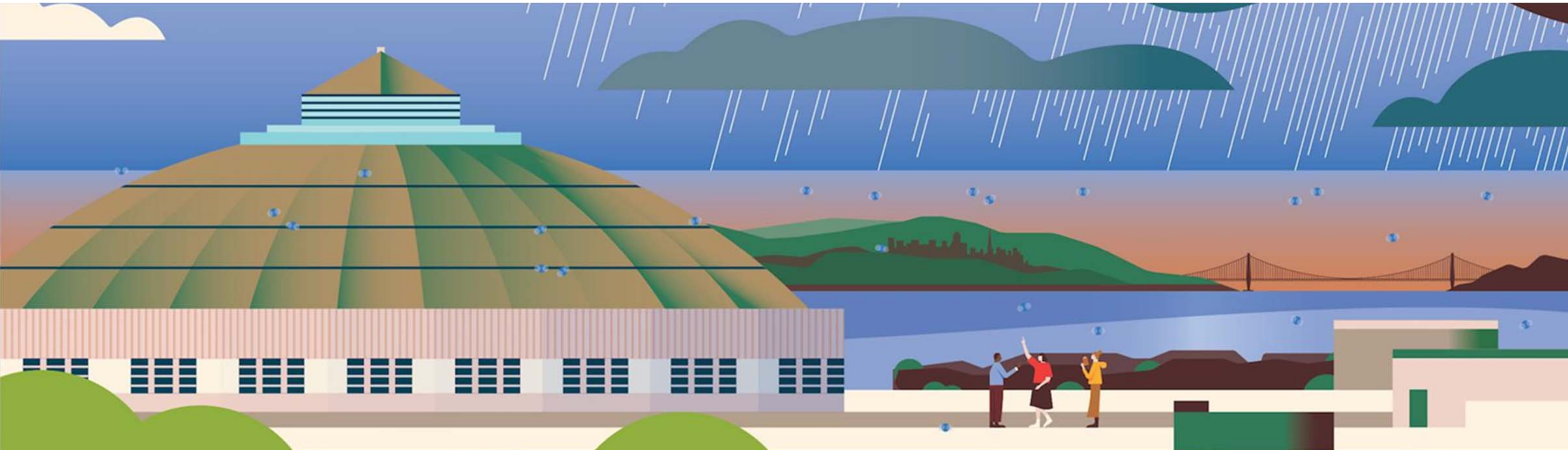


Advances in Long-term Monitoring Technologies for Supporting Bioremediation

Haruko Wainwright, Ken Williams

06/05

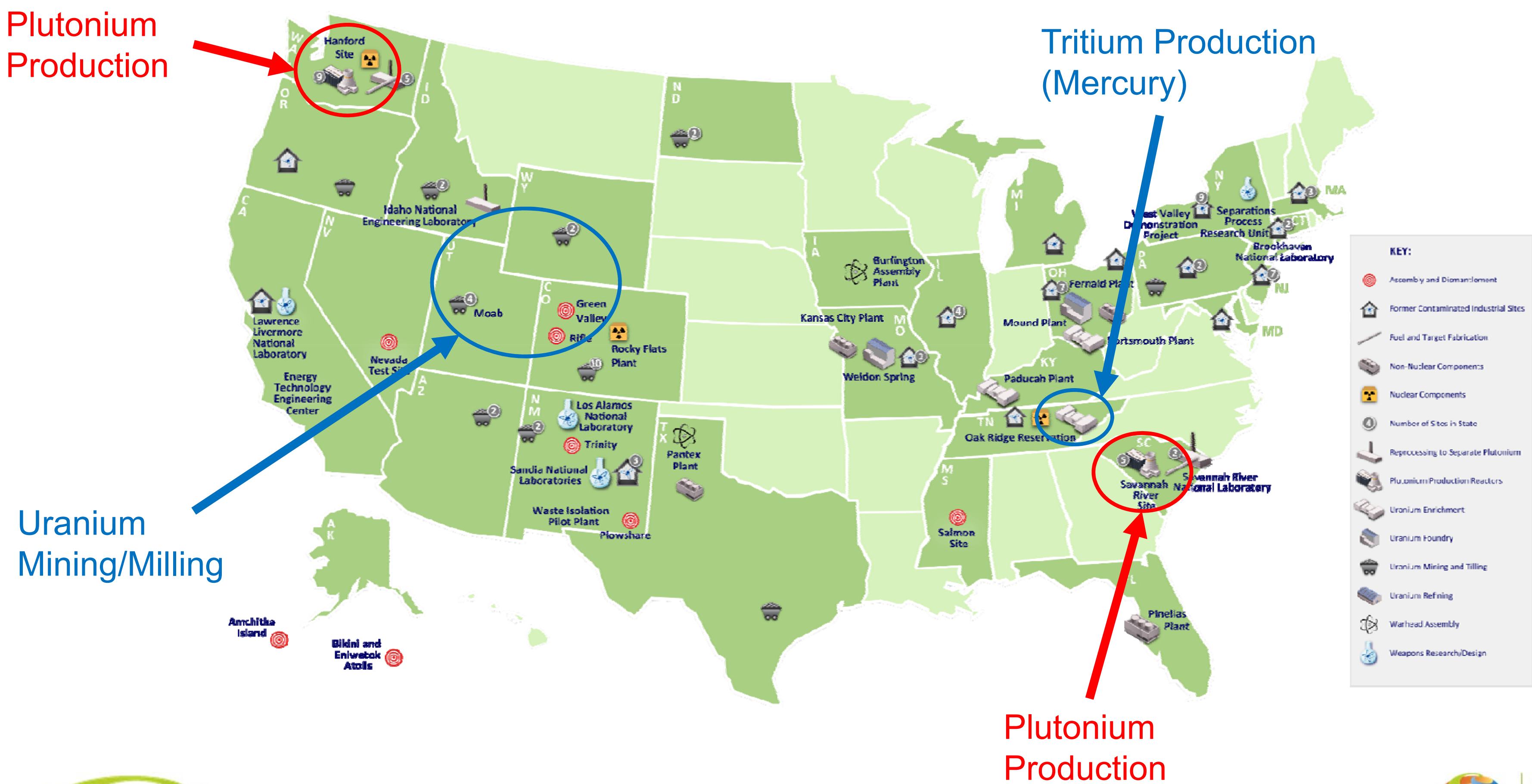
BERKELEY LAB

EARTH & ENVIRONMENTAL SCIENCES

Nuclear Weapon Production Sites

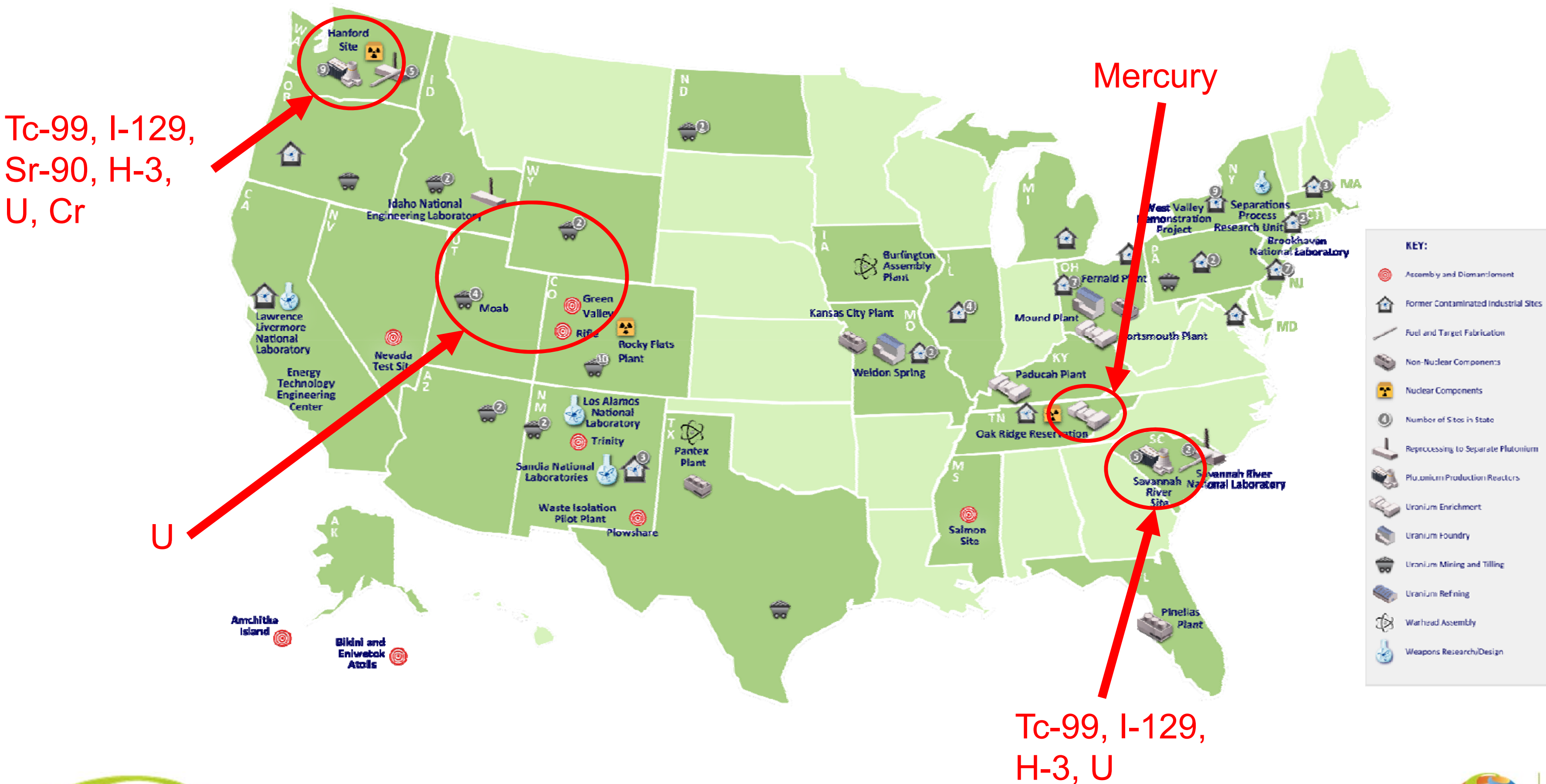
EARTH & ENVIRONMENTAL SCIENCES

Nuclear Weapon Production Sites



EARTH & ENVIRONMENTAL SCIENCES

Key/Priority Elements of Existing Contamination



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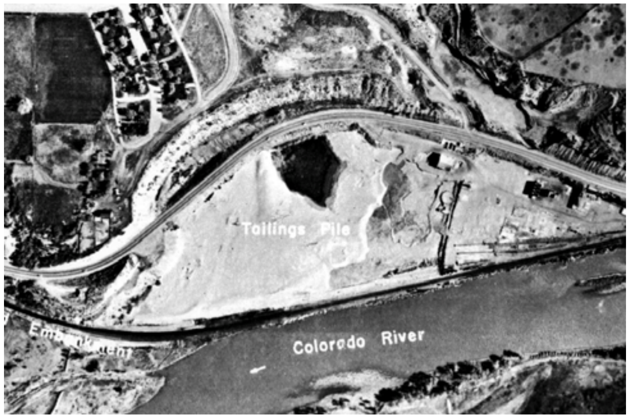
Low-level Radioactive Waste Disposal

Hanford 300 Area



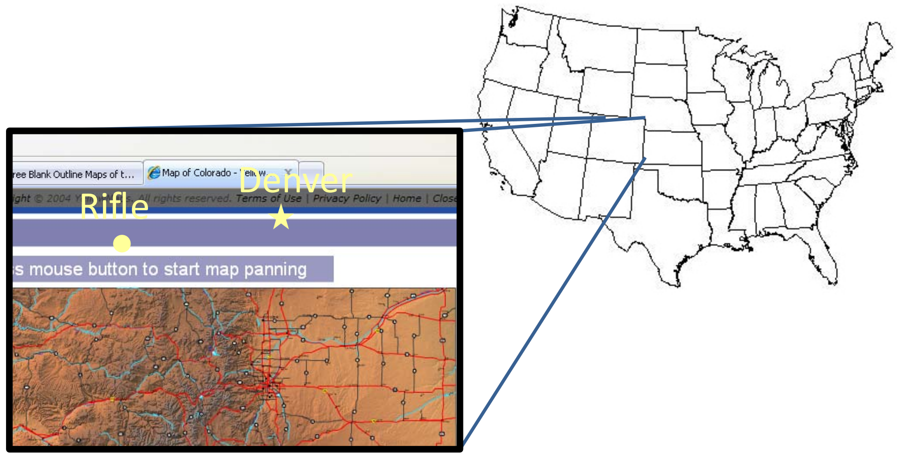
Rifle, CO

Savannah River Site F-Area

EARTH & ENVIRONMENTAL SCIENCES

DOE's Rifle Site

- U.S. Department of Energy (DOE)
- Uranium/vanadium ore processing facility: 1924-1958
- 761,000 tons of ore processed
- 2,000 tons of U concentrate



Rifle, CO: Mill site in ca. 1957

- Tailings were consolidated & stabilized late 1950's & 60's
- Site stabilized; surface cover added and closure in 1996
- **GCAP:** ***Natural flushing*** of residual groundwater U(VI) ca. 0.5-1.5µM

EARTH & ENVIRONMENTAL SCIENCES

Prime Site for U Bioremediation

APPLIED AND ENVIRONMENTAL MICROBIOLOGY, Oct. 2005, p. 6308–6318 Vol. 71, No. 10
0099-2240/05/$08.00+0 doi:10.1128/AEM.71.10.6308–6318.2005

Microbiological and Geochemical Heterogeneity in an In Situ Uranium Bioremediation Field Site

Helen A. Vrionis,[1]* Robert T. Anderson,[1] Irene Ortiz-Bernad,[1] Kathleen R. O'Neill,[1] Charles T. Resch,[2] Aaron D. Peacock,[3] Richard Dayvault,[4] David C. White,[3] Philip E. Long,[2] and Derek R. Lovley[1]

Department of Microbiology, University of Massachusetts, Amherst, Massachusetts 01003[1]; Pacific Northwest National Laboratory, Richland, Washington 99352[2]; S. M. Stoller Corporation, Lafayette, Colorado 80026[4]; and Center for Biomarker Analysis, University of Tennessee, Knoxville, Tennessee 37932[3]

Geomicrobiology Journal, 28:519–539, 2011

ISSN: 0149-0451 print / 1521-0529 online
DOI: 10.1080/01490451.2010.520074

Acetate Availability and its Influence on Sustainable Bioremediation of Uranium-Contaminated Groundwater

Kenneth H. Williams,[1] Philip E. Long,[2] James A. Davis,[3] Michael J. Wilkins,[2] A. Lucie N'Guessan,[2] Carl I. Steefel,[1] Li Yang,[1] Darrell Newcomer,[2] Frank A. Spane,[2] Lee J. Kerkhof,[4] Lora McGuinness,[4] Richard Dayvault,[5] and Derek R. Lovley[6]

[1]*Lawrence Berkeley National Laboratory, Berkeley, California, USA*
[2]*Pacific Northwest National Laboratory, Richland, Washington, USA*
[3]*U.S. Geological Survey, Menlo Park, California, USA*
[4]*Institute of Marine and Coastal Science, Rutgers University, New Jersey, USA*
[5]*S.M. Stoller Corporation, Grand Junction, Colorado, USA*
[6]*Department of Microbiology, University of Massachusetts, Amherst, Massachusetts, USA*

Mineral Transformation and Biomass Accumulation Associated With Uranium Bioremediation at Rifle, Colorado

LI LI,*,† CARL I. STEEFEL,† KENNETH H. WILLIAMS,† MICHAEL J. WILKINS,‡ AND SUSAN S. HUBBARD†

Earth Sciences Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, MS 90-1116, Berkeley, California 94720, and Department of Earth and Planetary Science, University of California, Berkeley, California 94720

Received January 4, 2009. Revised manuscript receivec May 21, 2009. Accepted May 27, 2009.

Geophysical Imaging of Stimulated Microbial Biomineralization

KENNETH H. WILLIAMS,*,†,‡ DIMITRIOS NTARLAGIANNIS,§ LEE D. SLATER,§ ALICE DOHNALKOVA,‖ SUSAN S. HUBBARD,‡ AND JILLIAN F. BANFIELD†,‡

Department of Environmental Science, Policy, and Management, University of California, Berkeley, California 94720, Lawrence Berkeley National Laboratory, Berkeley, California 94720, Department of Earth and Environmental Sciences, Rutgers University, Newark, New Jersey 07102, and Pacific Northwest National Laboratory, Richland, Washington 99352

ELSEVIER

Current Opinion in Biotechnology
Volume 24, Issue 3, June 2013, Pages 489-497

Bioremediation of uranium-contaminated groundwater: a systems approach to subsurface biogeochemistry

Kenneth H Williams [1] ✉, John R Bargar [2], Jonathan R Lloyd [3], Derek R Lovley [4]

Fundamental Understanding of Microbiology

LETTER

doi:10.1038/nature14486

Unusual biology across a group comprising more than 15% of domain Bacteria

Christopher T. Brown[1], Laura A. Hug[2], Brian C. Thomas[2], Itai Sharon[2], Cindy J. Castelle[2], Andrea Singh[2], Michael J. Wilkins[3,4], Kelly C. Wrighton[4], Kenneth H. Williams[5] & Jillian F. Banfield[2,5,6]

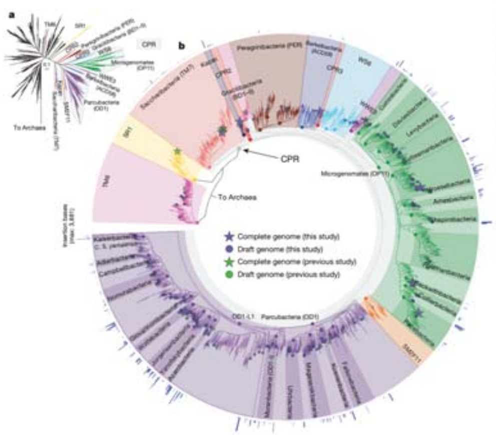
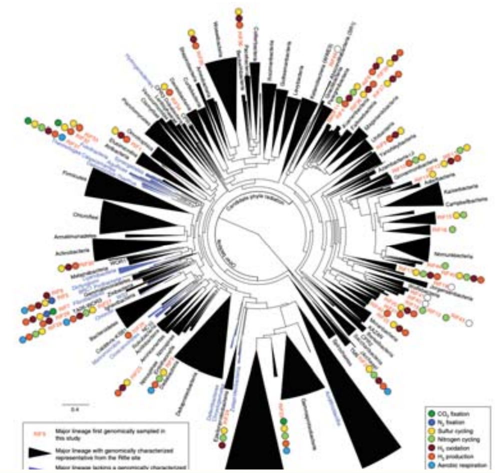


Figure 1 | Phylogeny and genomic sampling of the CPR. a, b, Subsets of a maximum-likelihood 16S rRNA gene phylogeny (Supplementary Fig. 1) showing the CPR, a monophyletic radiation of candidate phyla (**a**), and genomic sampling of candidate phyla (**b**). Proposed names for phyla within the superphyla Parcubacteria and Microgenomates are explained in Extended Data Table 1. Many CPR 16S rRNA genes encode insertions (length shown by blue bars, combined length for multiple insertions).



nature COMMUNICATIONS

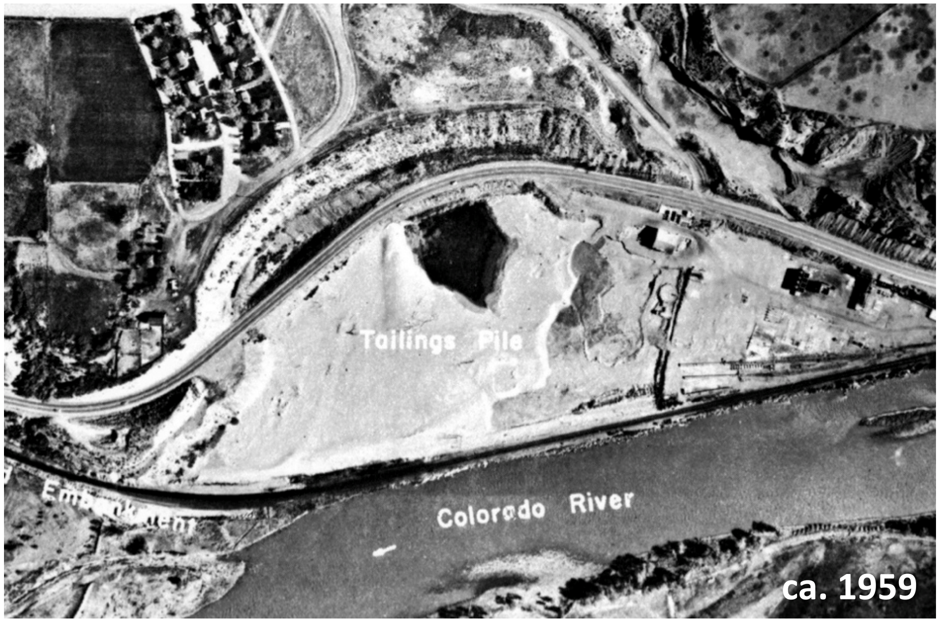
ARTICLE

Received 31 Mar 2016 | Accepted 13 Sep 2016 | Published 24 Oct 2016 DOI: 10.1038/ncomms13219 OPEN

Thousands of microbial genomes shed light on interconnected biogeochemical processes in an aquifer system

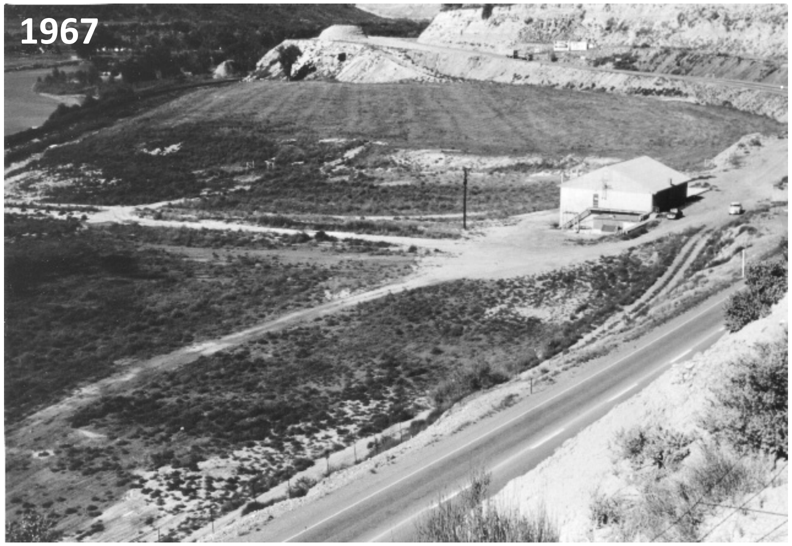
Karthik Anantharaman[1], Christopher T. Brown[2], Laura A. Hug[1], Itai Sharon[1], Cindy J. Castelle[1], Alexander J. Probst[1], Brian C. Thomas[1], Andrea Singh[1], Michael J. Wilkins[3], Ulas Karaoz[4], Eoin L. Brodie[4], Kenneth H. Williams[4], Susan S. Hubbard[4] & Jillian F. Banfield[1,4]

Milling History: 1950



Union Carbide Corporation

Milling History: 1960 - 1996



Tailings consolidated and stabilized by 1967; new ores processed at New Rifle site after 1958

Site 'closure' and remediation finished in 1996.

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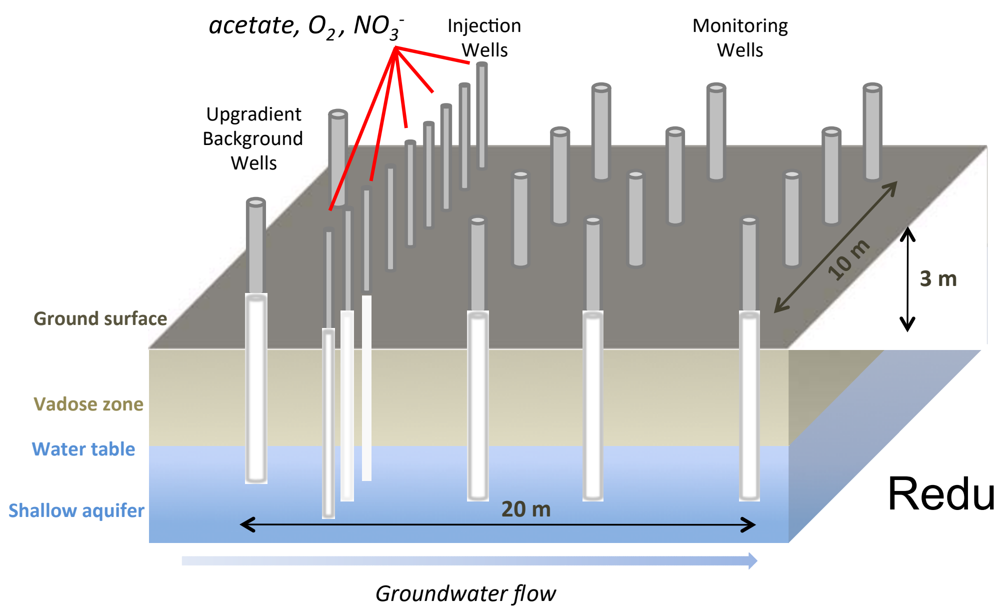
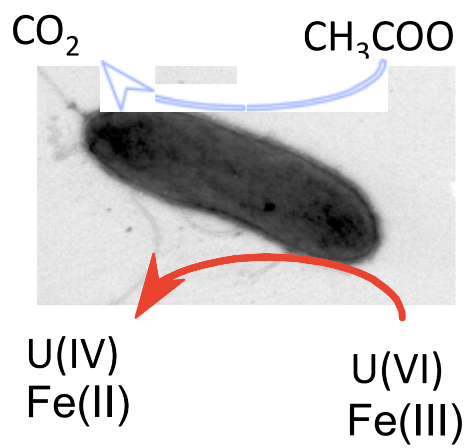
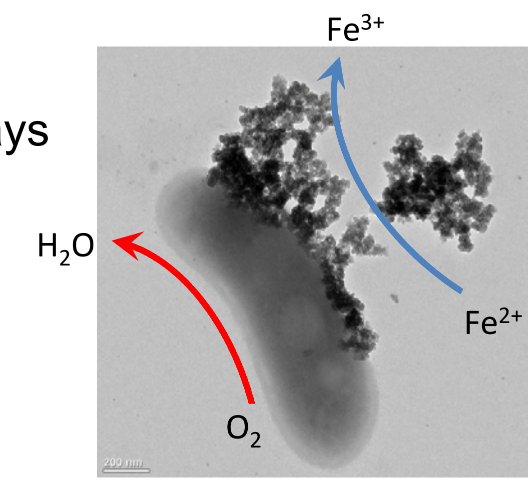
Bioremediation Experiments



- ***Amplify*** pathways of interest (microbial, geochemical, mineralogical)
- Enable ***high resolution sampling***
- Experimentally ***tractable timelines***

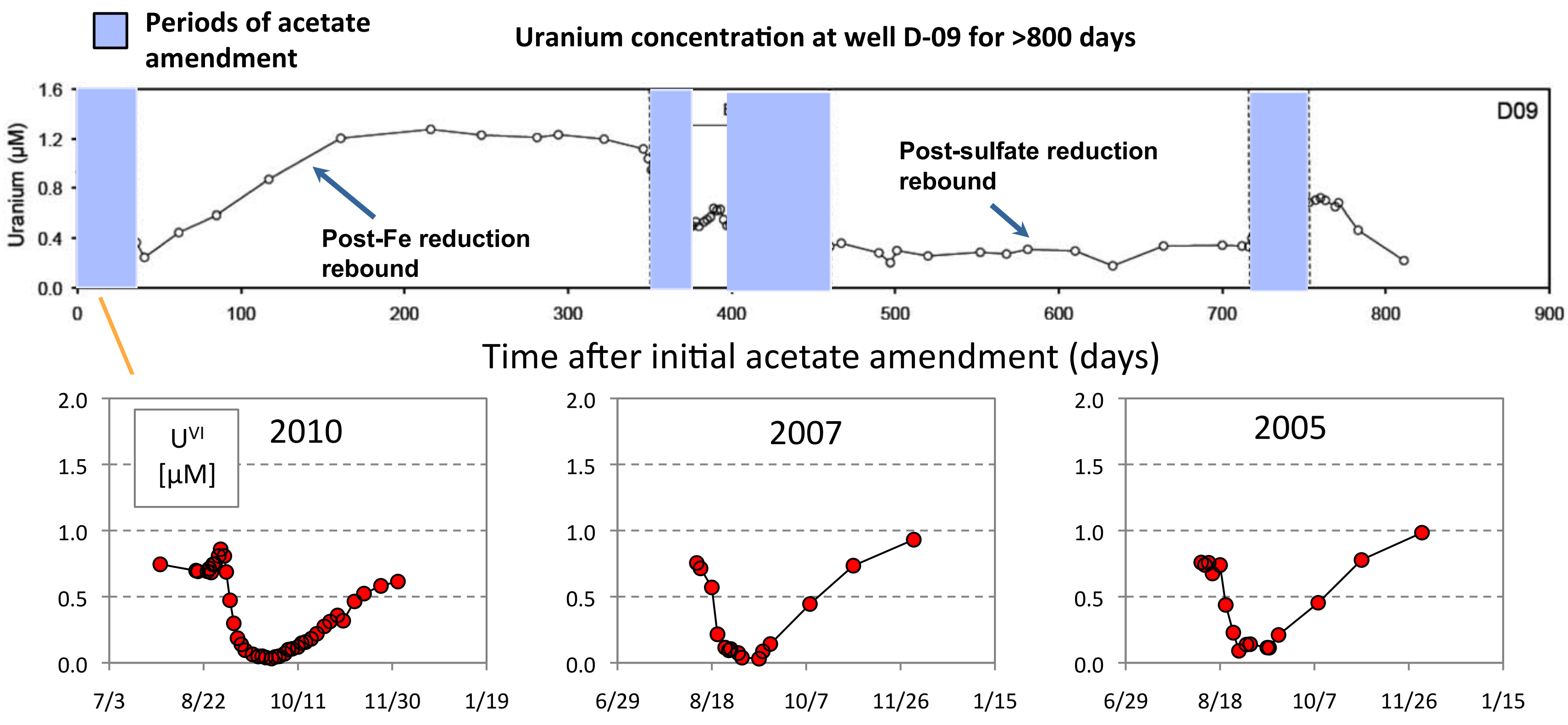


Reductive vs. oxidative pathways



Courtesy: Clara Cha

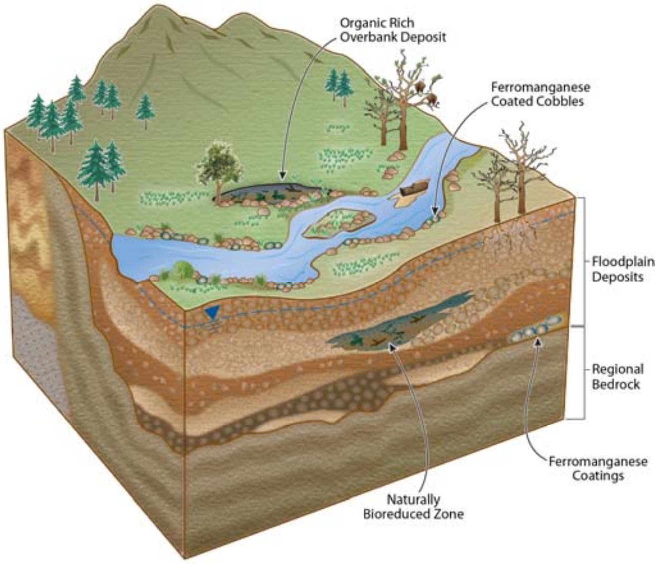
Bioremediation: Acetate Injection

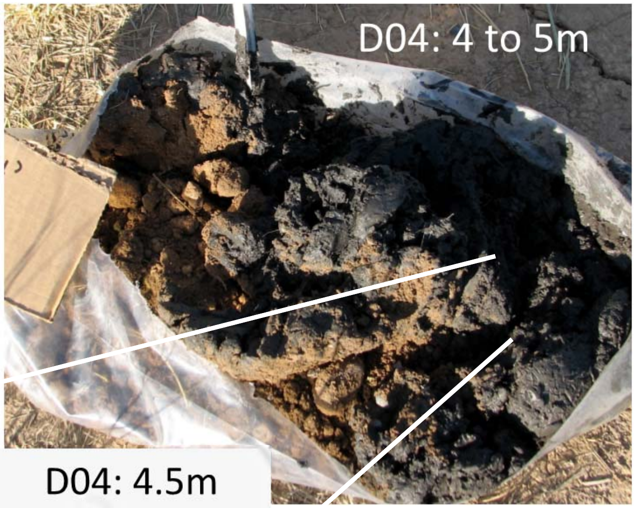


Very repeatable U removal across space and time; [U] remains low so long as acetate remains.

Naturally Reduced Zones

- Drilling delineated regions of refractory organic carbon accumulation (e.g. twigs, roots, cones, etc.)
- Visibly reduced sediments (e.g. FeS)
- Elevated uranium levels *likely* due to same processes catalyzed by acetate injection





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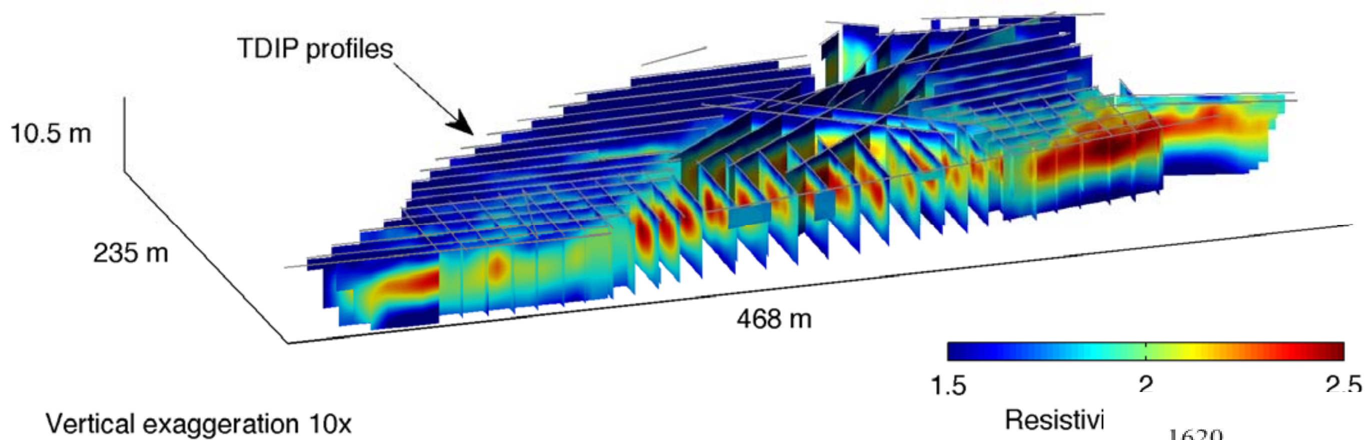
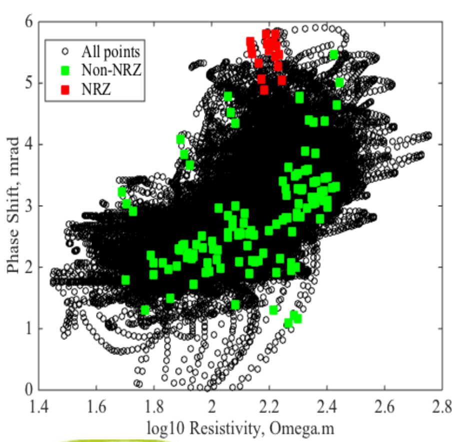
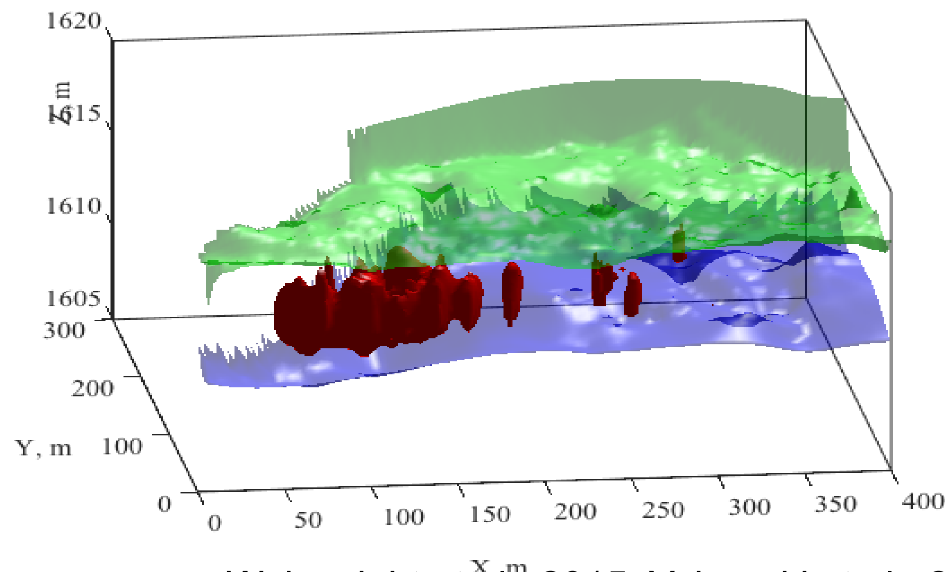
3D Mapping of NRZ





- Induced polarization method
- Phase shift
- Resistivity

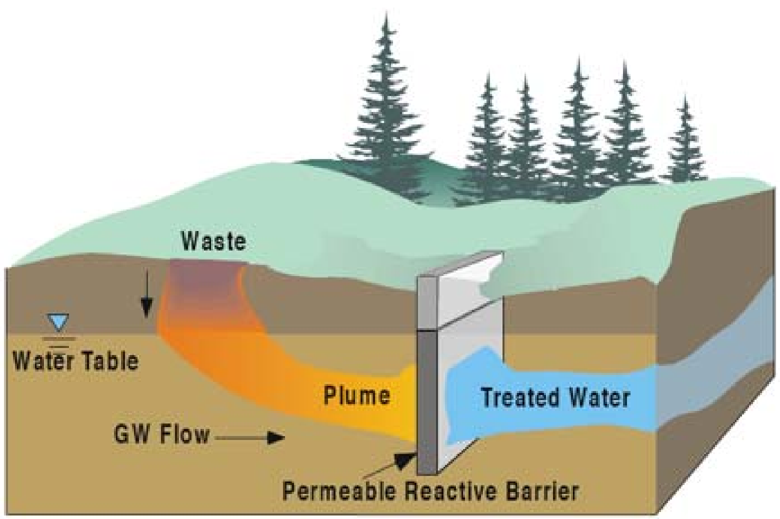
Mapped NRZs



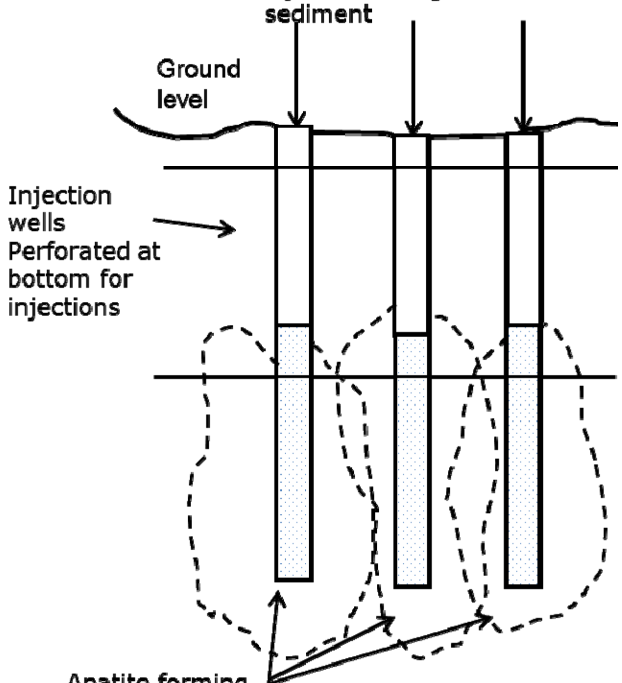
Wainwright et al., 2015; Yabusaki et al., 201

More Effective Alternative?

Apatite-based “Chemically Induced” Permeable Reactive Barrier (PRB) Technology



Citrate degradation



Slow release: calcium–(citrate)$_2$ + sodium phosphate $\rightarrow$ apatite

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Hydroxyapatite as a PRB Material

- 3-dimensional lattice of calcium phosphate, $Ca_{10}(PO_4)_6(OH)_2$
- Very stable; extremely low solubility.
- Can sequester a wide variety of radionuclides, heavy metals and other contaminants through substitution into the structure or sorption onto the surface as metal phosphate compounds.
- Immobilization and sequestration of uranium as an oxidized (U^{6+}) form → less prone to (re)oxidative dissolution
- Can be formed in situ by solution injection in the subsurface (No need to trench)

Experiment Design

☐ Upgradient control well [CU02]

● Injection well [CG08]

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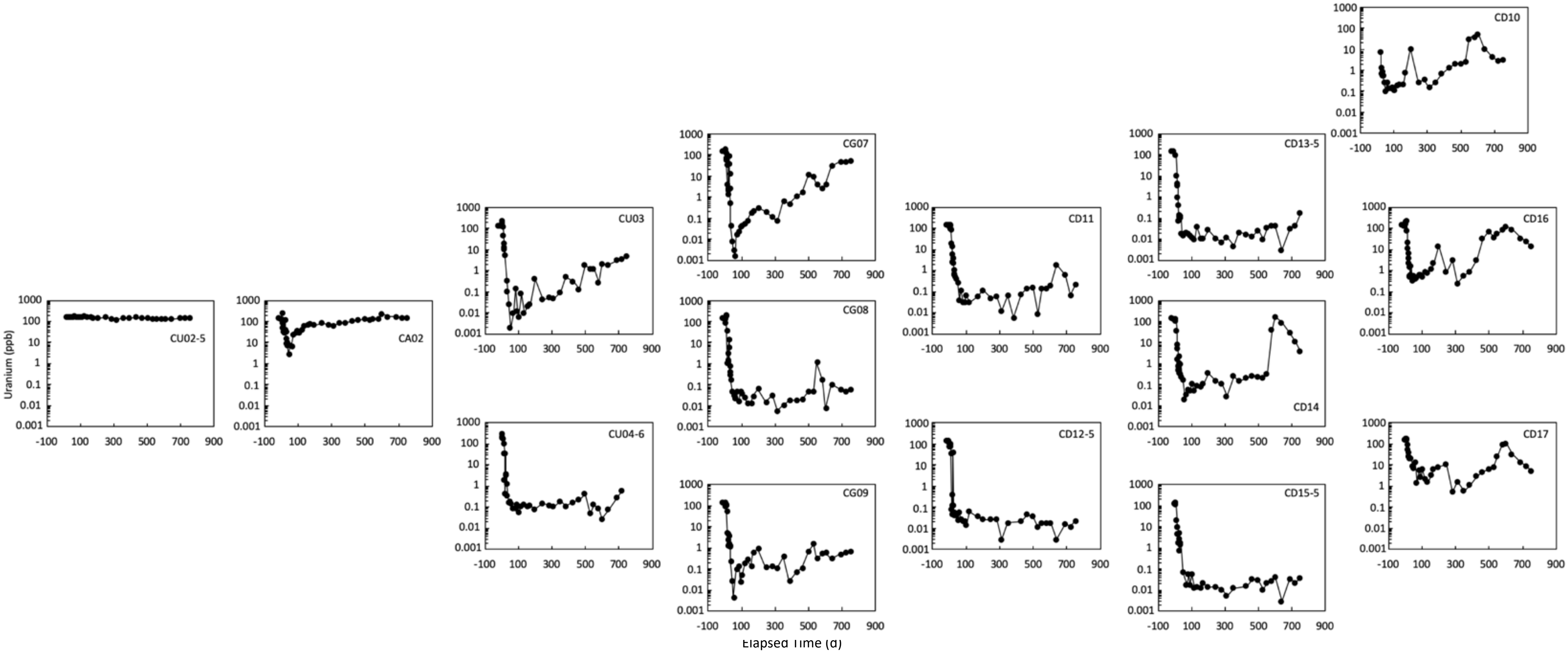
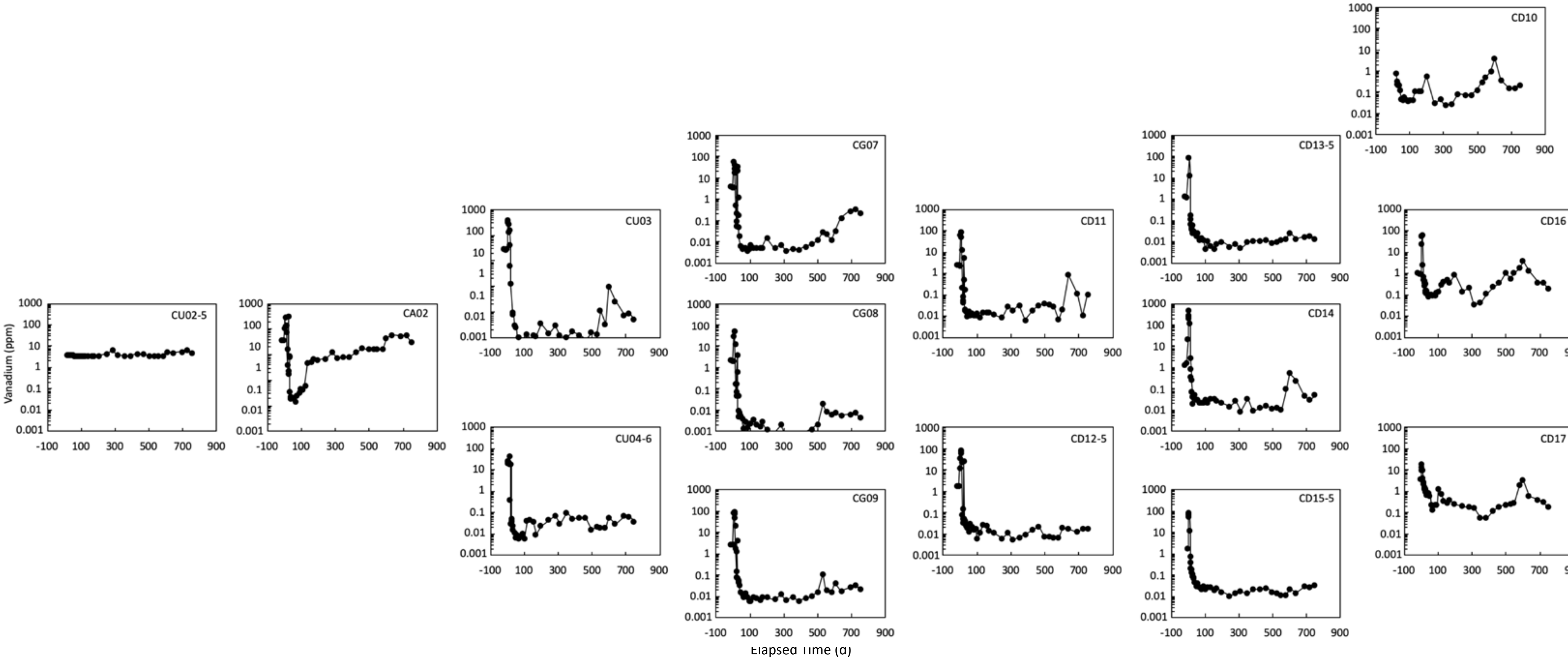
Uranium (ppb)

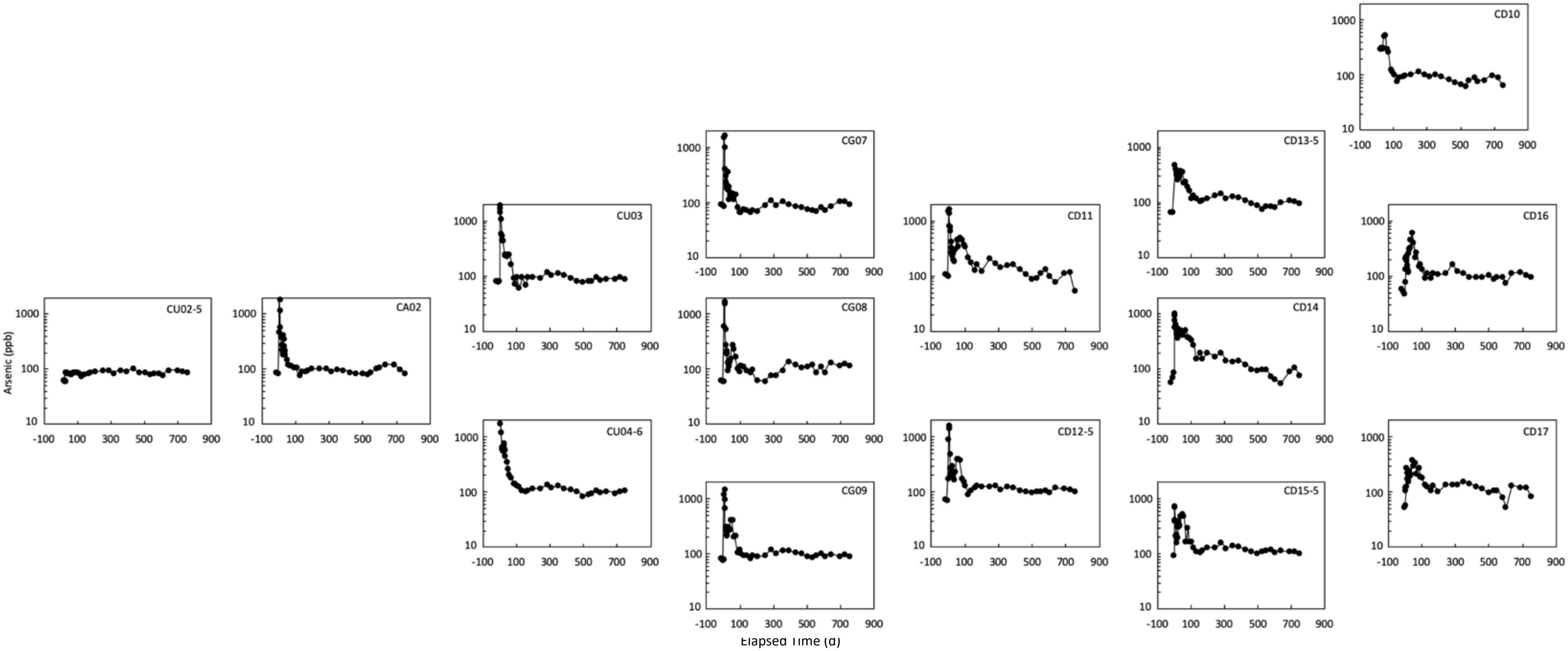


CU02-5
CA02
CU03
CU04-6
CG07
CG08
CG09
CD11
CD12-5
CD13-5
CD14
CD15-5
CD10
CD16
CD17
Uranium (ppb)
Elapsed Time (d)
1000
100
10
1
0.1
0.01
0.001
-100
100
300
500
700
900

Vanadium (ppm)

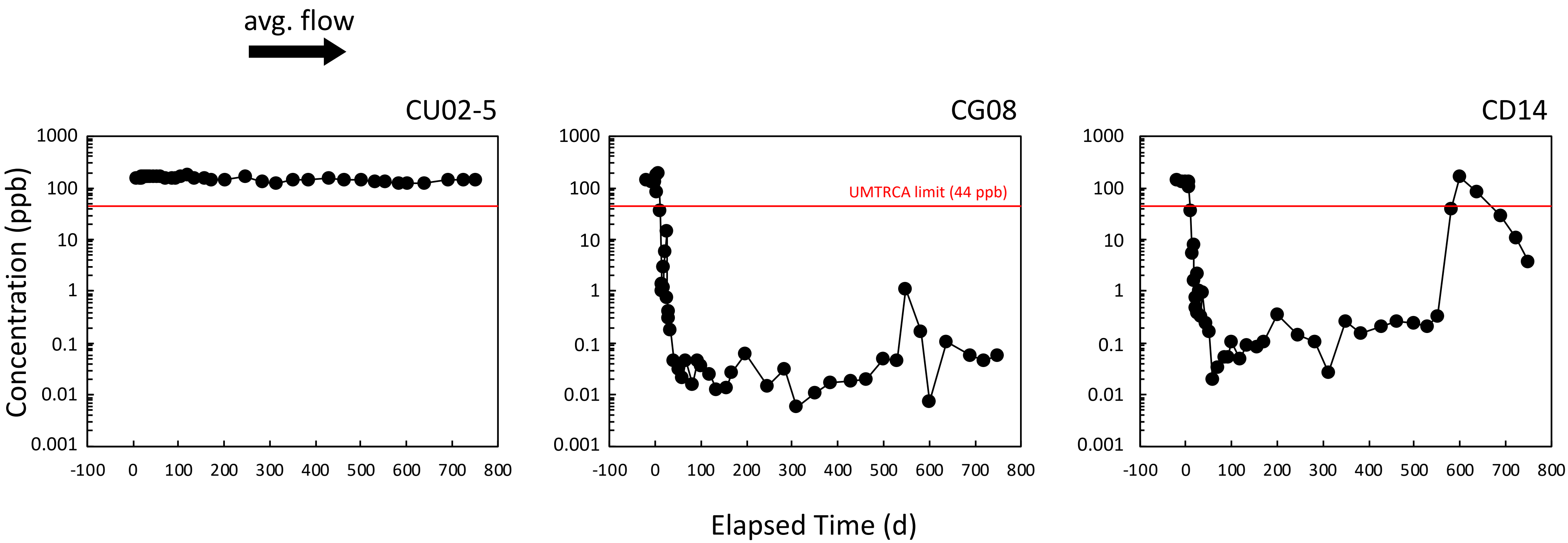


Arsenic (ppb)



Arsenic (ppb)
CU02-5
CA02
CU03
CU04-6
CG07
CG08
CG09
CD10
CD11
CD12-5
CD13-5
CD14
CD15-5
CD16
CD17
Elapsed Time (d)

Uranium (ppb)

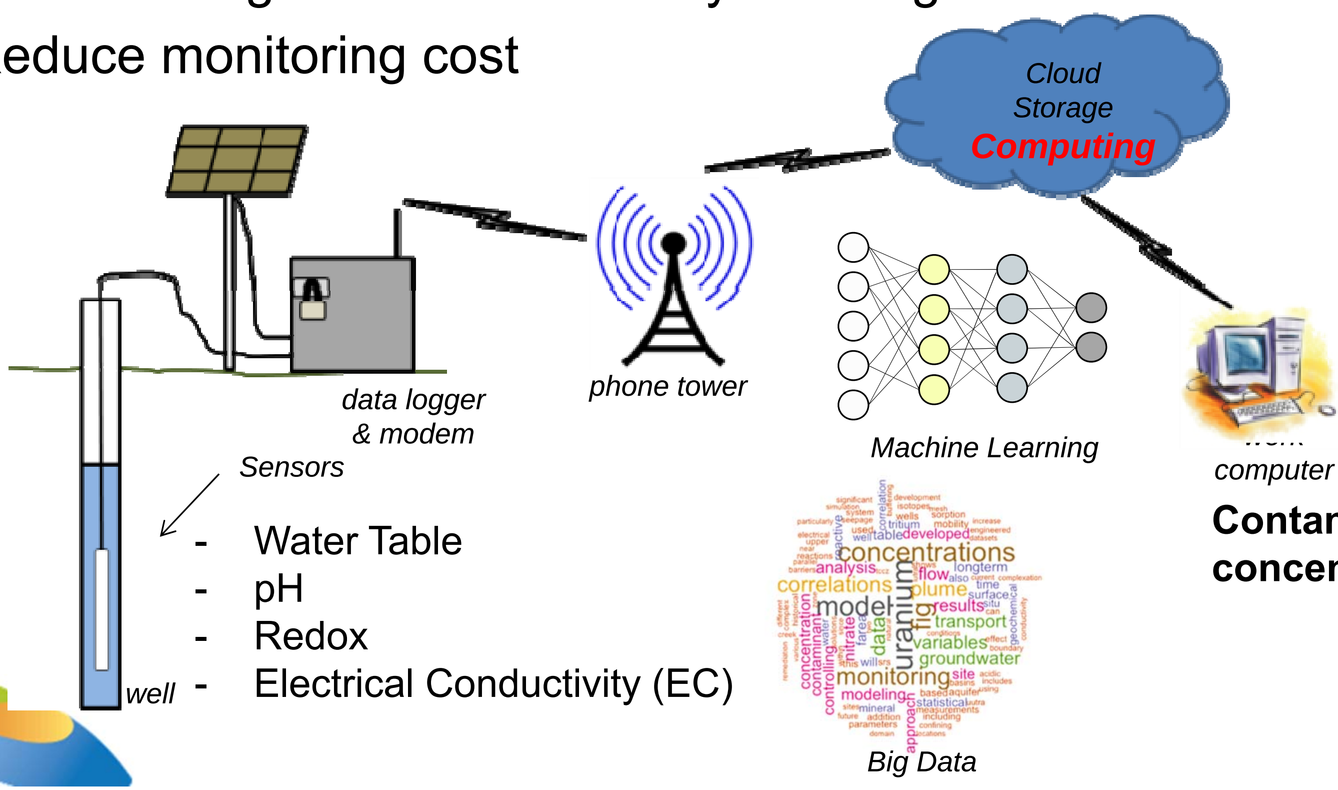


avg. flow
CU02-5
CG08
CD14
UMTRCA limit (44 ppb)
Concentration (ppb)
1000
100
10
1
0.1
0.01
0.001
-100
0
100
200
300
400
500
600
700
800
Elapsed Time (d)

Residual Contaminants: Groundwater Flow Direction

New Paradigm of Groundwater Monitoring

- **Low-cost in situ sensors, wireless network, cloud computing**
  - → Autonomous continuous monitoring
  - → Detect changes real-time = Early Warning
  - → Reduce monitoring cost



Contaminant concentrations

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Importance of Long-Term Monitoring


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Activists ignore the science that says Rocky Flats National Wildlife Refuge is safe

By VINCENT CARROLL | The Denver Post
PUBLISHED: June 16, 2017 at 12:00 pm | UPDATED: June 16, 2017 at 2:36 pm

14

Andy Cross, Denver Post file

om/opinion/

- Ensure public safety
- Prepare for liability issues
- Tackle fake news

Beneficial for both residents and site operators

Good example: Monitoring data proves that the site is safe to dismiss false claims

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Climate Change Impact: What to expect?


Contents lists available at ScienceDirect

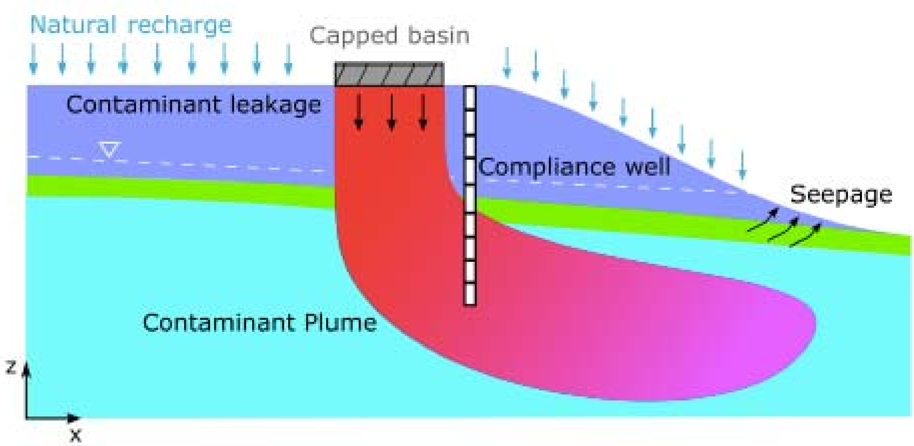
Journal of Contaminant Hydrology

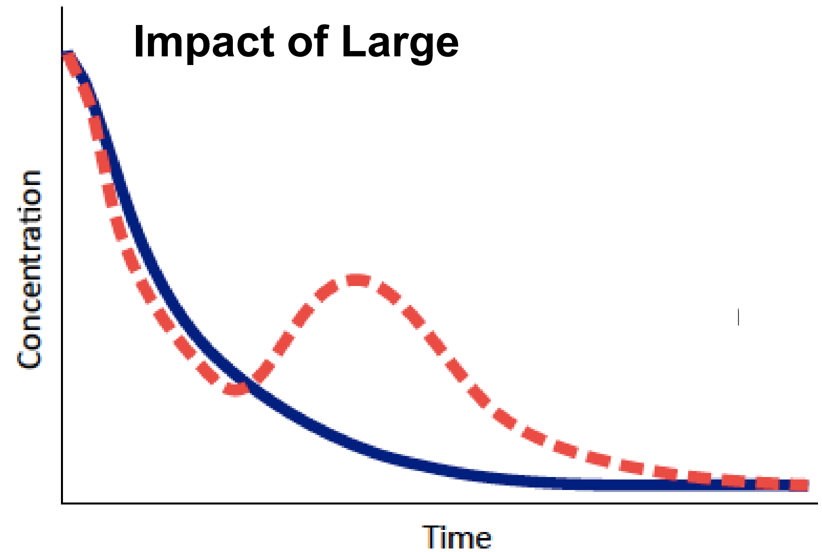
journal homepage: www.elsevier.com/locate/jconhyd

Climate change impact on residual contaminants under sustainable remediation

Arianna Libera[a,*], Felipe P.J. de Barros[a], Boris Faybishenko[b], Carol Eddy-Dilek[c], Miles Denham[d], Konstantin Lipnikov[e], David Moulton[e], Barbara Maco[f], Haruko Wainwright[b]

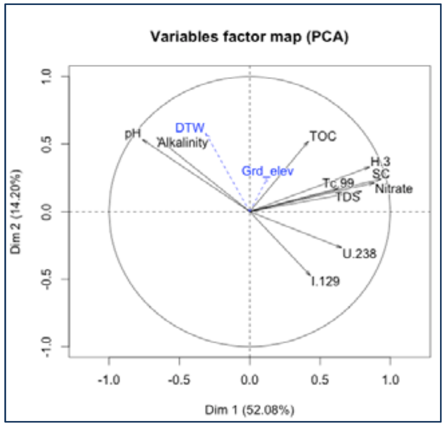
[a] Sonny Astani Dept. of Civil and Environmental Engineering, University of Southern California, Los Angeles, California, USA
[b] Lawrence Berkeley National Laboratory, Berkeley, CA, USA
[c] Savannah River National Laboratory, Aiken, SC, USA
[d] Panoramic Environmental Consulting, LLC, Aiken, SC, USA
[e] Los Alamos National Laboratory, Los Alamos, NM, USA
[f] Wactor & Wick LLP Environmental Lawyers, Oakland, CA, USA





Importance of
- **Surface capping: Limit infiltration through the source zone**
- **Source-zone monitoring to detect re-mobilization**

Data Analytics Workflow

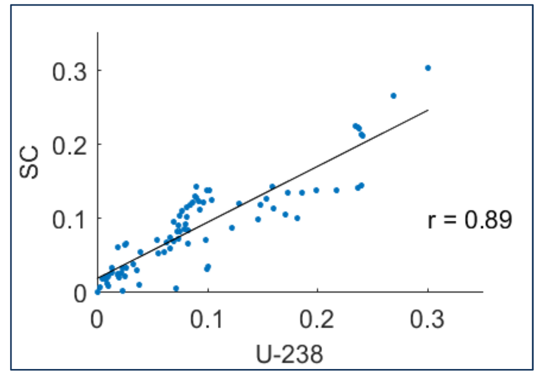


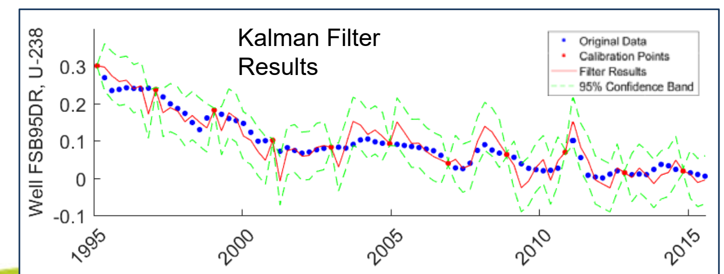
Exploratory Data Analysis

Quantification of Correlations

Contaminant Concentration Estimation

Machine Learning





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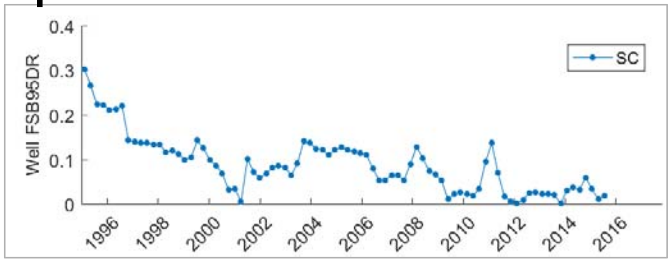
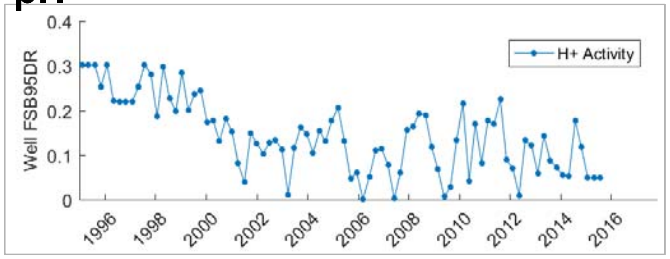
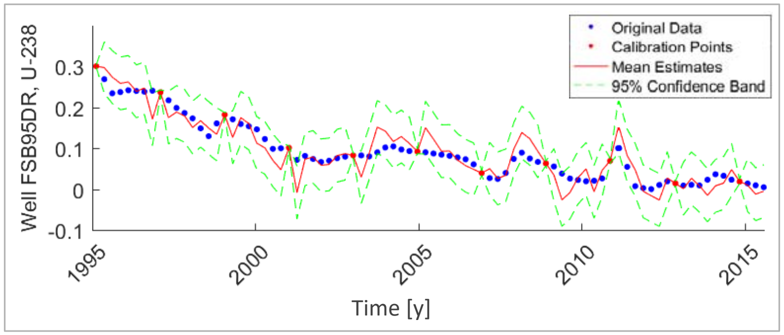
Kalman Filter: Application at Savannah River Siste

Specific Conductance

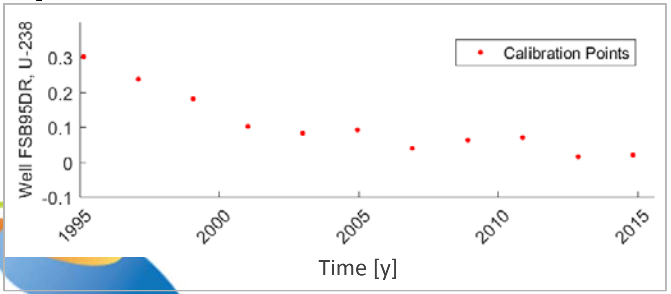


pH





Sparse Direct Measurements



- Confidence interval captures validation points
- Mean estimate captures natural fluctuation

Schmidt et al, 2019 EST

EARTH & ENVIRONMENTAL SCIENCES

Big Interest in ML x Environment

Environmental Science & Technology

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Article

Previous Ar

In Situ Monitoring of Groundwater Contamination Using the Kalman Filter

Franziska Schmidt[†], Haruko M. Wainwright[*‡], Boris Faybishenko[§], Miles Denham[ǁ], and Carol Eddy-Dilek[⊥]

[†] Department of Nuclear Engineering, University of California Berkeley, Etcheverry Hall, 2521 Hearst Avenue, Berkeley, California 94709, United States

[‡] Climate and Ecosystem Sciences Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, MS 74R-316C, Berkeley, California 94720-8126, United States

[§] Energy Geosciences Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720-8126, United States

[ǁ] Panoramic Environmental Consulting, LLC, P.O. Box 906, Aiken, South Carolina 29802,

[⊥] Savannah River National Laboratory, Savannah River Site, Aiken, South Carolina 2980

Environ. Sci. Technol., **2018**, *52* (13), pp 7418–7425

DOI: 10.1021/acs.est.8b00017

Publication Date (Web): June 22, 2018

*E-mail: hmwainwright@lbl.gov.

Cite this: *Environ. Sci.* 7425

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PUBLIC RELEASE: 13-AUG-2018

Algorithm provides early warning system for tracking groundwater contamination

Berkeley Lab researchers devise system to monitor contaminant plumes

DOE/LAWRENCE BERKELEY NATIONAL LABORATORY

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New Algorithm Provides Real-Time Monitoring Of Groundwater Pollutants

Sam Benezra | 8 Months Ago

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Efficiency & Environment

Scientists develop new method to track groundwater pollutants in real-time

It is expected to reduce the frequency of manual groundwater sampling and lab analysis and therefore cut the monitoring cost

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Machine learning improves contamination monitoring

BY MATT LEONARD | AUG 14, 2018

Because groundwater is susceptible to pollution from automotive fuel, fertilizer or naturally occurring substances like iron, the Environmental Protection Agency and its state-level counterparts conduct annual or quarterly sampling and analysis.

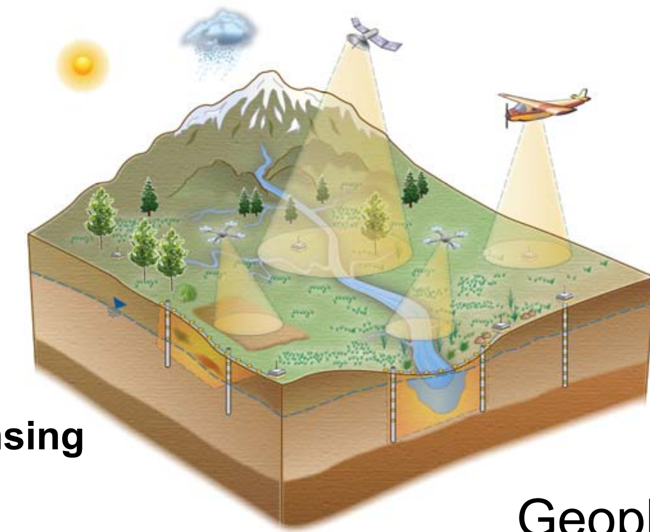
Advanced Long-term Monitoring Systems (ALTEMIS)

AI FOR SCIENCE TOWN HALL

R/Python packages
- Historical data analysis
- Well placement optipization

ML/AI

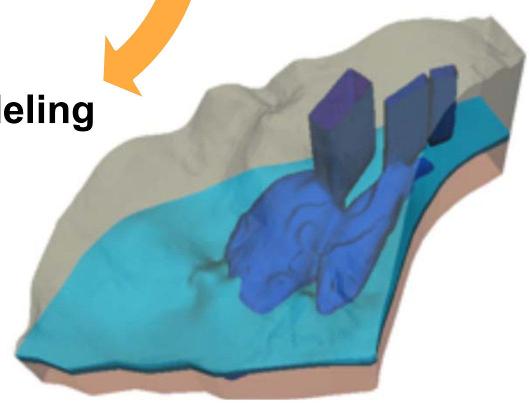
Sensing



Remote sensing
- Wetland
- Surface Barrier

Geophysics
Fiber optics

Modeling



EARTH & ENVIRONMENTAL SCIENCES

Summary

- **Bioremediation of Uranium or Heavy Metal in general**
  - Control redox conditions to reduce solubility: Microbial stimulation
    - Problem with rebound/remobilization
  - Naturally reduced zone: organic rich layer
    - Persistent plume
  - Permeable reactive barrier: Create stable co-precipitates
    - Successful immobilization for 2+ years
- **Monitoring for Bioremedaition**
  - Critical to understand the variability of bioremediation effects
    - Groundwater flow direction changes, multiple sources
  - Stability of immobilized contaminants need to be monitored for an extended time
  - New technologies (AI/Sensing/Modeling capabilities) have a great potential to improve the risk quantification at contaminated sites

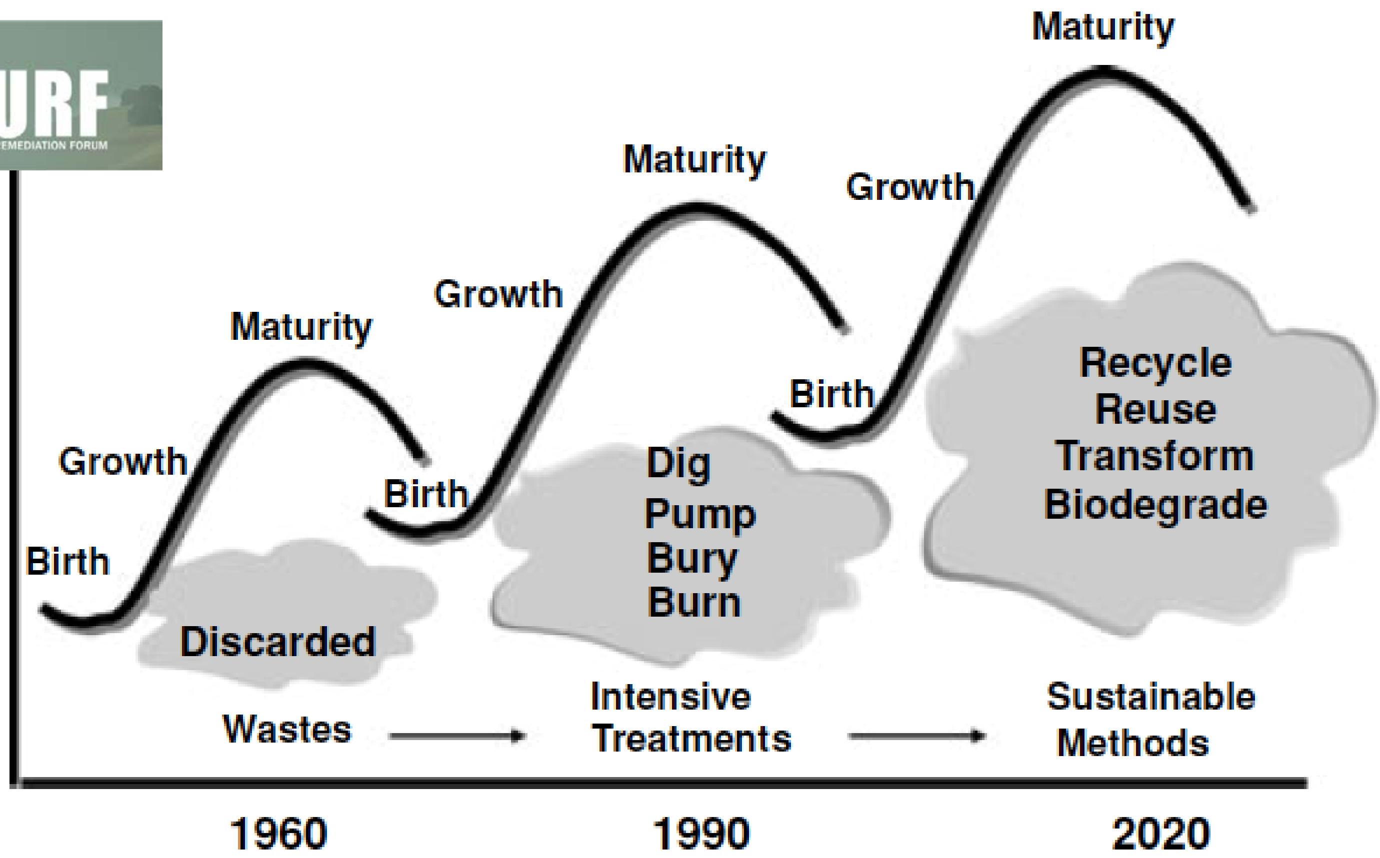
Thank You!

Contact
Haruko Wainwright
HMWainwright@LBL.gov

Ken Williams
KHWilliams@lbl.gov

Acknowledgment
DOE Office of Science
DOE Office of Environmental Management

Environmental Remediation: Evolution



Sustainable Remediation Forum (SURF), "Integrating sustainable principles, practices, and metrics into remediation projects", Remediation Journal, 19(3), pp 5 - 114, editors P. Hadley and D. Ellis, Summer 2009

Sustainable Remediation: Net Environmental Impact

- **Reuse/recycle**
- **Reduce energy, water use and waste**
- **Passive remediation**
- **Monitored natural attenuation**
- **Longer institutional control with alternative/attractive end-use**


Rocky Flats National Wildlife Refuge


Former Reilly Tar & Chemical Corporation Plant

EARTH & ENVIRONMENTAL SCIENCES