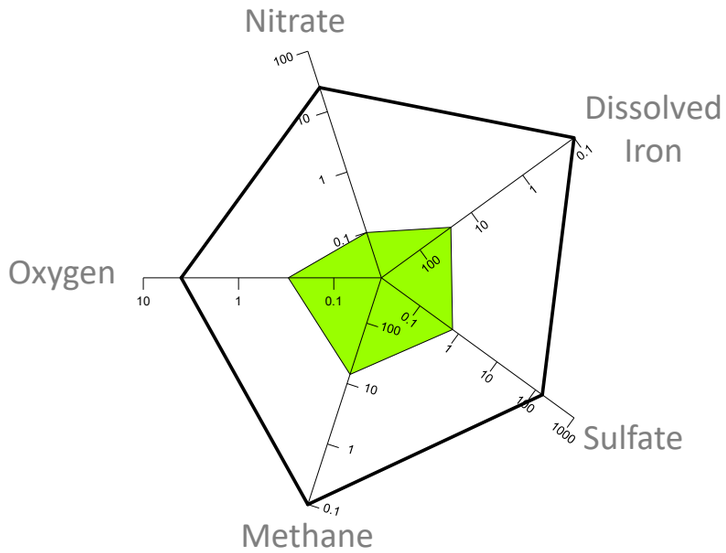
SO_4 = C_{min}

$$\text{Relative Redox Area (RRA)} = \frac{\text{Area of monitoring well polygon}}{\text{Area of reference polygon (Aerobic)}}$$

Relative Redox Area

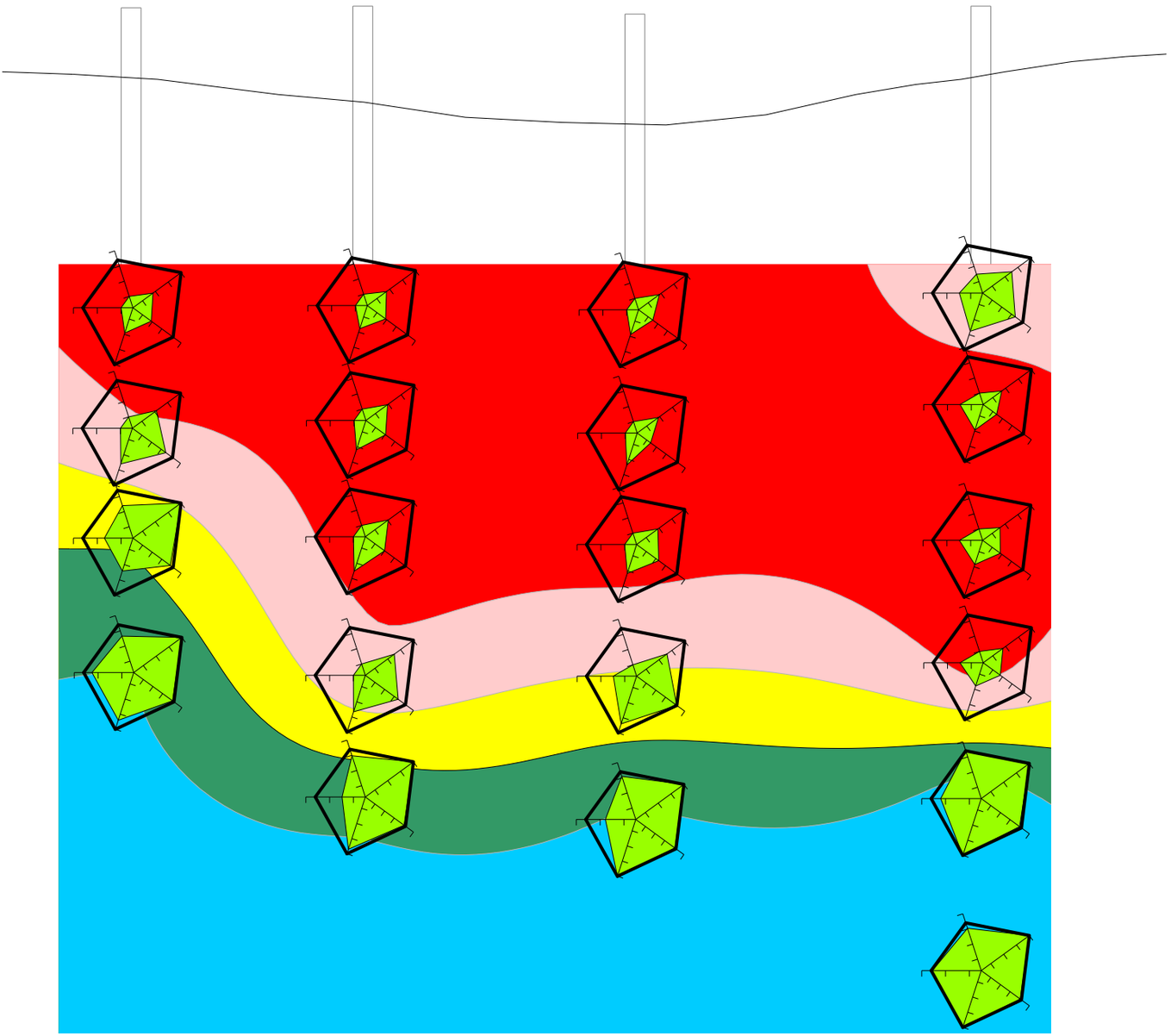


Aerobic:	78 to 100%	
Nitrate-reducing:	60 to 78%	
Iron-reducing:	42 to 60%	
Sulfate-reducing:	24 to 42%	
Methanogenic:	≤24%	

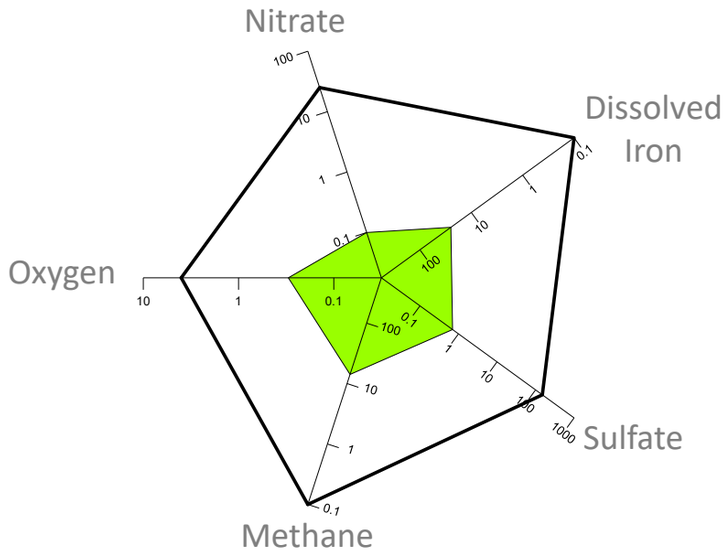


All concentrations in mg/L.

Relative Redox Area Contours

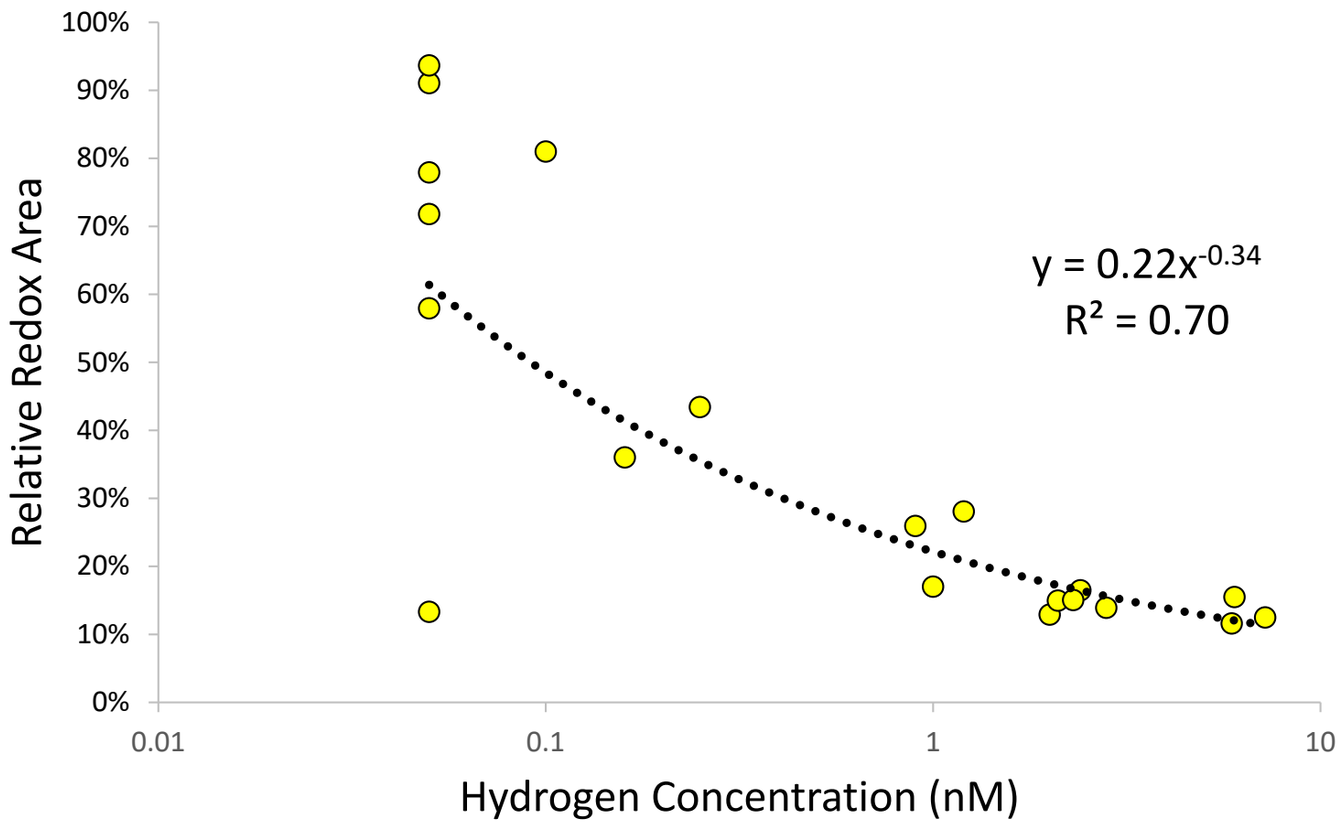


Aerobic:	78 to 100%	
Nitrate-reducing:	60 to 78%	
Iron-reducing:	42 to 60%	
Sulfate-reducing:	24 to 42%	
Methanogenic:	≤24%	

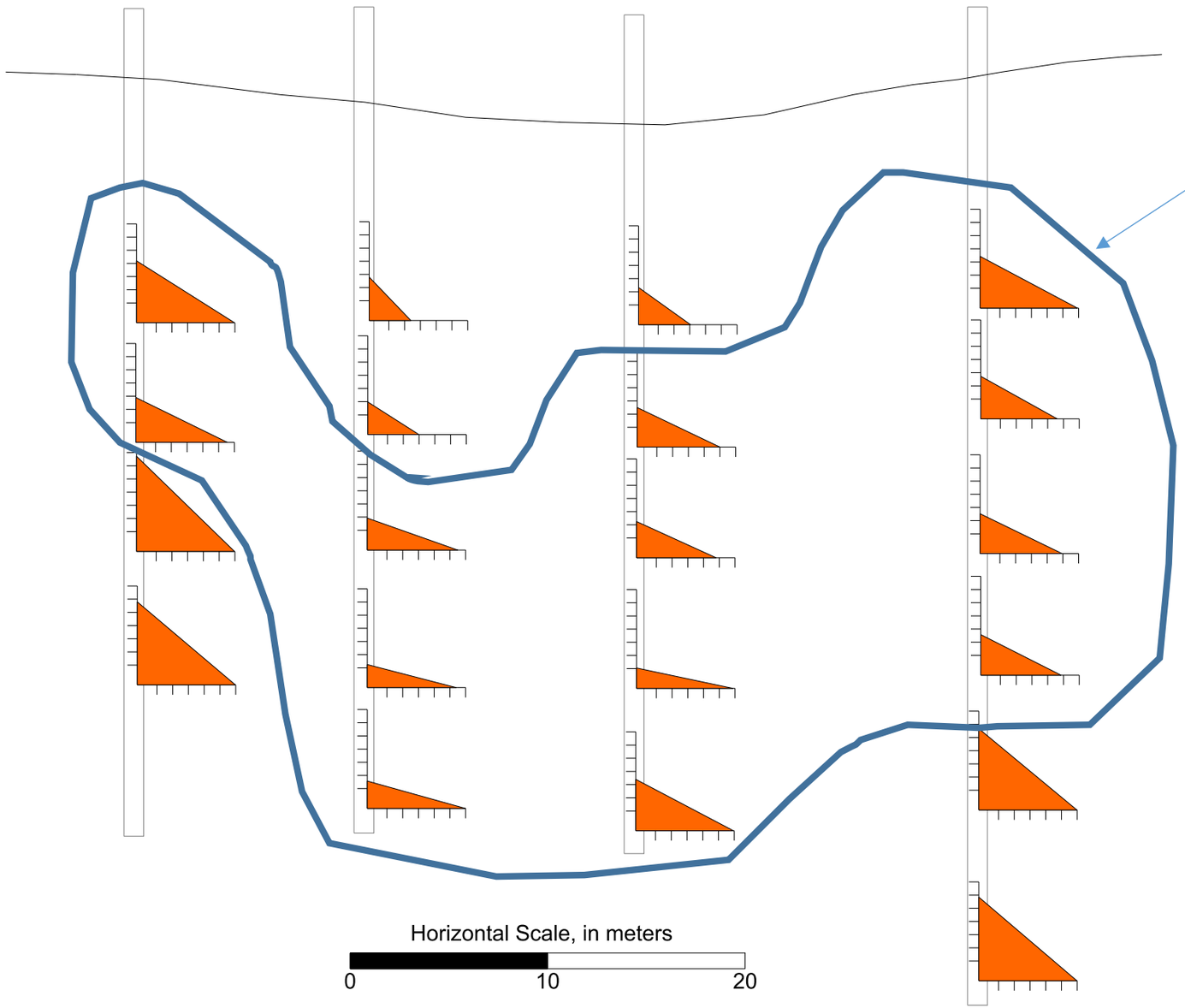


All concentrations in mg/L.

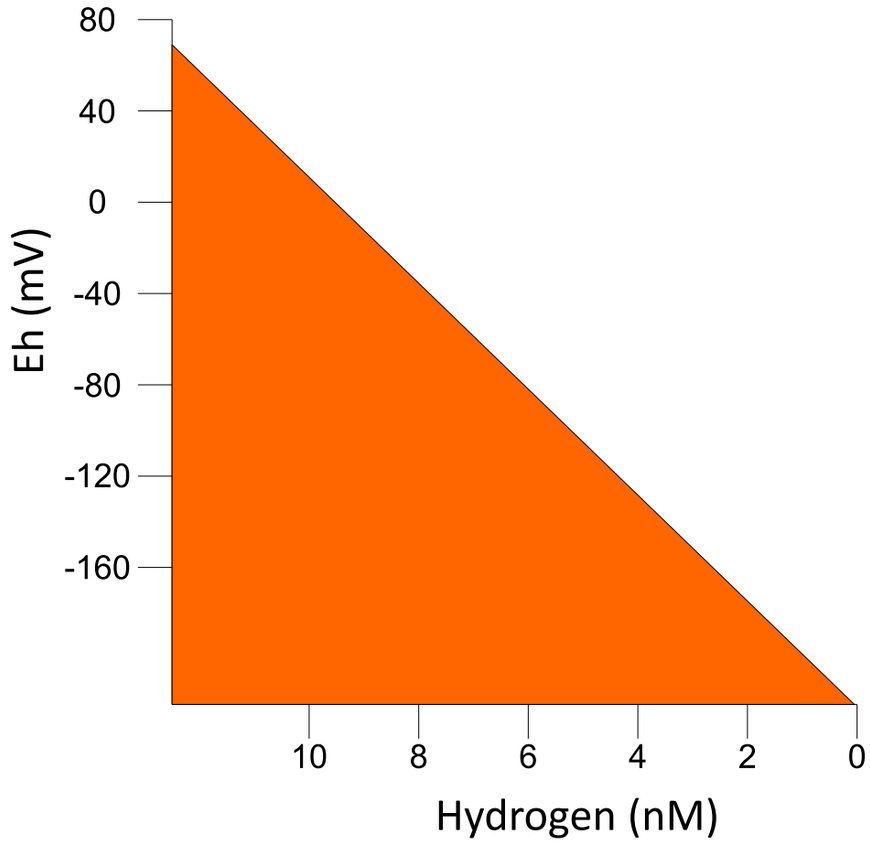
RRA versus Hydrogen Concentration



Eh vs. Hydrogen Concentrations



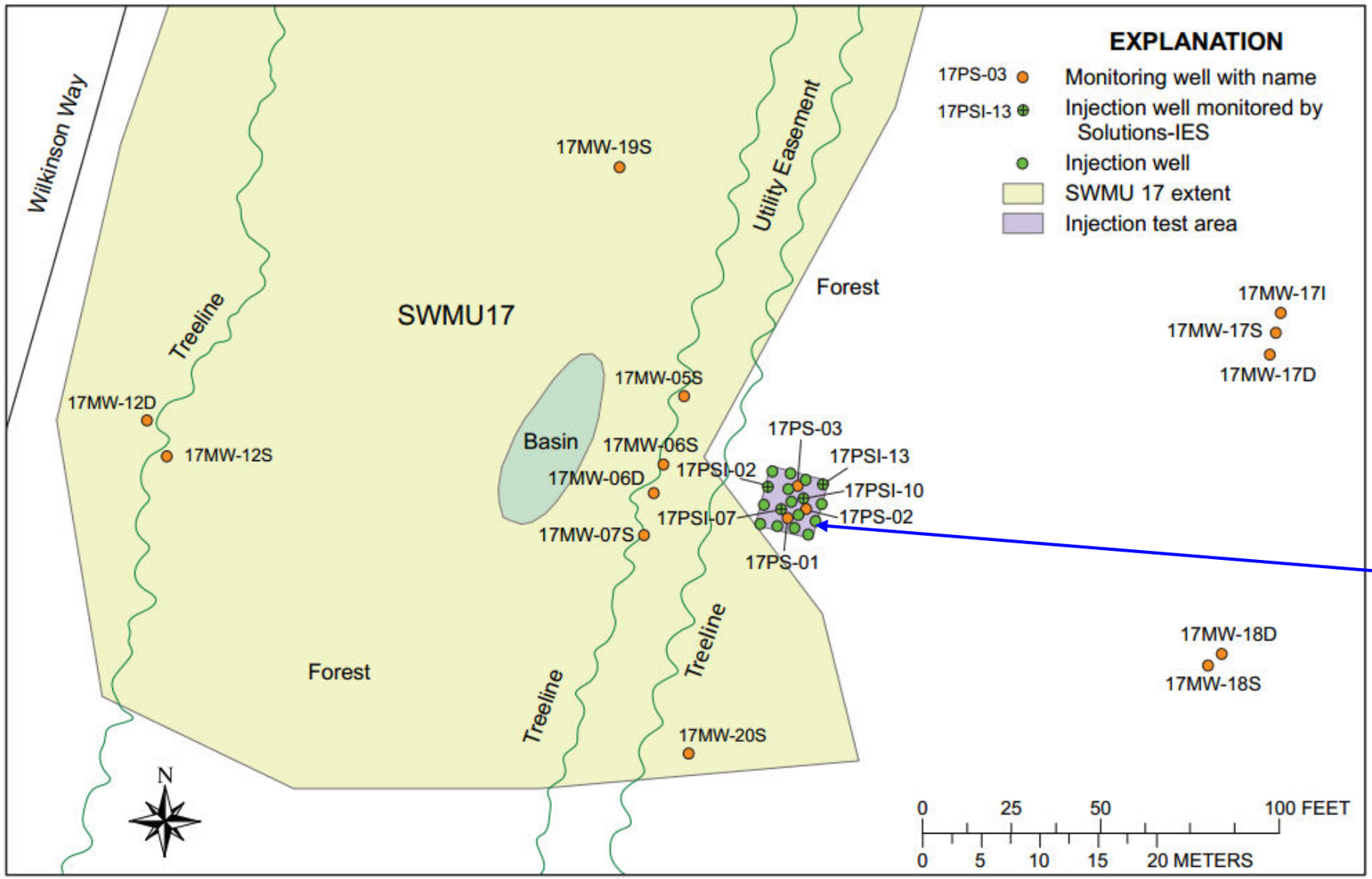
Low Eh and low Hydrogen



Charleston Naval Weapons Station Case Study

Section 3.4

Charleston Naval Weapons Station, South Carolina

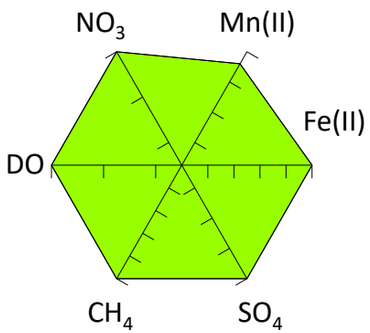


Emulsified Oil Pilot Test Area

USGS, 2009

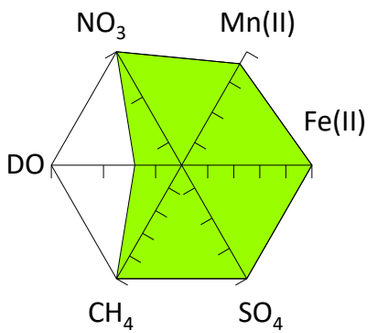
Charleston NWS Relative Redox Area by Zone

Aerobic



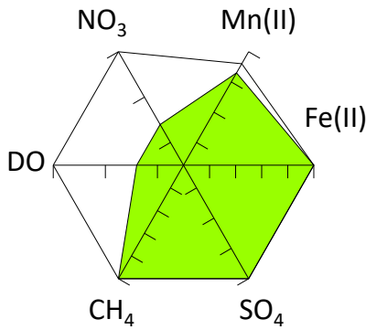
RRA=100%

NO_3-reduction



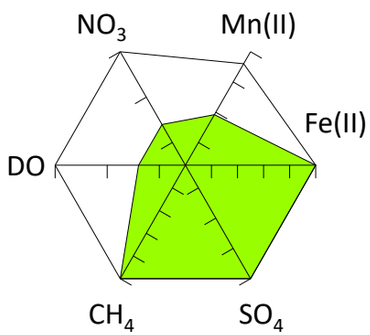
RRA=78%

Mn-reduction



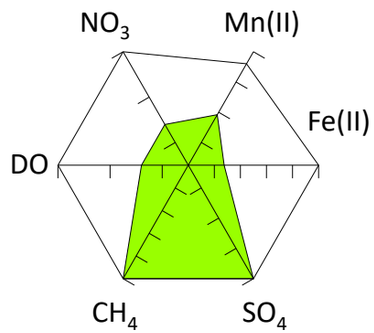
RRA=62%

Fe-reduction



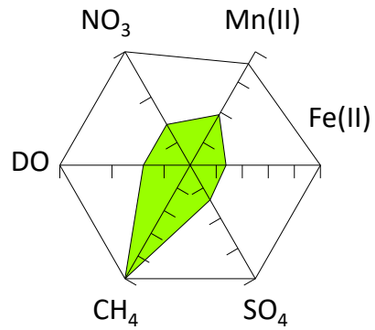
RRA=53%

SO_4-reduction



RRA=35%

Methanogenesis



RRA=20%

RRA=100%

RRA=78%

RRA=60%

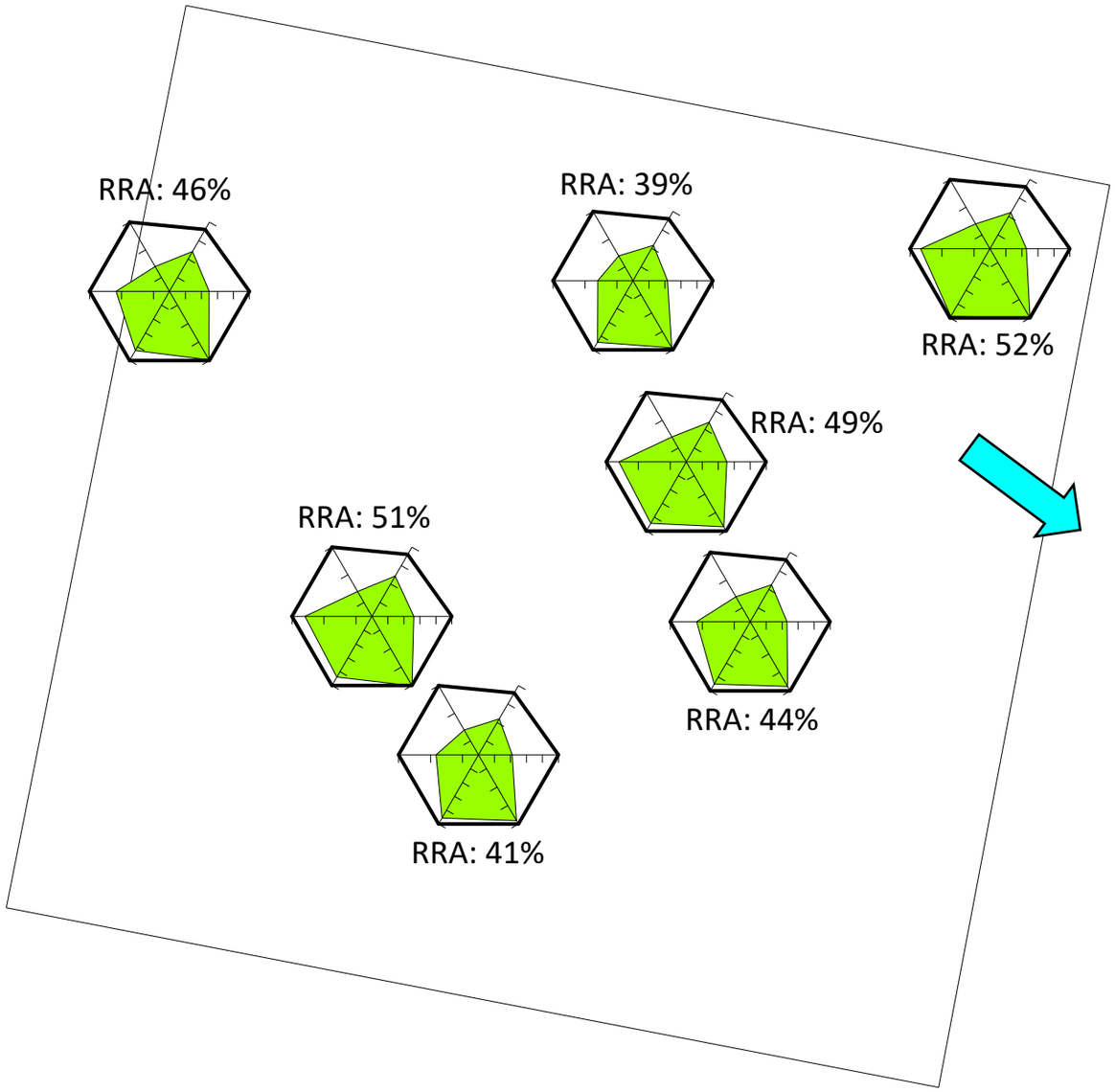
RRA=42%

RRA=24%

Wurtsmith AFB redox zone thresholds (p. 1.57):

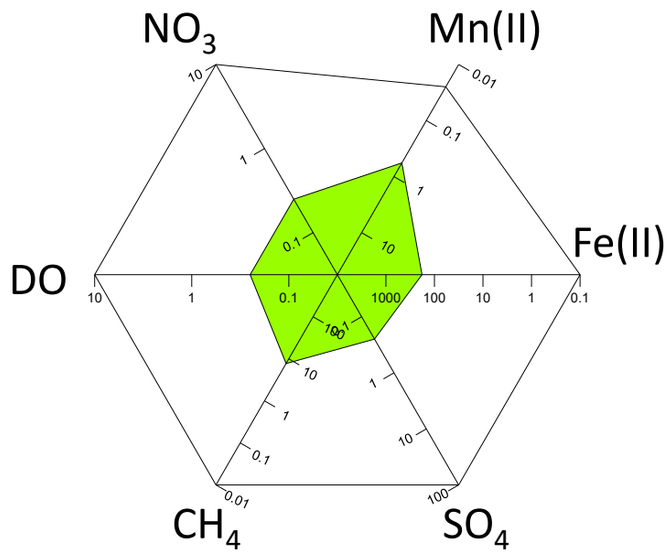
Redox Indicator Event 1: 2004-04-01 (Pre-Injection)

Days after start of Phase I injection: -42
Days after start of Phase II injection: -



Phase I injection well

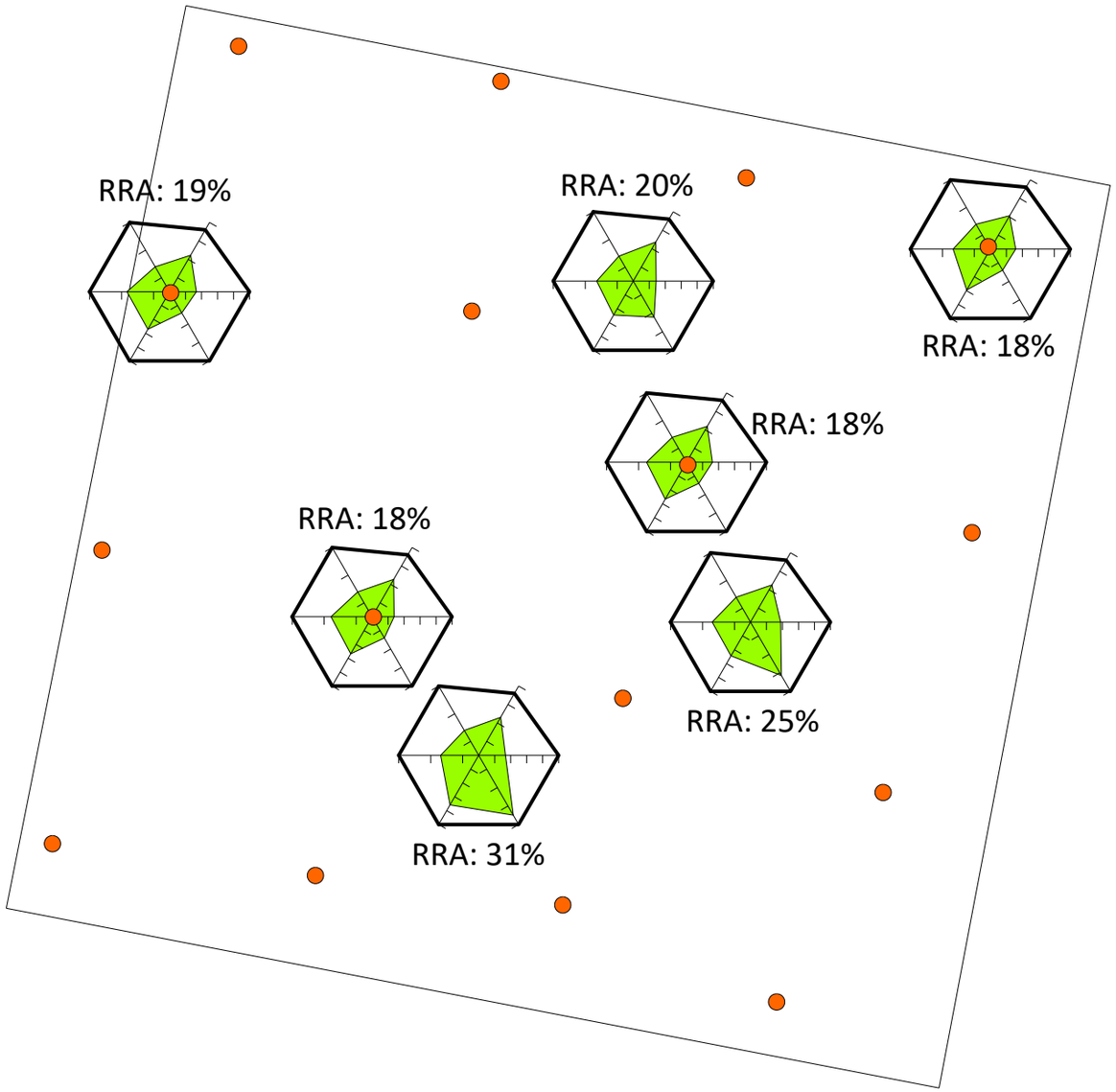
Redox Zone	RRA (%)
Aerobic	78-100
NO_3	62-78
Mn(II)	53-62
Fe(II)	35-53
SO_4	20-35
CH_4	≤20



Concentrations in mg/L

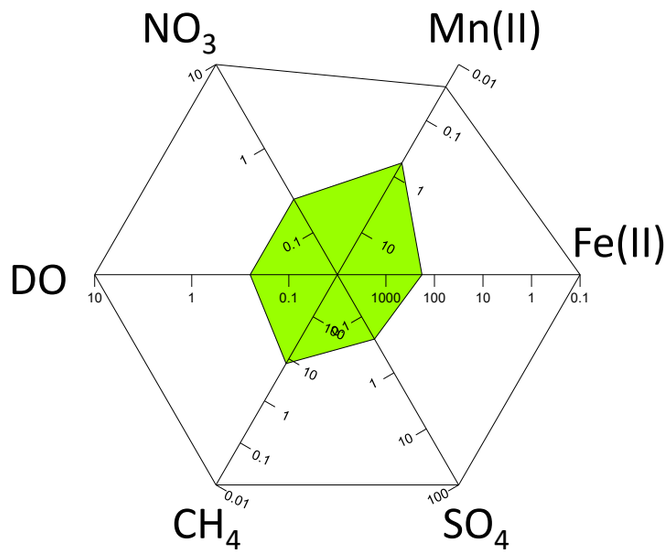
Redox Indicators Event 8: 2006-03-29

Days after start of Phase I injection: 685
Days after start of Phase II injection: -



Phase I injection well

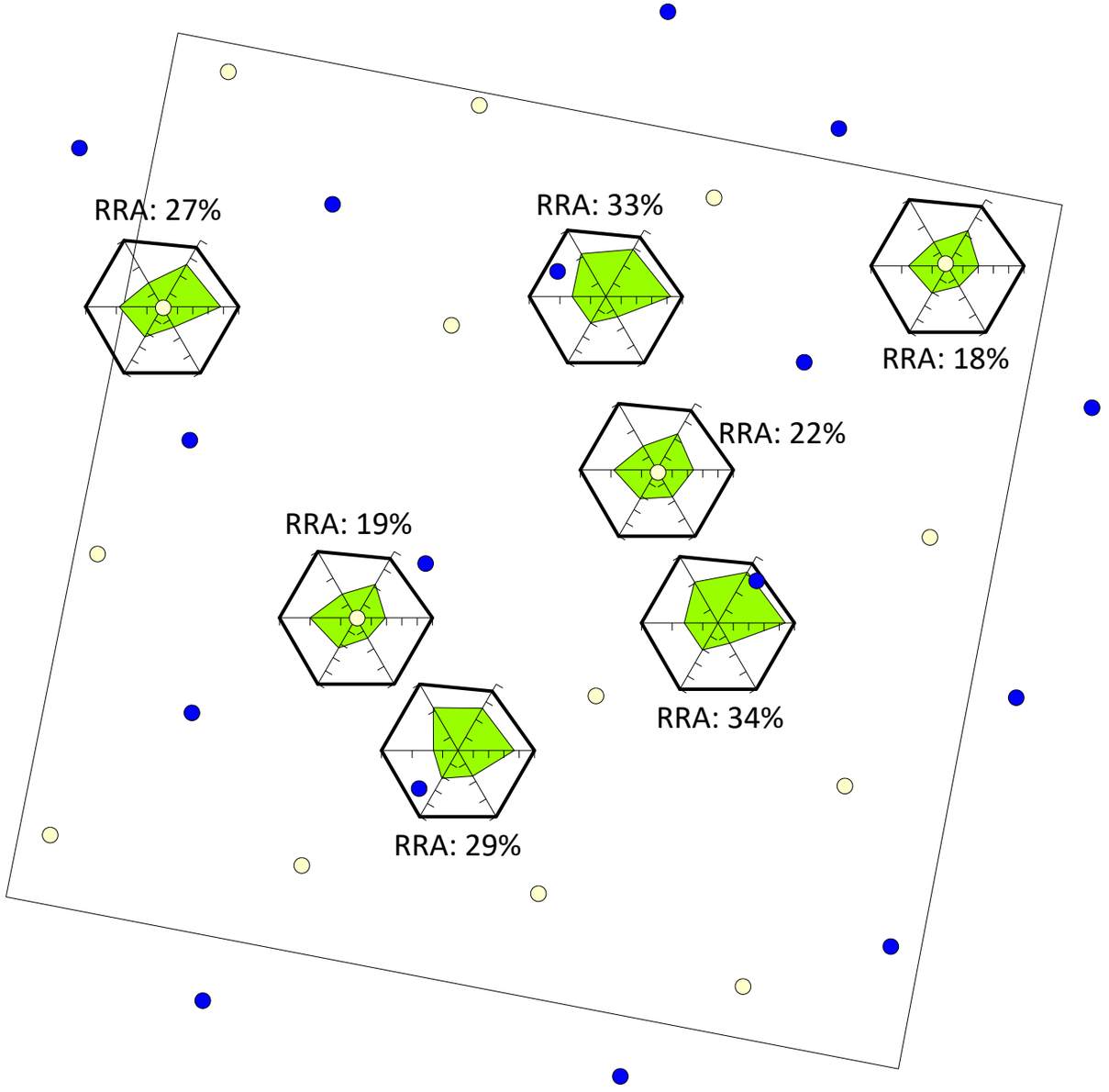
Redox Zone	RRA (%)
Aerobic	78-100
NO_3	62-78
Mn(II)	53-62
Fe(II)	35-53
SO_4	20-35
CH_4	≤20



Concentrations in mg/L

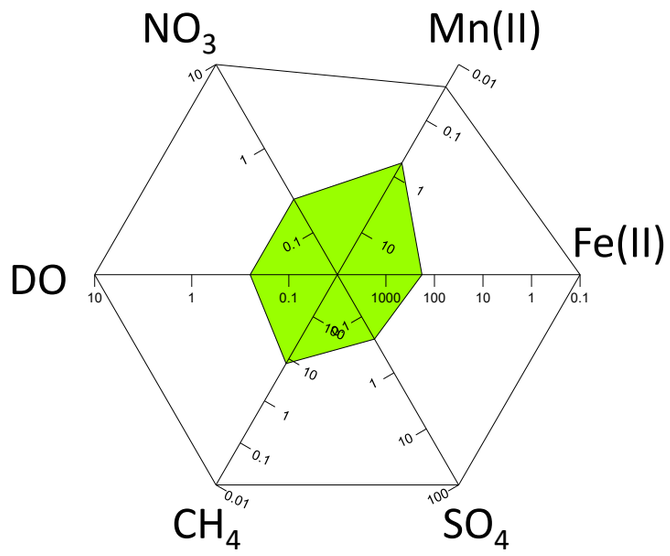
Redox Indicators Event 12: 2007-10-17

Days after start of Phase I injection: 1252
Days after start of Phase II injection: 386



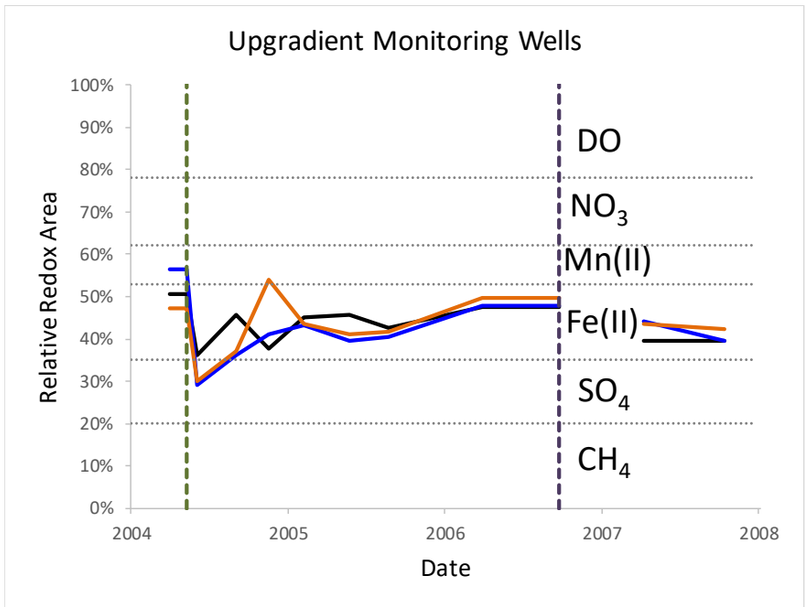
Phase I injection well
Phase II injection well

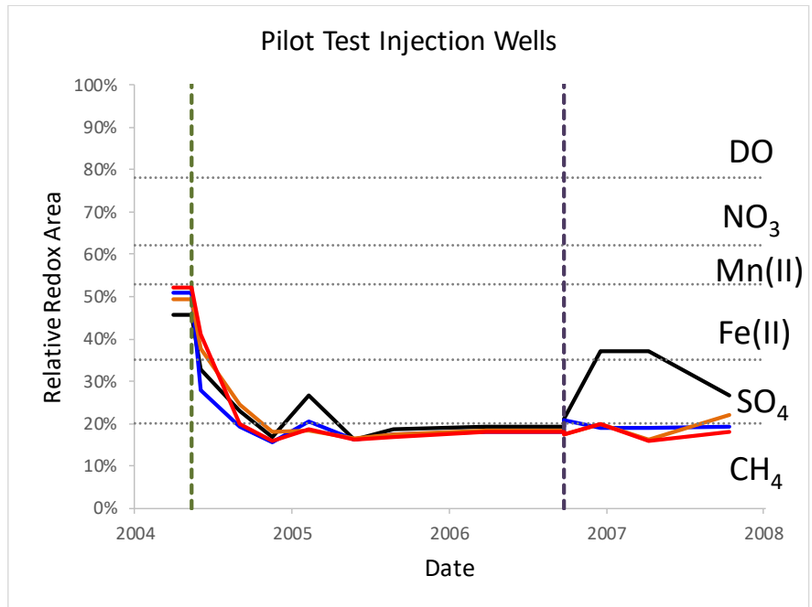
Redox Zone	RRA (%)
Aerobic	78-100
NO_3	62-78
Mn(II)	53-62
Fe(II)	35-53
SO_4	20-35
CH_4	≤20

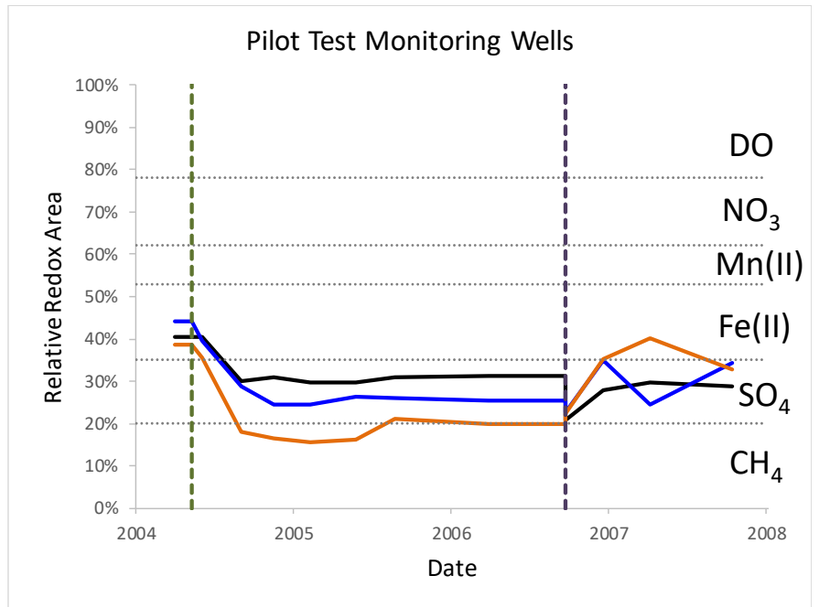


Concentrations in mg/L

Relative Redox Area versus Time





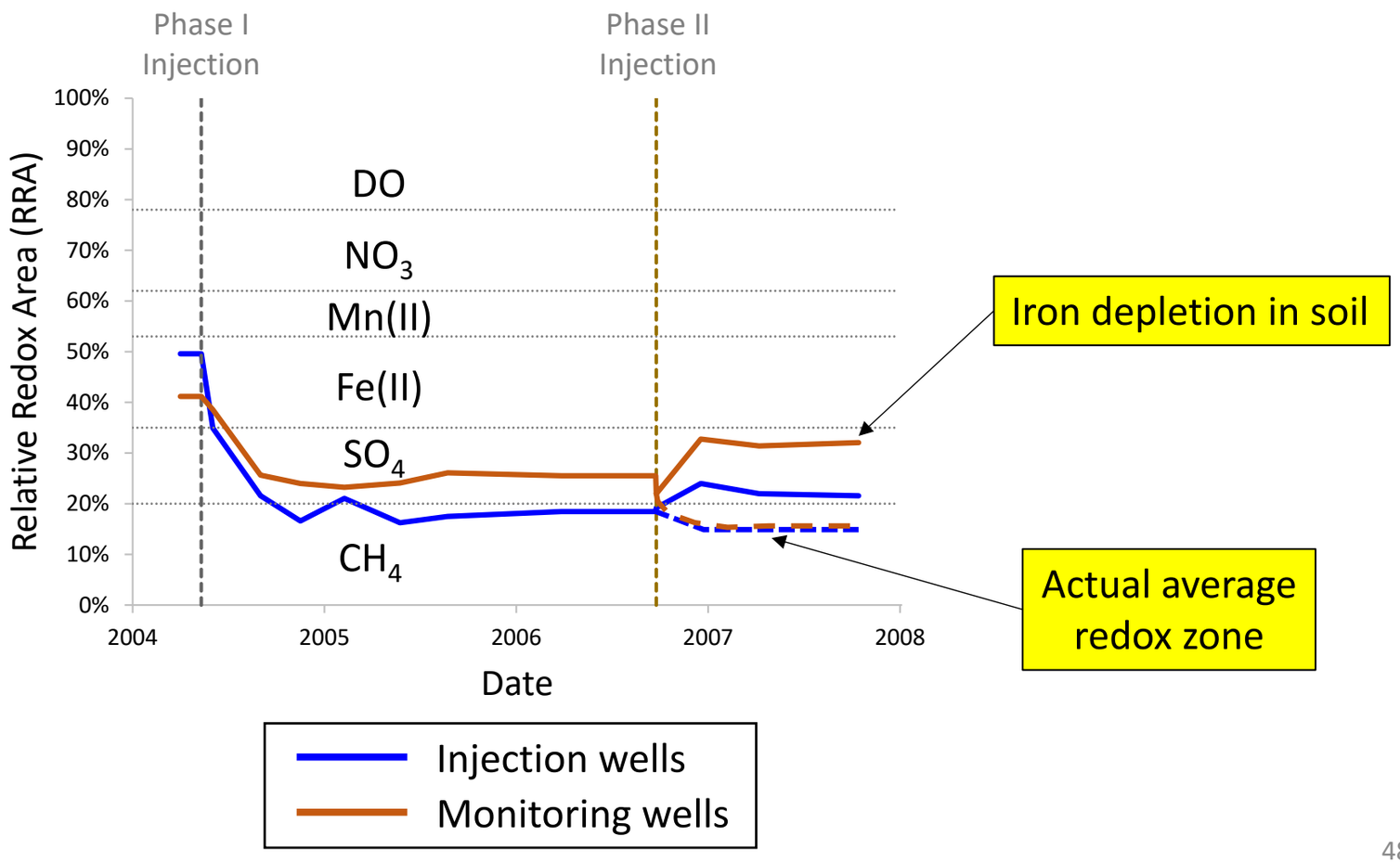


Redox Zone	RRA (%)
Aerobic	78-100
NO_3	62-78
Mn(II)	53-62
Fe(II)	35-53
SO_4	20-35
CH_4	≤20

Charleston Naval Weapons Station

Location	Days Since Injection 5/13/2004	Sample Date	Dissolved Oxygen (mg/L)	Nitrate (mg/L)	Manganese (mg/L)	Dissolved Iron (mg/L)	Sulfate (mg/L)	Methane (µg/L)
17PSI-02	-43	3/31/04	1.48	<0.5	0.390	33	91.5	53.2
17PSI-02	20	6/2/04	0.39	<0.5	0.570	150	18.0	47.4
17PSI-02	111	9/1/04	0.42	<0.5	0.510	160	<0.5	42.6
17PSI-02	188	11/17/04	0.14	<0.5	0.530	210	<0.5	256.3
17PSI-02	271	2/8/05	0.44	1.0/1.0	0.550	210	0.95	429.6
17PSI-02	377	5/25/05	0.19	< 0.5	0.660	210	< 0.5	1135
17PSI-02	468	8/24/05	0.35	< 0.5	0.630	180	< 0.5	812.8
17PSI-02	684	3/28/06	0.68	<0.5	0.590	210	<0.5	1933.2
17PSI-02	865	9/25/06	0.62	<0.5	0.530	60	<0.5	1366.9
17PSI-02	951	12/20/06	NM	<0.5	0.100	6.9	28.3	2135.8
17PSI-02	1062	4/10/07	0.36	<0.5	0.300	0.6	32.8/35.8	9433.9
17PSI-02	1252	10/17/07	0.80	<0.5	0.230	1.5	<0.5	5269.8
17PSI-07	-43	3/31/04	3.93	<0.5	0.370	24	102.5	40.7
17PSI-07	20	6/2/04	0.60	<0.5	0.710	180	1.8	53.7
17PSI-07	111	9/1/04	0.13	<0.5	0.820	300	0.5	26.6
17PSI-07	188	11/17/04	0.09	<0.5	0.740	240	<0.5	156.3
17PSI-07	271	2/8/05	0.48	<0.5	0.790	320	<0.5	151.7
17PSI-07	377	5/25/05	0.26	< 0.5	0.810	310	< 0.5	1469.4
17PSI-07	468	8/24/05	0.39	< 0.5	0.710	260	< 0.5	1816.0
17PSI-07	684	3/28/06	0.61	<0.5	0.530	420	<0.5	2121.1
17PSI-07	865	9/25/06	1.81	<0.5	0.620	320	<0.5	2684.9
17PSI-07	951	12/20/06	0.62	<0.5	0.750	220	<0.5/0.7	5509.0
17PSI-07	1062	4/10/07	0.98	<0.5	0.700	250	<0.5	4086.0
17PSI-07	1252	10/17/07	1.00	<0.5	0.720	120	<0.5	5377.2
17PSI-10	-43	3/31/04	4.05	<0.5	0.400	29	58.7	35.5
17PSI-10	20	6/2/04	0.47	<0.5	0.920	150	53.5/52.6	16.9
17PSI-10	111	9/1/04	0.26	<0.5	0.700	130	0.7	20.1
17PSI-10	188	11/17/04	0.14	<0.5	0.940	190	<0.5	27.2
17PSI-10	271	2/8/05	0.41	<0.5	0.830	220	<0.5	851.9
17PSI-10	377	5/25/05	0.32	< 0.5	0.800	220	< 0.5	2626.4
17PSI-10	468	8/24/05	0.45	< 0.5	1.200	190	< 0.5	1884.3
17PSI-10	684	3/28/06	0.56	<0.5	0.640	240	<0.5	2152.8
17PSI-10	866	9/26/06	0.52	<0.5	0.720	210	<0.5	4147.0
17PSI-10	951	12/20/06	0.74	<0.5	0.590	170	0.7	5972.8
17PSI-10	1062	4/10/07	0.51	<0.5	0.750	200	<0.5	9990.4
17PSI-10	1252	10/17/07	0.80	<0.5	0.510	40	<0.5/0.6	6651.4
17PSI-13	-43	3/31/04	4.66	<0.5	0.610	53	102.6	13.4
17PSI-13	20	6/2/04	0.74	<0.5	0.920	120	82.6	17.5
17PSI-13	111	9/1/04	0.19	<0.5	0.840	200	<0.5	14.3
17PSI-13	187	11/16/04	0.10	<0.5/<0.5	0.920	210	<0.5/<0.5	78.7
17PSI-13	271	2/8/05	0.39	<0.5	0.880	190	<0.5	534.5
17PSI-13	376	5/24/05	0.29	<0.5/<0.5	0.800	160	<0.5/<0.5	3441.6
17PSI-13	468	8/24/05	0.35	< 0.5	0.990	160	< 0.5	2550.7
17PSI-13	684	3/28/06	NA	<0.5	0.880	260	<0.5	1105.7
17PSI-13	866	9/26/06	0.56	<0.5	0.830	180	<0.5	5069.7
17PSI-13	951	12/20/06	0.81	<0.5	0.850	260	1.1	5540.8
17PSI-13	1062	4/10/07	0.46	<0.5	0.840	280	<0.5	7879.1
17PSI-13	1252	10/17/07	0.60	<0.5	0.570	90	<0.5	9099.5
17PS-01	-42	4/1/04	0.67	<0.5	0.630	78	65.5	27.2
17PS-01	20	6/2/04	1.14	<0.5	0.720	120	44.1/44.6	25.8
17PS-01	111	9/1/04	0.15	<0.5	0.540	110	15.3	37.7
17PS-01	187	11/16/04	0.17	<0.5	0.780	130	23.4	33.1
17PS-01	271	2/8/05	0.23	<0.5	0.680	150	27.9	145.0
17PS-01	377	5/25/05	0.34	< 0.5	0.690	130	20.3	231.9
17PS-01	468	8/24/05	0.33	< 0.5	0.570	190	21.6	92.2
17PS-01	685	3/29/06	0.49	<0.5	0.490	210	30.9	261.2
17PS-01	866	9/26/06	0.81	<0.5	0.690	110	<0.5	1232.6
17PS-01	951	12/20/06	NA	<0.5	0.190	7.2	1.4	7415.3
17PS-01	1062	4/10/07	0.72	<0.5	0.050	1.0	<0.5	11308.5
17PS-01	1252	10/17/07	0.20	1.3	0.230	2.1	0.5	7759.2
17PS-02	-42	4/1/04	1.50	<0.5	0.560	50	58	30.8
17PS-02	20	6/2/04	3.36	<0.5	0.740	81	5.4	30.6
17PS-02	111	9/1/04	0.14	<0.5	0.570	170	15.0	36.7
17PS-02	187	11/16/04	0.16	<0.5	0.590	150	2.8	66.0
17PS-02	271	2/8/05	0.20	<0.5/<0.5	0.520	120	10.0	1144.8
17PS-02	377	5/25/05	0.47	< 0.5	0.660	92	6.7	1176.5
17PS-02	468	8/24/05	0.32	< 0.5	0.540	150	20.8	1681.8
17PS-02	685	3/29/06	0.50	<0.5	0.550	130	14	3639.3
17PS-02	866	9/26/06	0.48	<0.5	0.620	170	2.8	2133.3
17PS-02	951	12/20/06	NA	<0.5	0.180	1.10	9.6	9880.6
17PS-02	1062	4/10/07	0.75	<0.5	0.260	12.0	<0.5/0.57	8896.9
17PS-02	1252	10/17/07	0.40	1.1	0.075	0.41	<0.5	9148.4
17PS-03	-42	4/1/04	0.40	<0.5	0.680	69	77.5	36.0
17PS-03	20	6/2/04	1.22	<0.5	0.810	110	10.0	50.7
17PS-03	111	9/1/04	0.14	<0.5	0.460	130	<0.5	173.3
17PS-03	187	11/16/04	0.18	<0.5/<0.5	0.800	200	0.5/<0.5	2062.5
17PS-03	271	2/8/05	0.25	<0.5	0.570	180	<0.5	7737.5
17PS-03	377	5/25/05	0.31	< 0.5	0.700	180	< 0.5	4425.3
17PS-03	468	8/24/05	0.37	< 0.5	0.470	190	2.10	3136.5
17PS-03	685	3/29/06	0.44	<0.5	0.430	370	1.6	3522.2
17PS-03	866	9/26/06	0.57	<0.5	0.580	96	1.9	4852.4
17PS-03	951	12/20/06	NA	<0.5	0.170	1.1	9.6/9.5	9839.1
17PS-03	1062	4/10/07	0.68	<0.5	0.055	0.38	5.0	4281.3
17PS-03	1252	10/17/07	0.40	1.3	0.120	0.58	<0.5	10127.1

Average RRA versus time in Pilot Test Area (IWs)



Relative Redox Area Findings

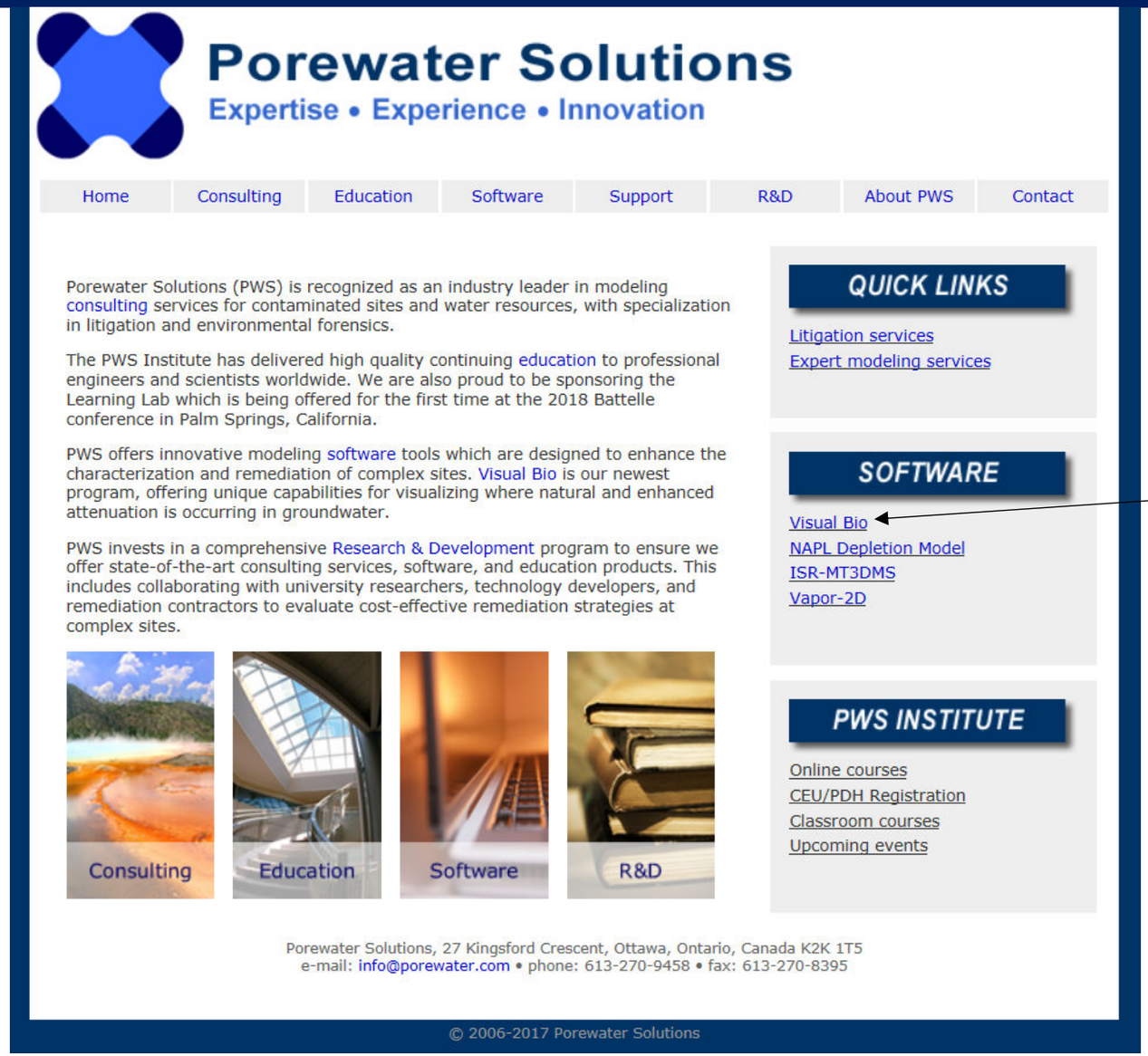
- CHECK RRA RESULTS – Do they make sense?
- Single metric that integrates trends for 5-6 redox indicators, relative to aerobic conditions
- Good predictor of dominant redox processes
- Useful for contouring key redox zones (e.g. aerobic, moderately anaerobic, and strongly anaerobic)
- Higher uncertainty at RRA transition points
- RRA limitations:
  - Downgradient transport of indicators (e.g. methane)
  - Concomitant redox processes

Potential RRA Zones for delineation:

1. Aerobic
2. Nitrate-reducing
3. Manganese / Iron-reducing
4. Sulfate-reducing / Methanogenesis

FREE Visual Bio Software

www.porewater.com



Free Download

- User's Guide
- Software
- Plattsburgh AFB examples

Visual Bio Software

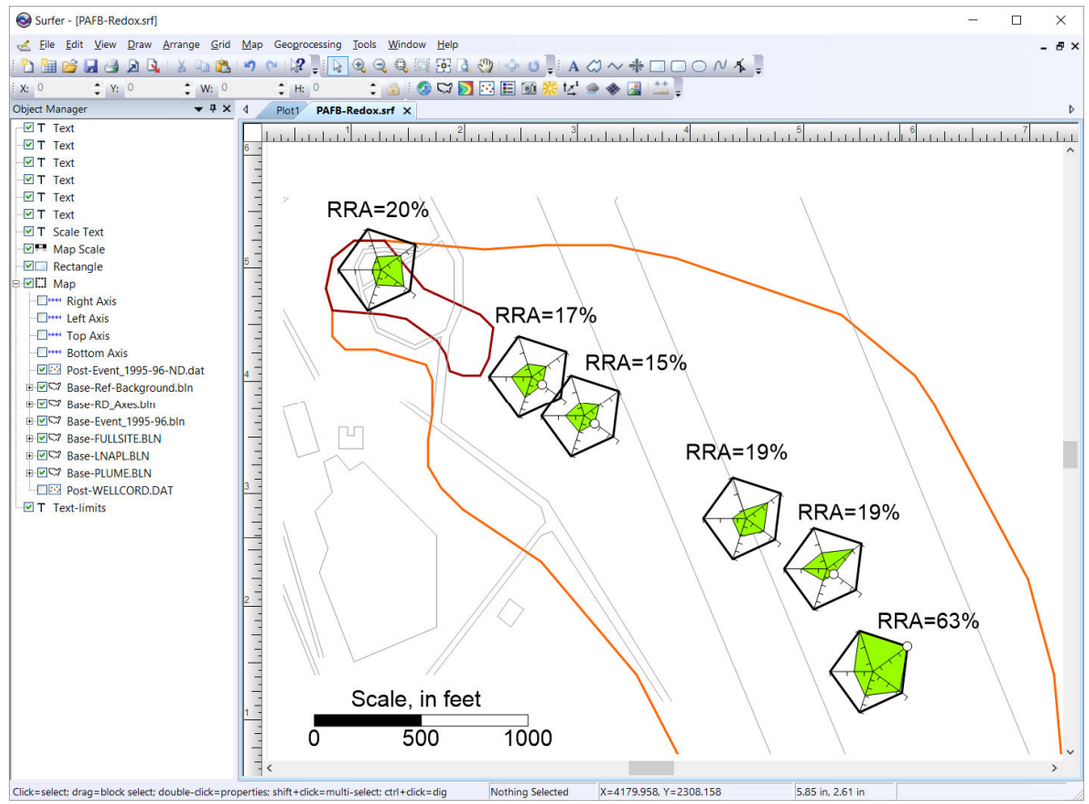
Text Input Files

RD_Properties.dat - Notepad

File Edit Format View Help

```
PAFB - Redox
      5                                'Line 2:  nRD_Axes
 2  180  150  2   0.1    10.  1  3  -1. 'Line 3.1: DO ScaleFlag, angle, chemID, unitID, Min, Max, Direction, nMajorTicks, MCL
 2  108  151  2   0.1    10.  1  3  -1. 'Line 3.2: NO3 ScaleFlag, angle, chemID, unitID, Min, Max, Direction, nMajorTicks, MCL
 2   36  173  2   0.1   100. -1  4  -1. 'Line 3.3: Fe2+  ScaleFlag, angle, chemID, unitID, Min, Max, Direction, nMajorTicks, MCL
 2  324  160  2   0.1   100.  1  4  -1. 'Line 3.4: SO4  ScaleFlag, angle, chemID, unitID, Min, Max, Direction, nMajorTicks, MCL
 2  252  175  2   0.001  10. -1  5  -1. 'Line 3.5: CH4  ScaleFlag, angle, chemID, unitID, Min, Max, Direction, nMajorTicks, MCL
   6                               'Line 4:    nRD_well
1   A                              'Line 5.1:  well ID
2   B                              'Line 5.2:  well ID
3   C                              'Line 5.3:  well ID
4   D                              'Line 5.4:  well ID
5   E                              'Line 5.5:  well ID
6   F                              'Line 5.6:  well ID
    1                              'Line 6:    nRD_EventSeries
    1    Event_1995-96             'Line 7.1:  Event ID, Filename
    1    2                         'Line 8:    nRD_RefSeries, input unitsID
Ref-Background                     'Line 9.1:  Ref Series filename
10.  10. -0.05  25. -0.001         'Line 10:   Background redox reference concentrations
    2                              'Line 11:   NDflag (1=DL, 2=0.5*DL, 3=axis minimum)
  200.                             'Line 12:   axis length (map units)
    0                              'Line 13:   Calculate ratio of detected parent to daughter products?  (0=no,1=yes)
    0.1                            'Line 15:   TickLengthMajorP
    1                              'Line 16:   Output symbols for Event series? (0=no, 1=yes)
    0                              'Line 17:   Output symbols for Reference series? (0=no, 1=yes)
```

Golden Surfer® for Making Figures



Key Functionality for Radial Diagrams

- Axes can increase in concentration away from, or towards the origin of the radial diagram
- Each axis has option of log or arithmetic scale
- Multiple events and reference data series

  e.g. background redox indicators, or source zone VOCs
- Option to shade in one or more data series, different line colors
- Symbols to represent non-detects, and/or MCL exceedances

Questions

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Porewater Solutions

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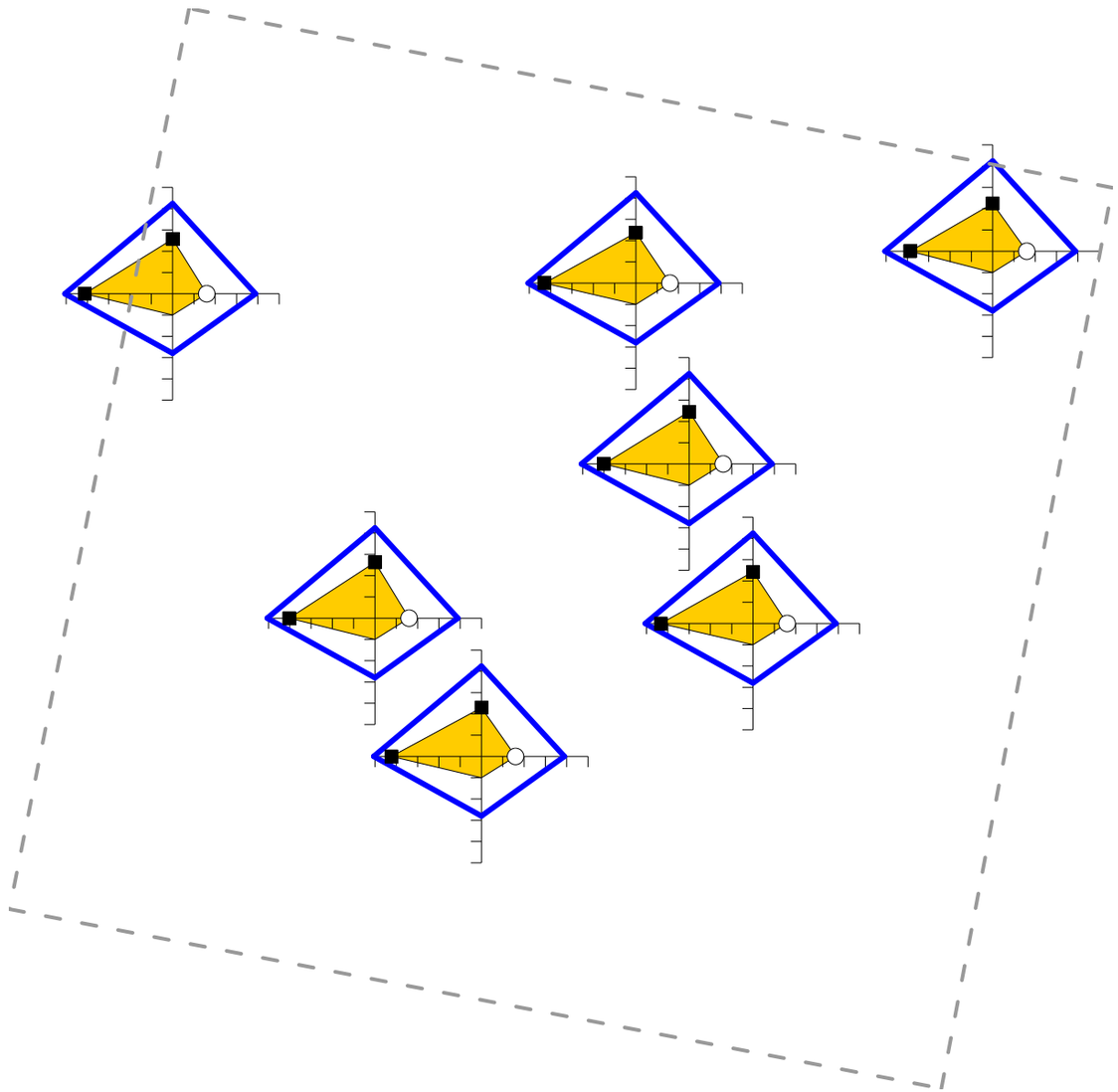
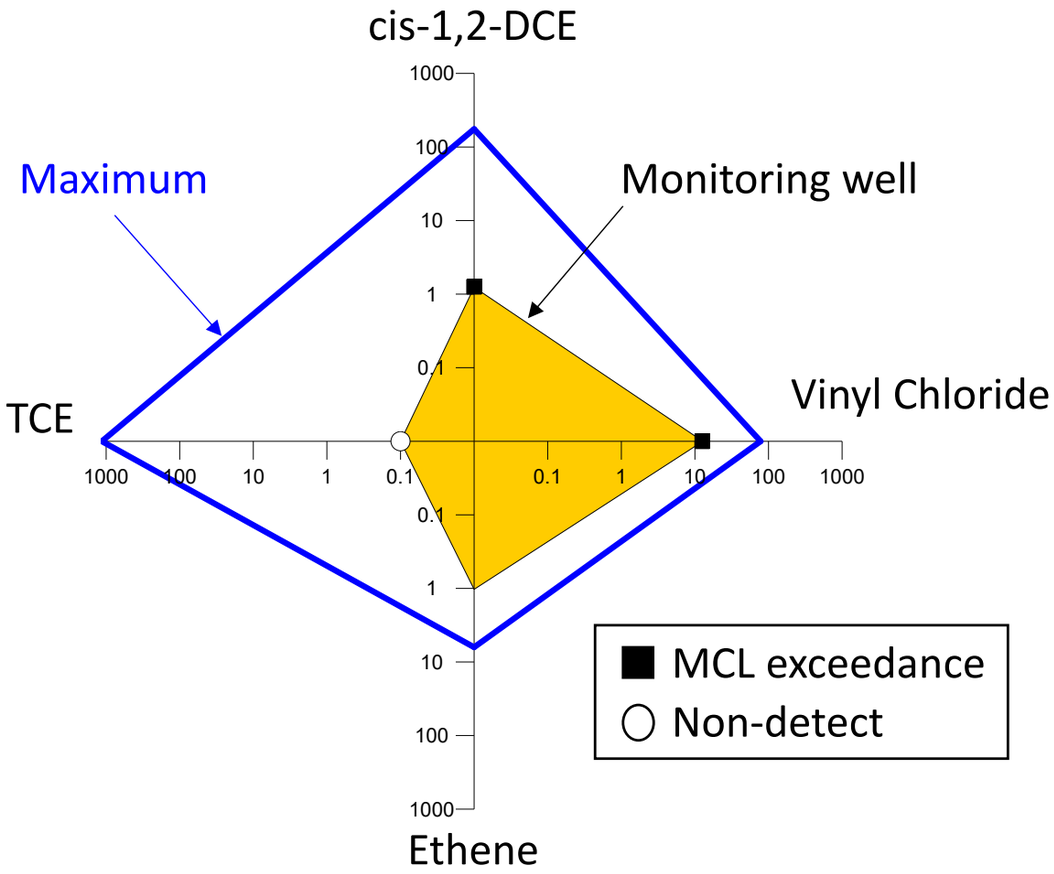
gcarey@porewater.com
www.porewater.com

Supplemental Slides Charleston NWS

VOC Trends Event 1: 2004-04-01 Pre-Injection

Days after start of Phase I injection: -42
Days after start of Phase II injection: -

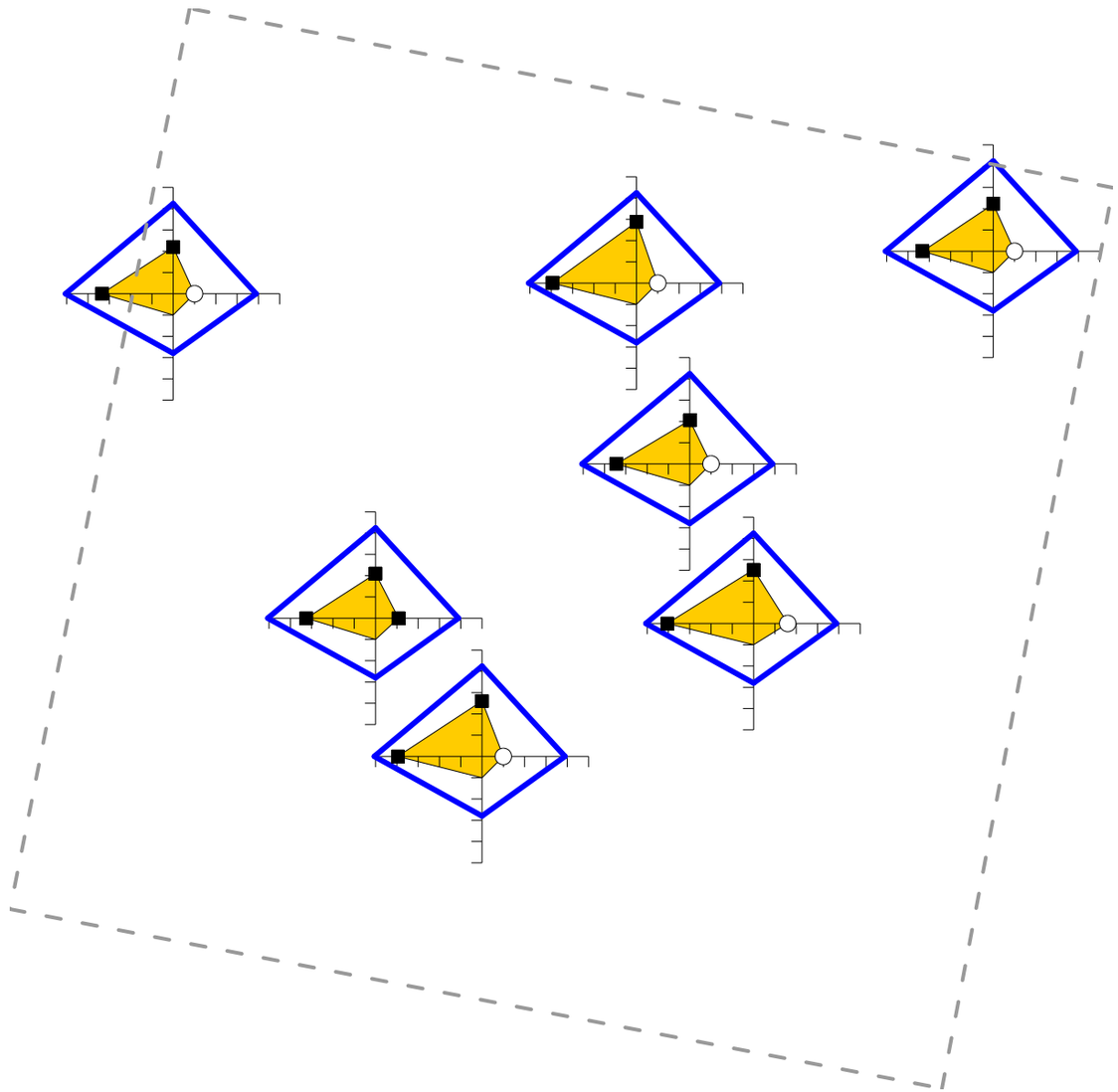


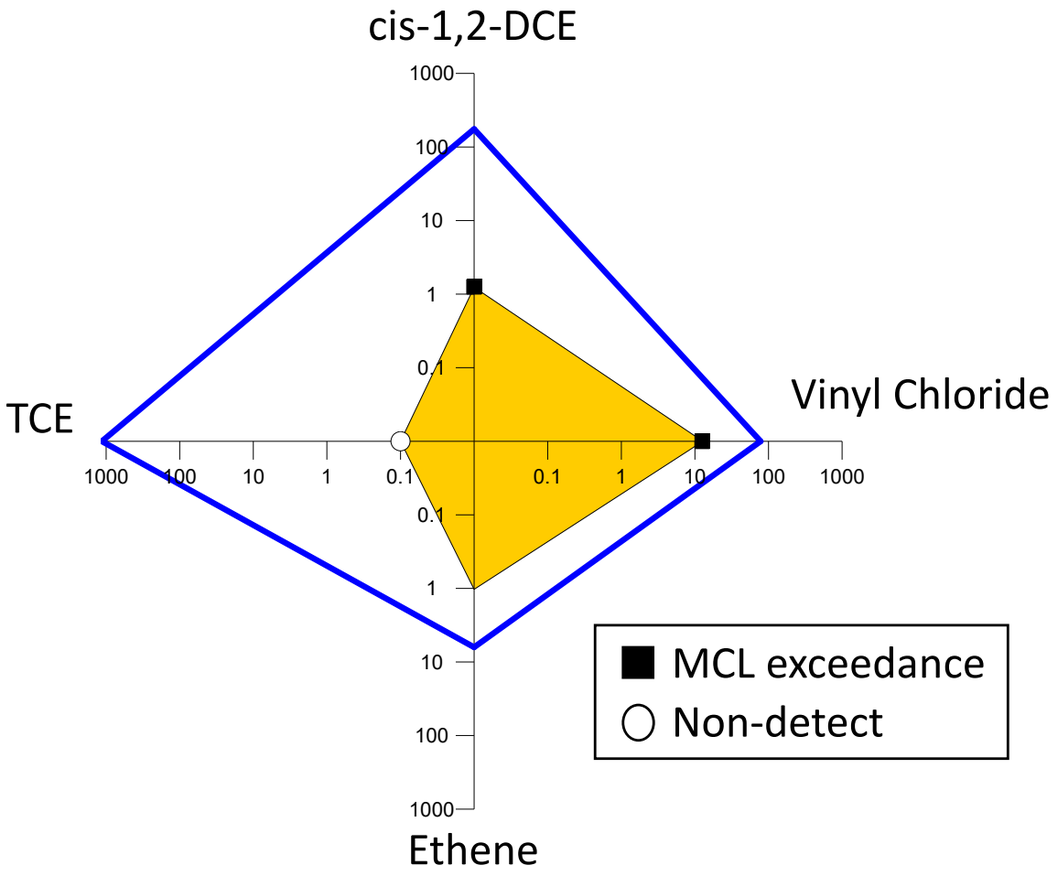


Concentrations in uM

VOCs Event 2: 2004-06-02

Days after start of Phase I injection: 20
Days after start of Phase II injection: -

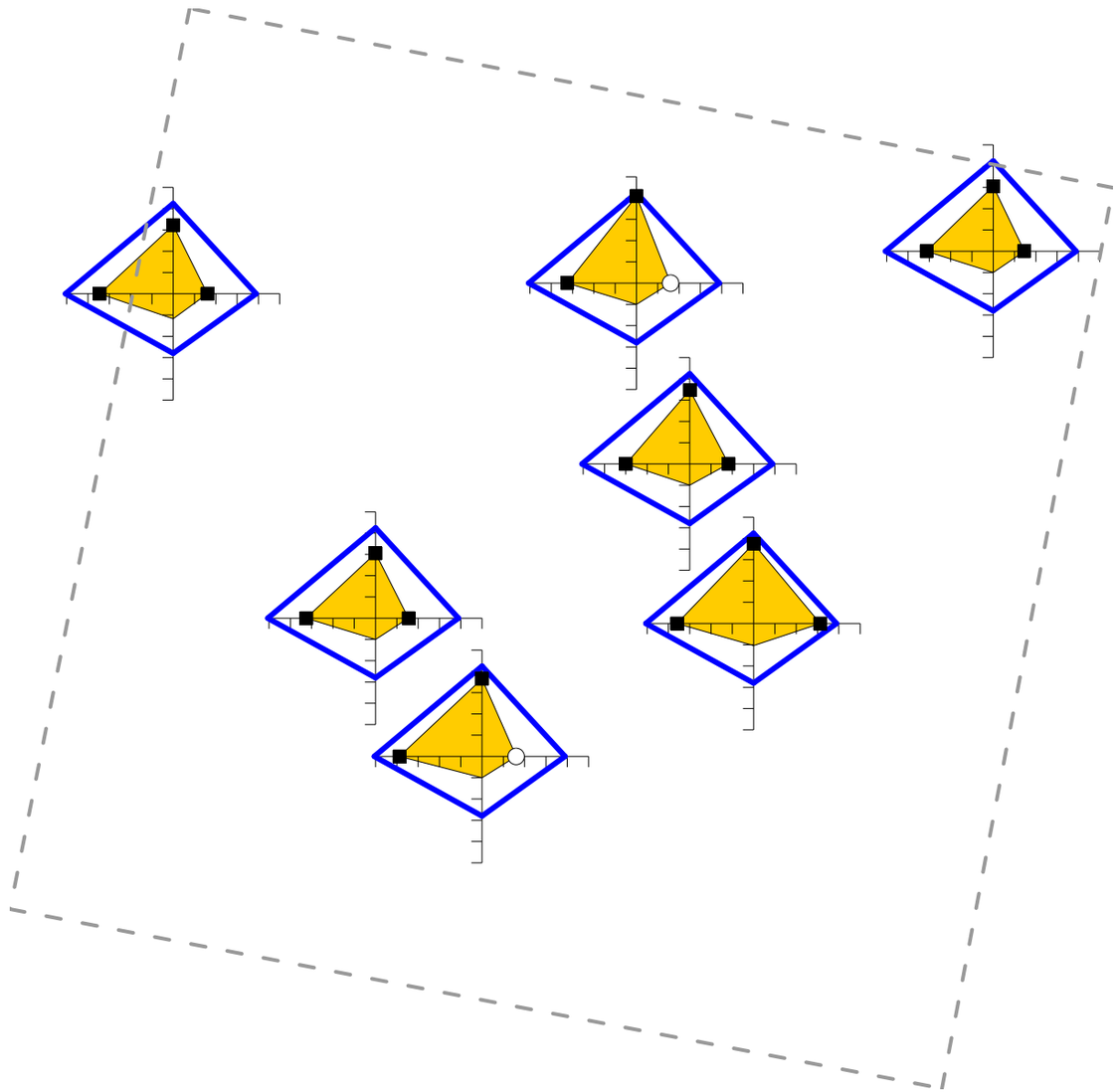


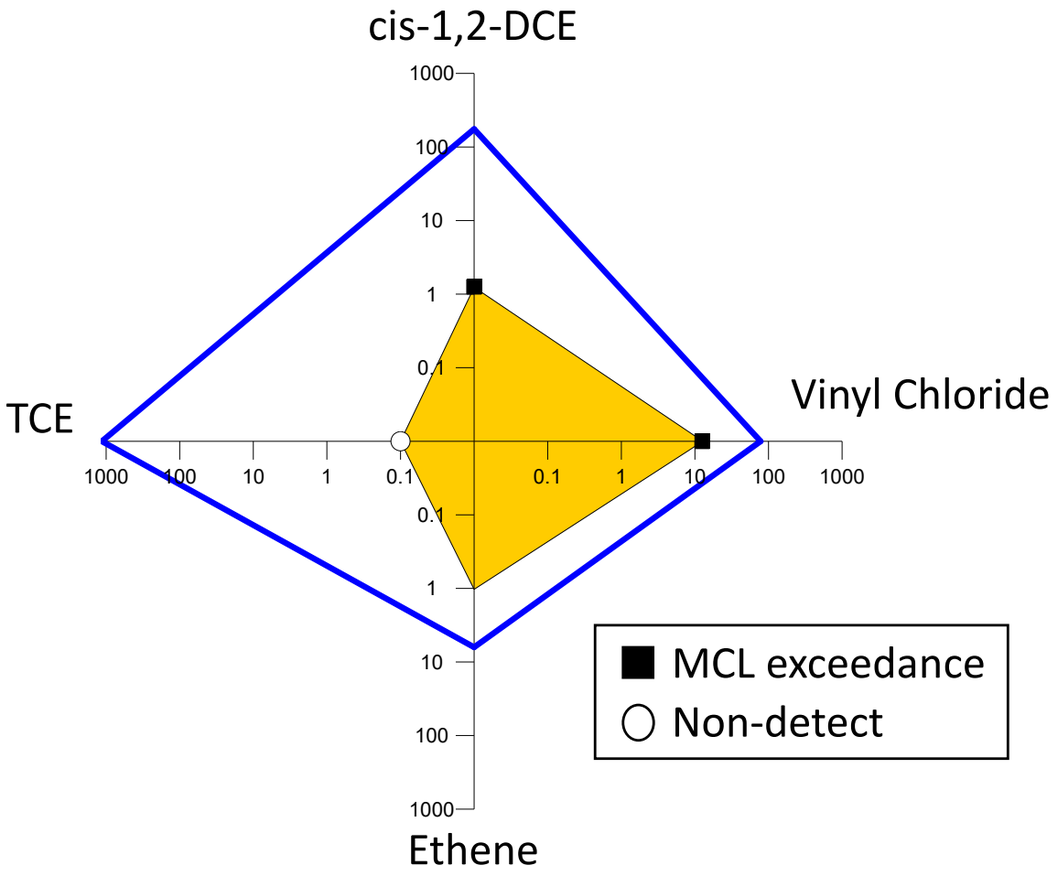


Concentrations in uM

VOCs Event 8: 2006-03-29

Days after start of Phase I injection: 685
Days after start of Phase II injection: -

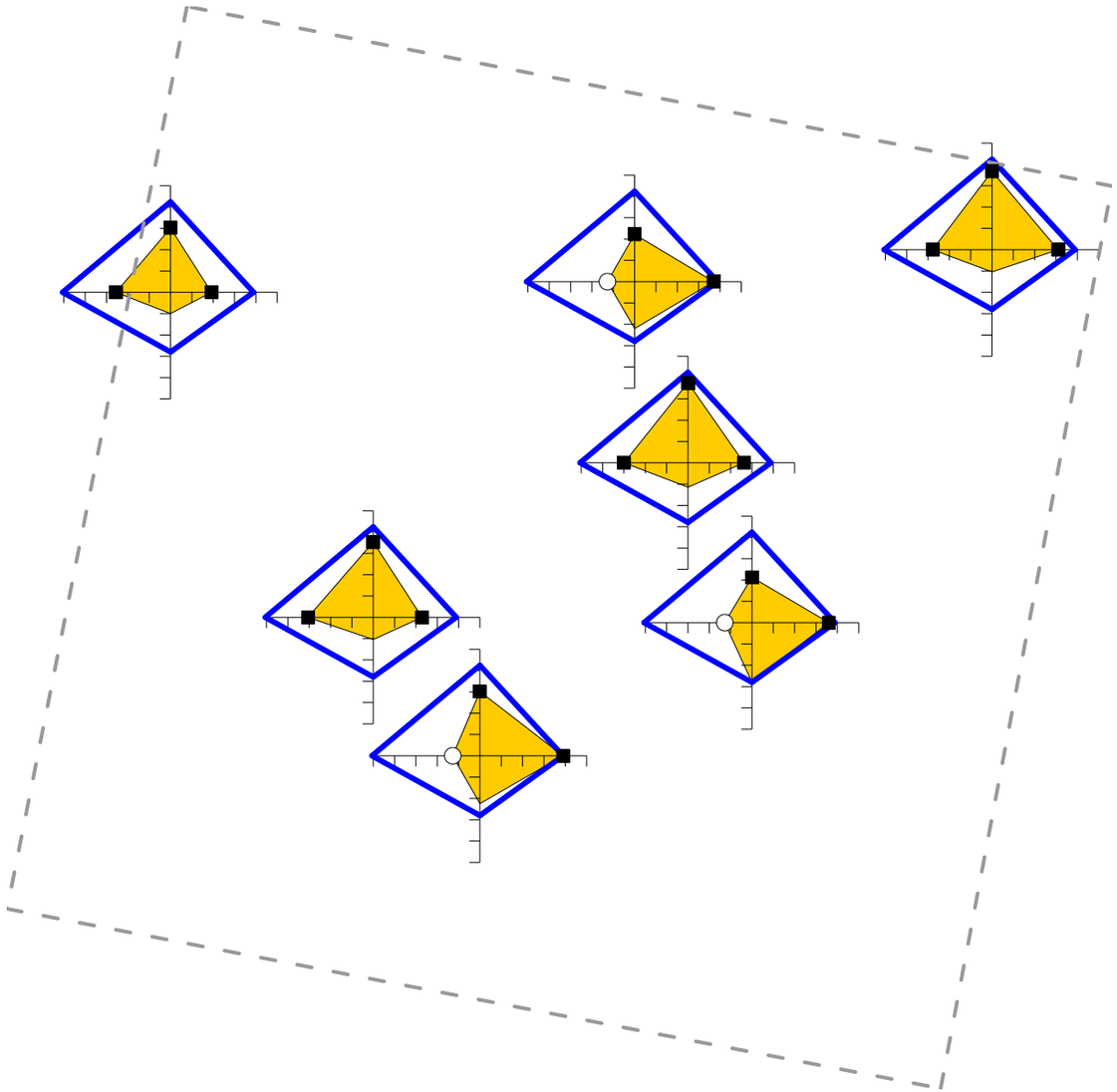


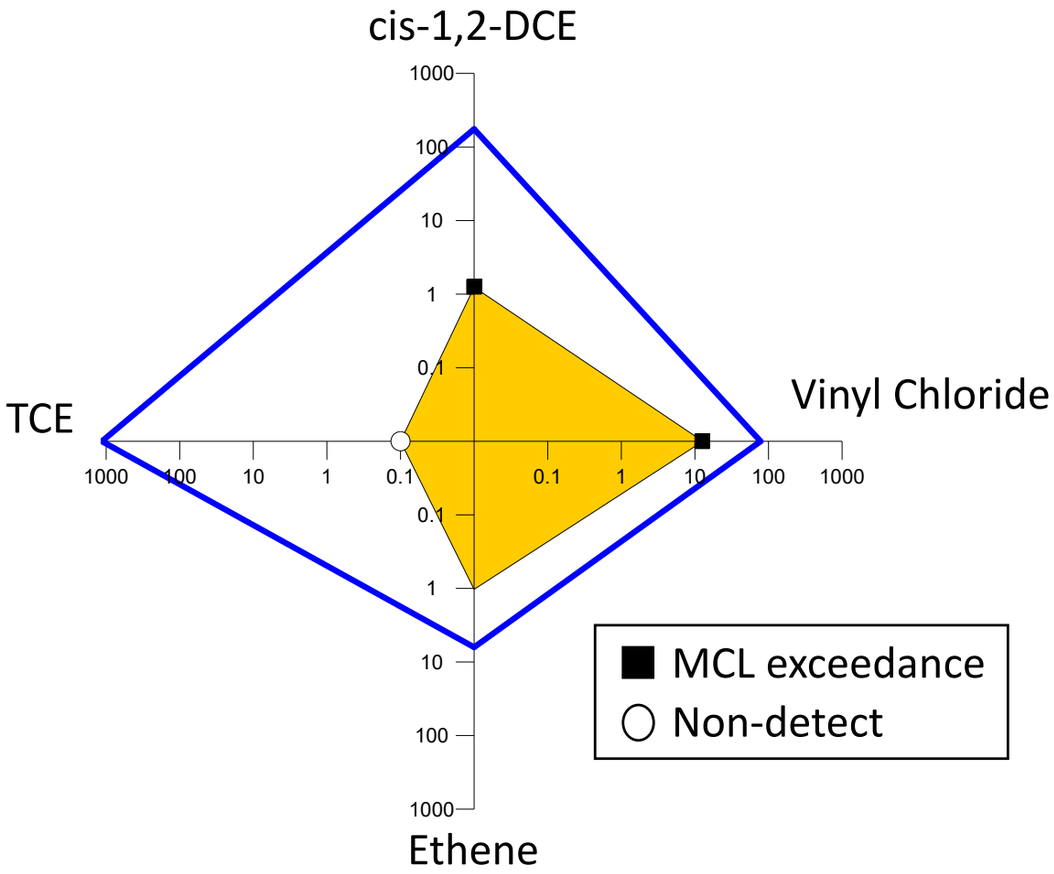


Concentrations in uM

VOCs Event 10: 2006-12-20

Days after start of Phase I injection: 951
Days after start of Phase II injection: 85

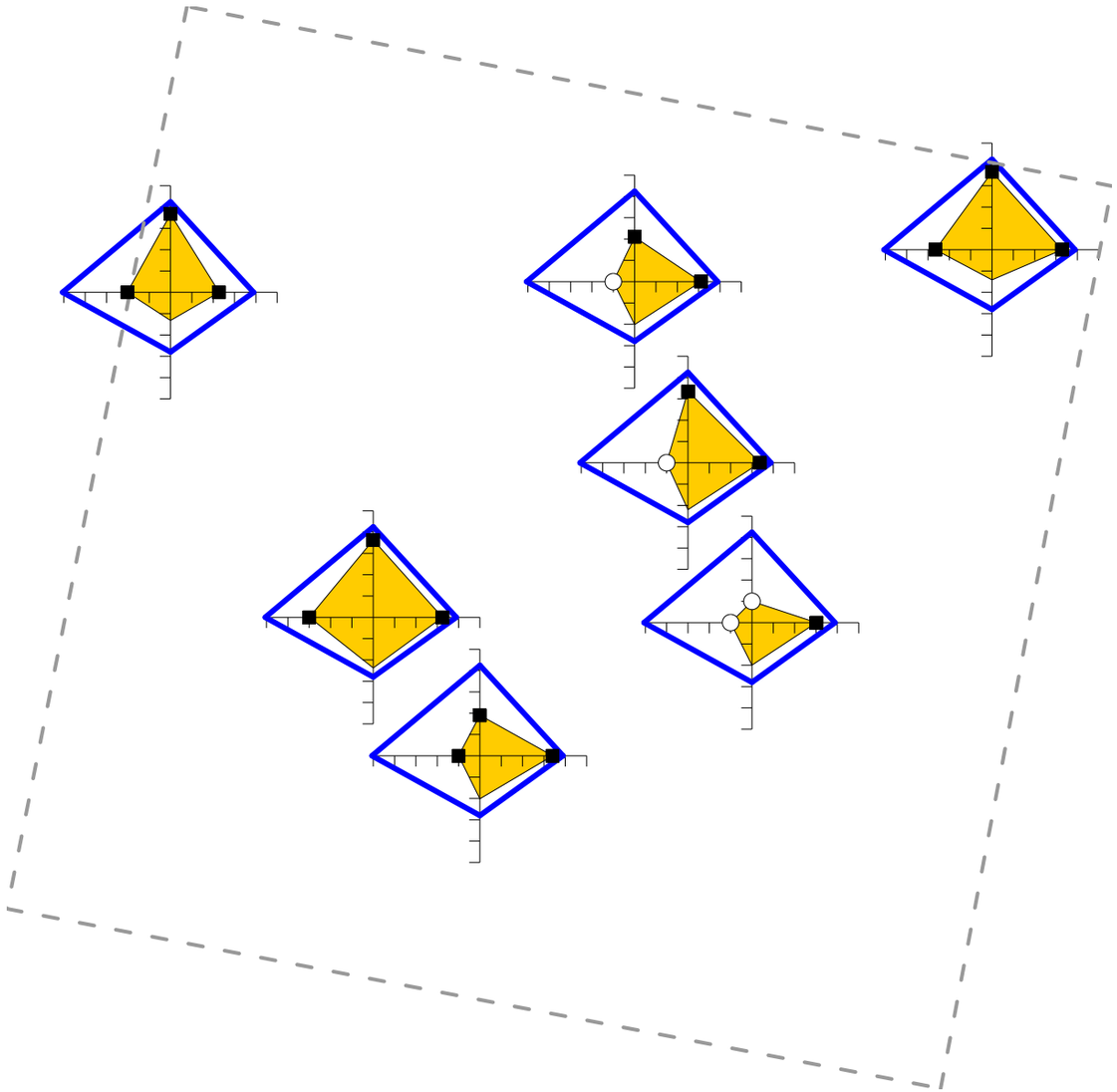


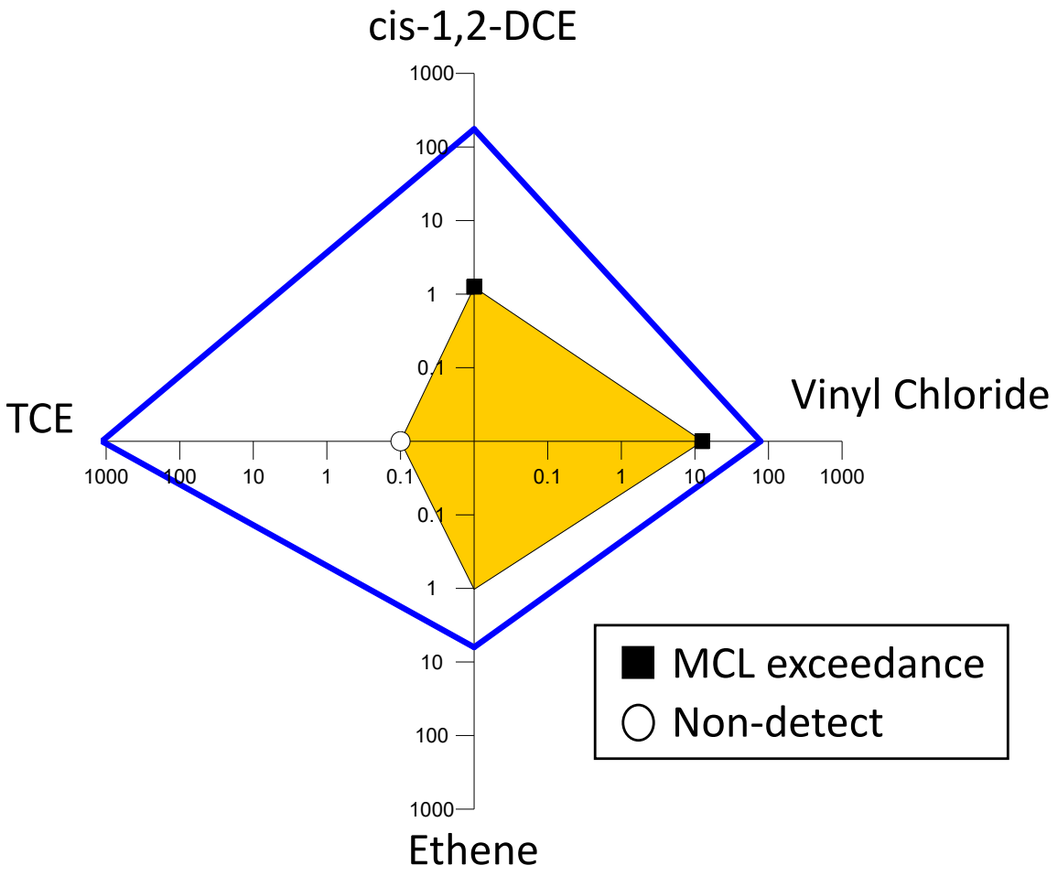


Concentrations in uM

VOCs Event 12: 2007-10-17

Days after start of Phase I injection: 1252
Days after start of Phase II injection: 386

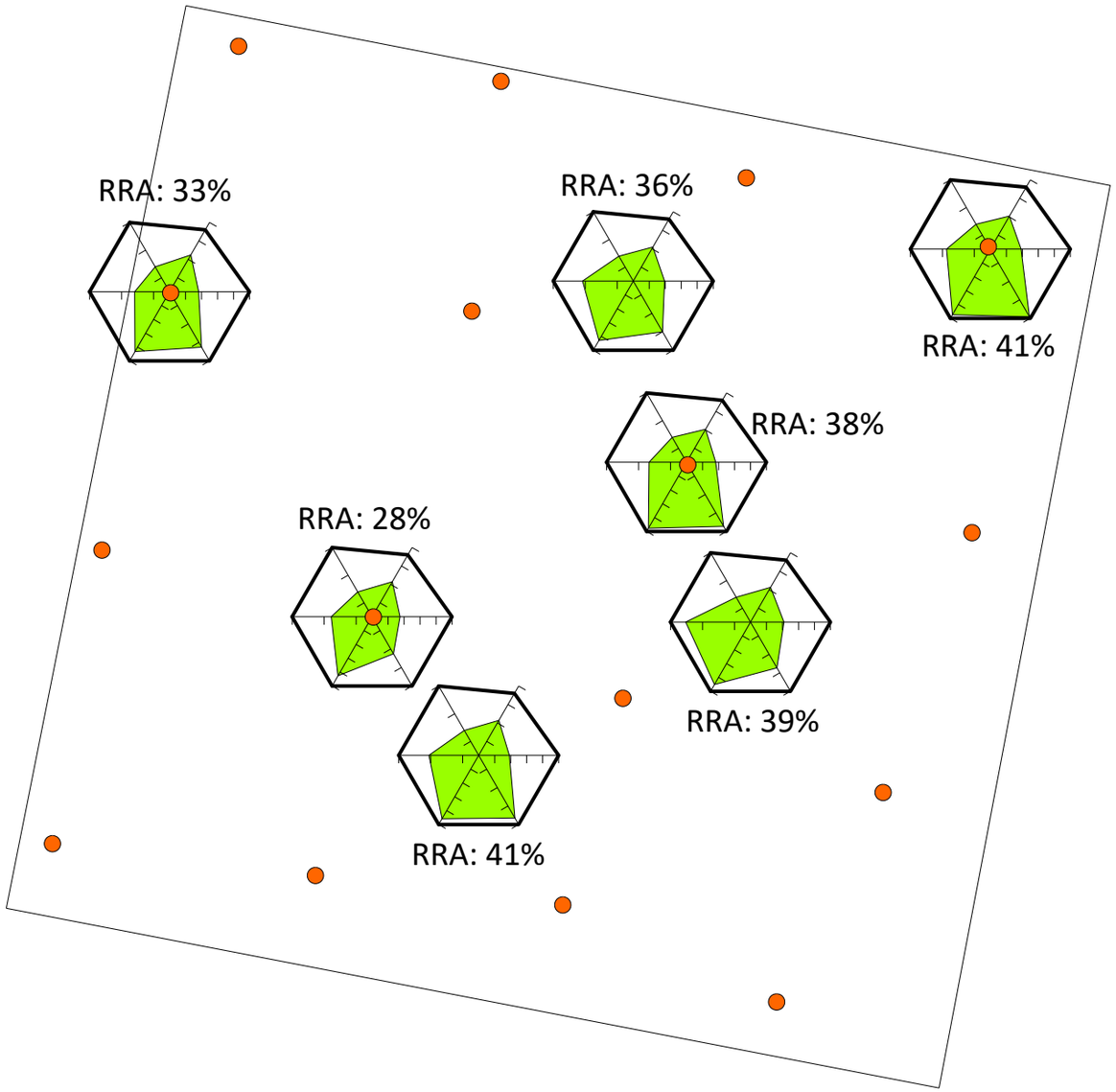




Concentrations in uM

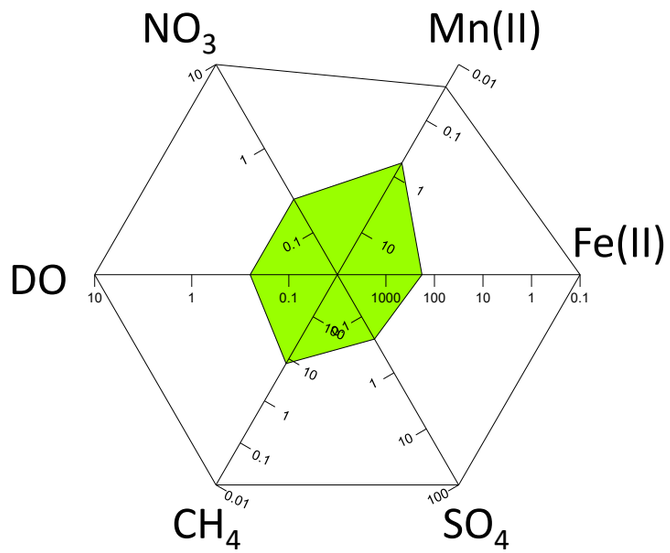
Redox Indicators Event 2: 2004-06-02

Days after start of Phase I injection: 20
Days after start of Phase II injection: -



Phase I injection well

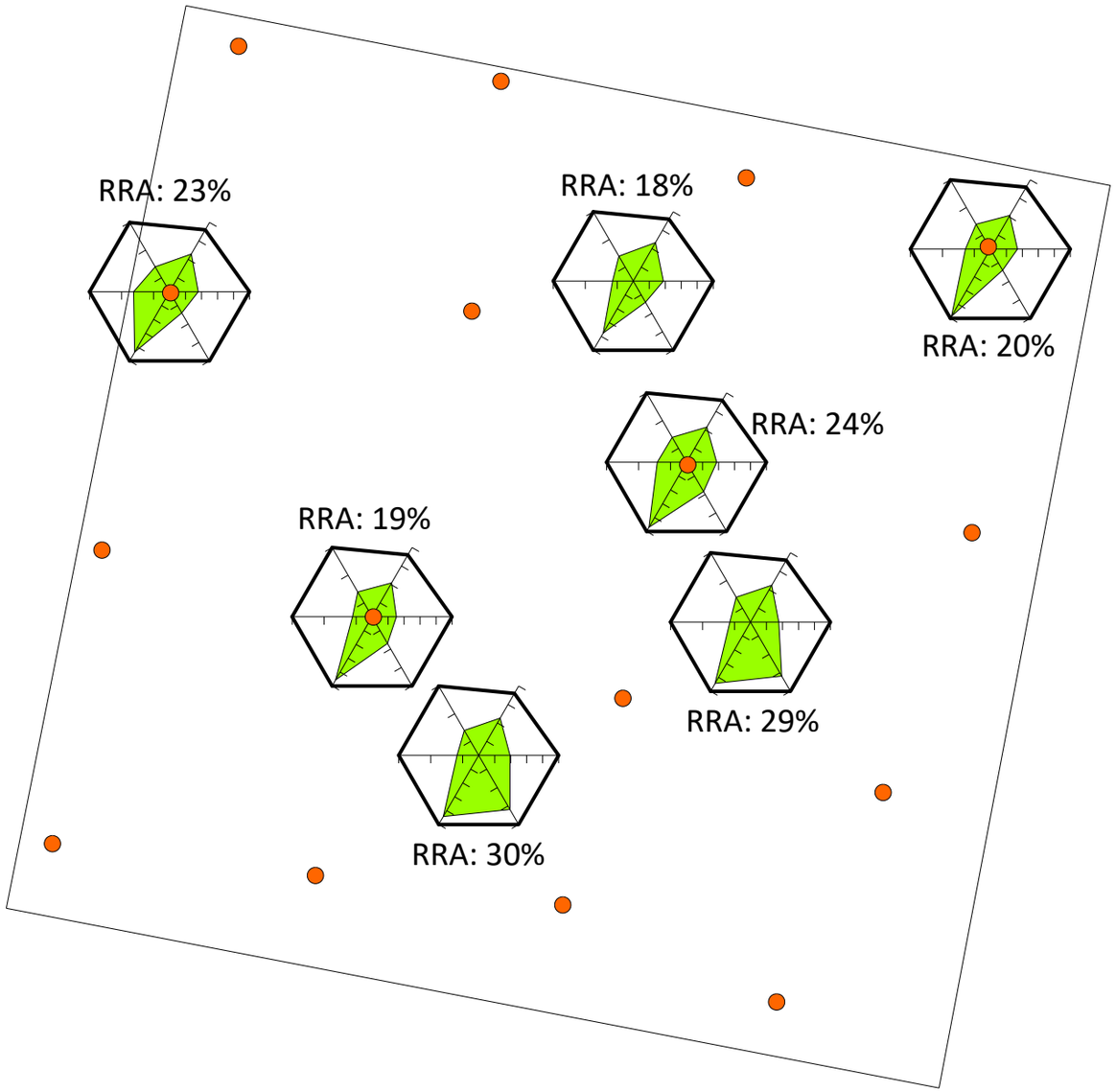
Redox Zone	RRA (%)
Aerobic	78-100
NO_3	62-78
Mn(II)	53-62
Fe(II)	35-53
SO_4	20-35
CH_4	≤20



Concentrations in mg/L

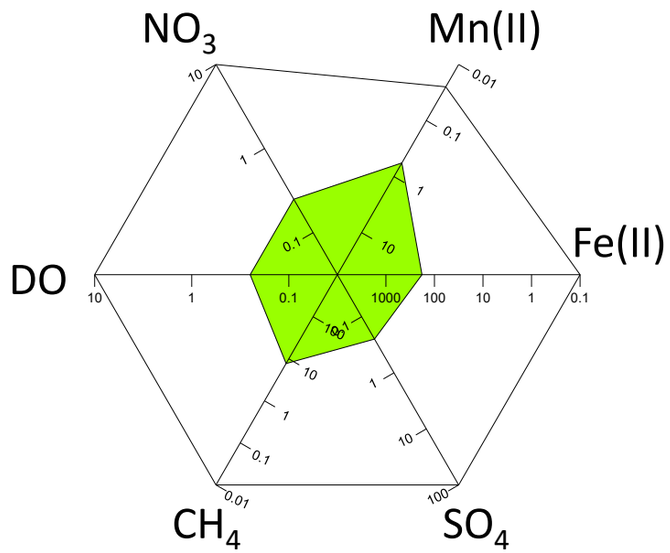
Redox Indicators Event 3: 2004-09-01

Days after start of Phase I injection: 111
Days after start of Phase II injection: -



Phase I injection well

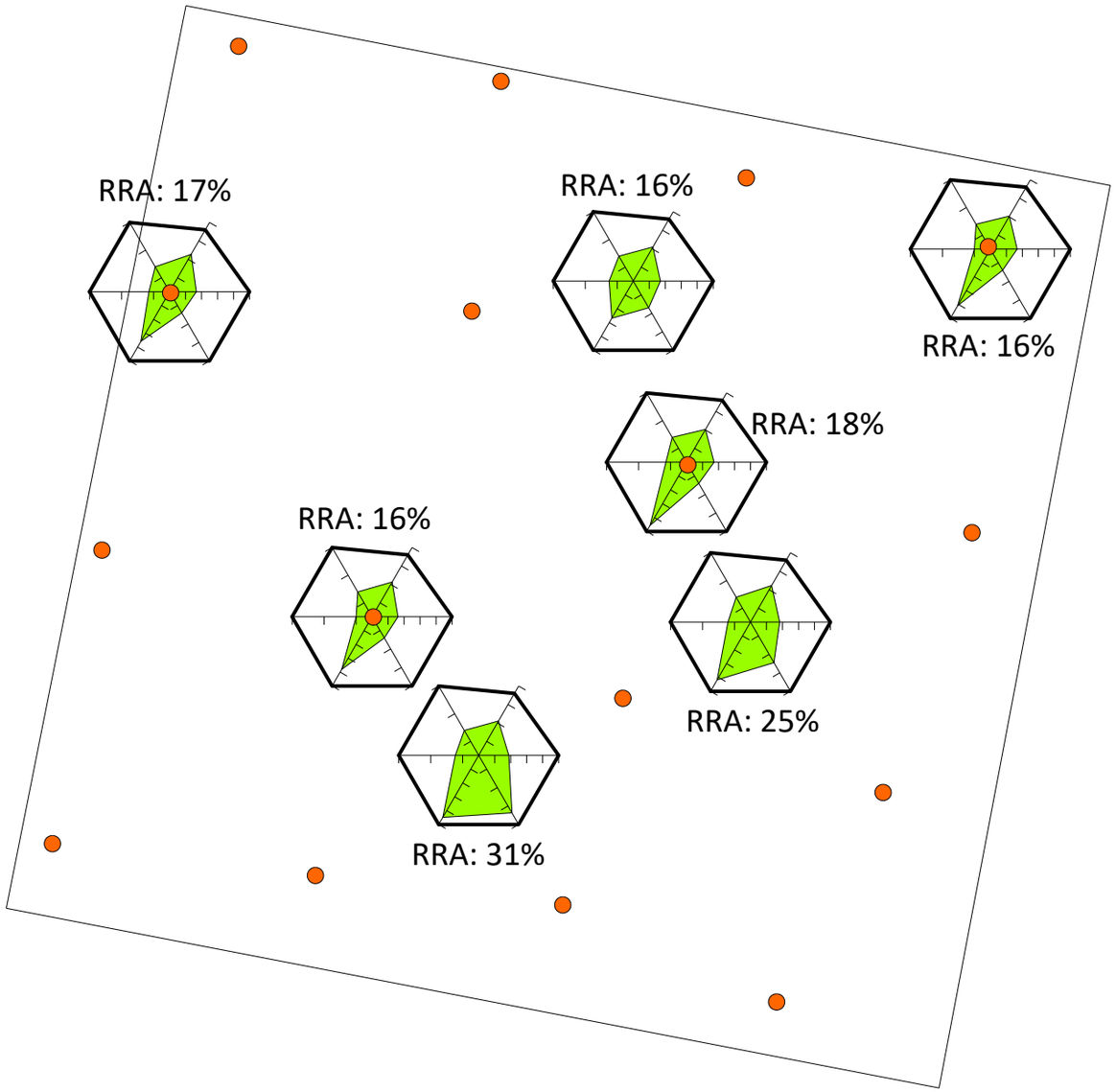
Redox Zone	RRA (%)
Aerobic	78-100
NO_3	62-78
Mn(II)	53-62
Fe(II)	35-53
SO_4	20-35
CH_4	≤20



Concentrations in mg/L

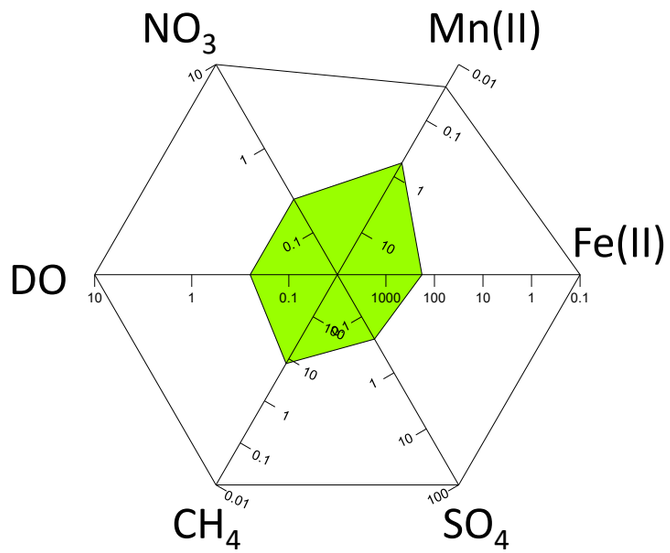
Redox Indicators Event 4: 2004-11-16

Days after start of Phase I injection: 187
Days after start of Phase II injection: -



Phase I injection well

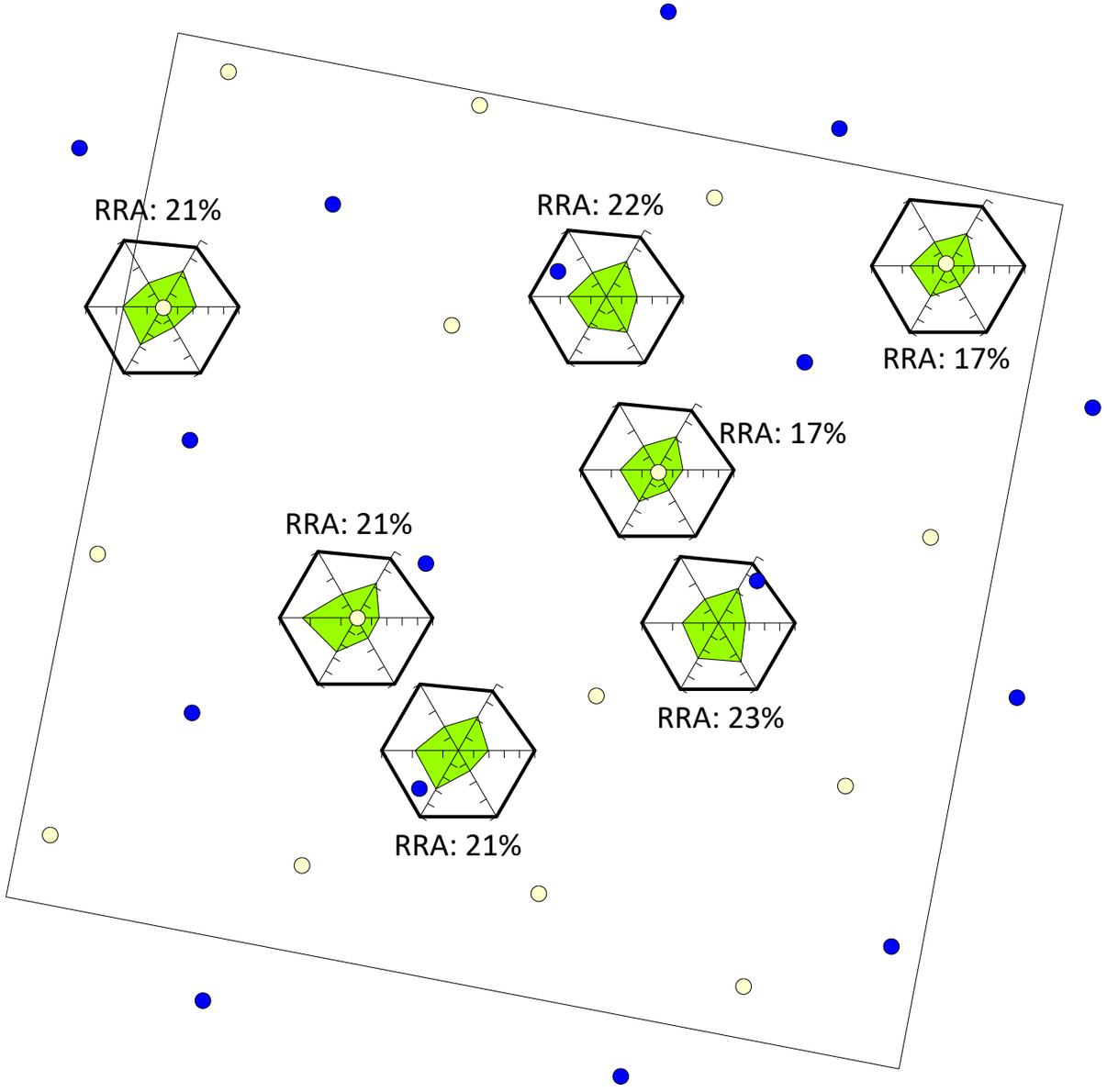
Redox Zone	RRA (%)
Aerobic	78-100
NO_3	62-78
Mn(II)	53-62
Fe(II)	35-53
SO_4	20-35
CH_4	≤20



Concentrations in mg/L

Redox Indicators Event 9: 2006-09-26

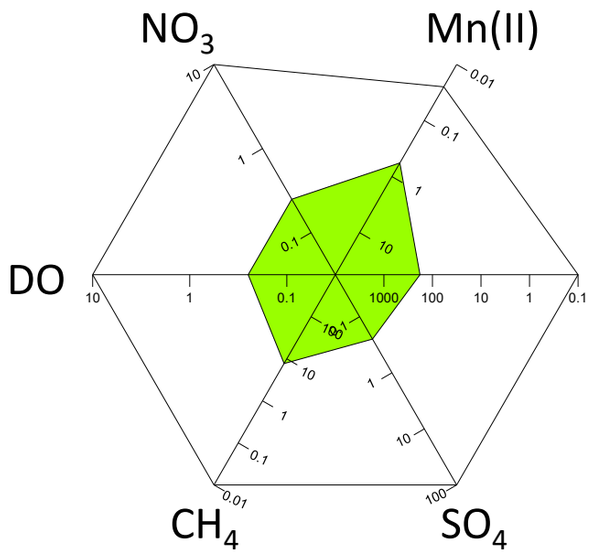
Days after start of Phase I injection: 866
Days after start of Phase II injection: 1



Phase I injection well

Phase II injection well

Redox Zone	RRA (%)
Aerobic	78-100
NO_3	62-78
Mn(II)	53-62
Fe(II)	35-53
SO_4	20-35
CH_4	≤20



Concentrations in mg/L