# Risk Assessment on $CO_2$ Leakage at $CO_2$ Storage Sites

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Tokyo, Japan

# Talk Outline

- Using risk assessment to optimize monitoring methods: an ALPMI approach
- The #1 risk to CCS projects NOT addressed by risk assessments
- Technical pproaches to minimizing this unaddressed risk
- Application to offshore sites
- Offshore initiative in the USA- GoMCARB partnership and Offshore workshops.

# Risk is Addressed Before the Project Begins

**1. Site Characterization-** Primary means of protection. High level of assurance required for permitting

**2. Risk Assessment-** Aided by modeling, identifies potential unwanted outcomes

**3. Project Design-** Design injection to further minimize perceived risk

**4. Monitoring Plan**

**Deep subsurface**

Verification Monitoring

Does what happened conform to predictions?

**Near-surface**

Assurance Monitoring

No unwanted outcomes

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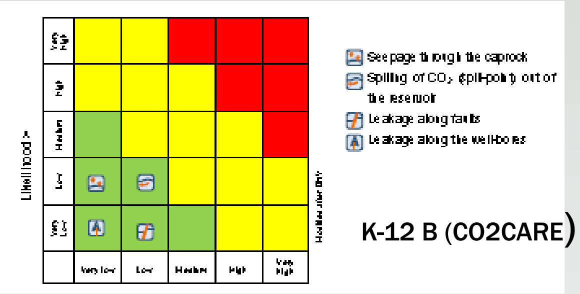
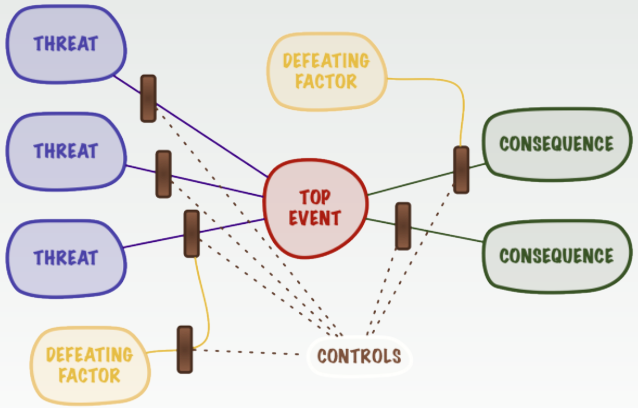
# Linking Risk Assessment and Monitoring

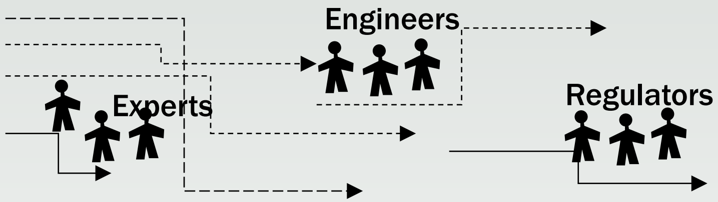
## Risk Assessment



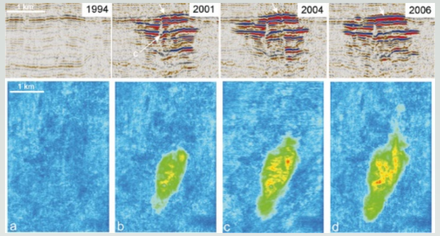

Hovorka, 2017; Hovorka et al, 2014

## Process is cloudy or obscured

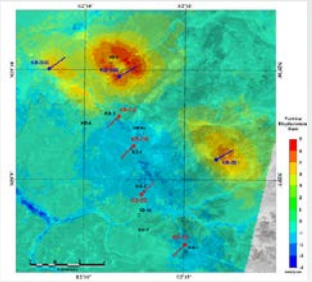



Process of designing and selecting monitoring can be complex, conducted without documented process, non-linear and therefore difficult to duplicate or justify

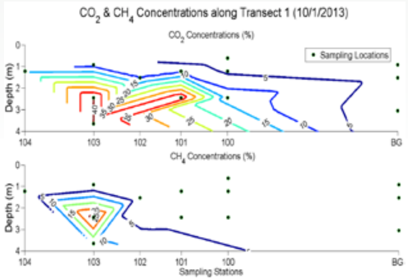
## Select monitoring systems




Chadwick BGS



Onuma and Ohkawa, 2009




Romanak et al., 2012

# Proposed "ALPMI" Method for Linking

- Matching monitoring to risk via forward modeling using an ALPMI process

Assessment of Low Probability Material Impact (ALPMI)

  - Part 1: Describing *material impact* quantitatively
  - Part 2: Sensitivity of monitoring strategy to *material impact*
  - Examples of optimizing leakage detection

- Monitoring tool selection that is reproducible and transparent.
- Makes clear why different monitoring is selected for different sites and for different business and stakeholder settings

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# ALPMI Workflow

**Risk assessment method as usual**

**Quantify risks to define material impact**

Specify magnitude, duration, location, rate of material impact

- Avoid subjective terms like safe and effective.
- E.g. : Specify mass of leakage at identified horizon or magnitude of seismicity.
- Specify certainty with which assurance is needed

**Model material impact scenarios**

Explicitly model unacceptable outcomes showing leakage cases.

ALPMI uses models differently than the typical history matching the expected performance

**Identify signals in the earth system that indicate or preferably precede material impact**

This method down selects to consider only signals that may indicate material impact is occurring or may occur.

**Select monitoring tools that can detect these signals at required sensitivity**

Approaches like those normally seismic survey design should be deployed for all modeling tools

Forward modeling tool response is essential to developing the expected negative finding: "No material impact was detected by a system that could detect this impact."

**Deploy tools and collecte and analyze data**

This activity as traditionally conducted. Include all the expected components, such as attribution, updating as needed, feedback , etc.

**Report if material impact did/did not occur**

Only via this ALPMI process can a finding that the material impact did not occur be robustly documented

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# Material impact examples (random)

- Loss of $CO_2$ at a rate greater than 10,000 tones per year for a period of more than 10 years @ 80% confidence
- >5% probability of earthquake > magnitude 4 within 100 years
- Pressure trend that will exceed calculation mechanical stability prior to project completion
- Plume migration such that location of saturation of >5% pore volume $CO_2$ at stabilization is within a footprint (shown on a map)

# ALPMI part 2: Assess sensitivity of monitoring strategy to material impact

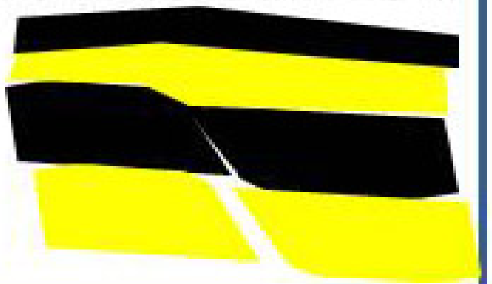
Essential to forward model the impact

1. Create material impact scenarios

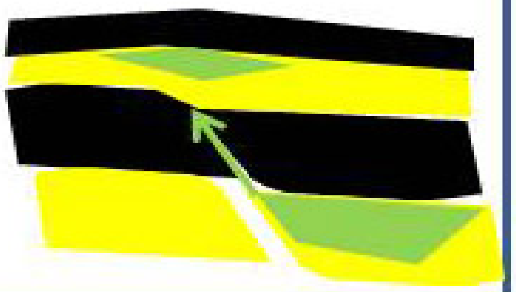
   e.g. for $CO_2$ leakage or change in pore pressure that would increase seismic risk

2. Evaluate sensitivity of instruments, spacing, frequency of data collection, other statistical measures against scenarios.

**Characterization Uncertainty: Fault-seal?**



**ALPMI**



**Monitoring options**

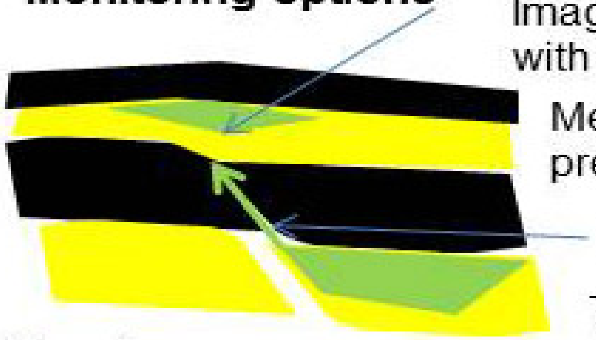


Image free-phase with surface 4-D

Measure change in pressure AZMI

Microseismic

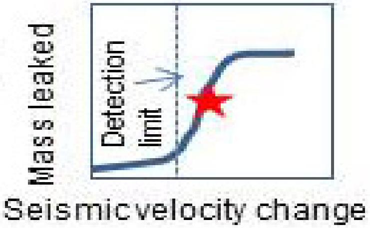
Temperature change along fault

Mass/pressure balance in reservoir

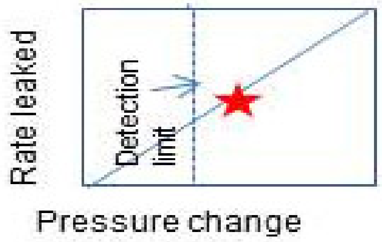
Microseismic

## Test Sensitivity of Monitoring Options

Image free-phase leaked $CO_2$ with surface 4-D

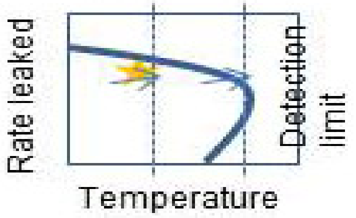



Measure change in pressure AZMI




Change in rate pressure increase in reservoir


Temperature change along fault




## Set triggers, stage monitoring options

- Select microseismic as pre-failure trigger
- AZMI pressure as most sensitive trigger
- Select Image with surface 4- D and change in rate of pressure change in reservoir as post-trigger follow up.
- Decrease analysis of microseismic after pressure peaks and plateaus

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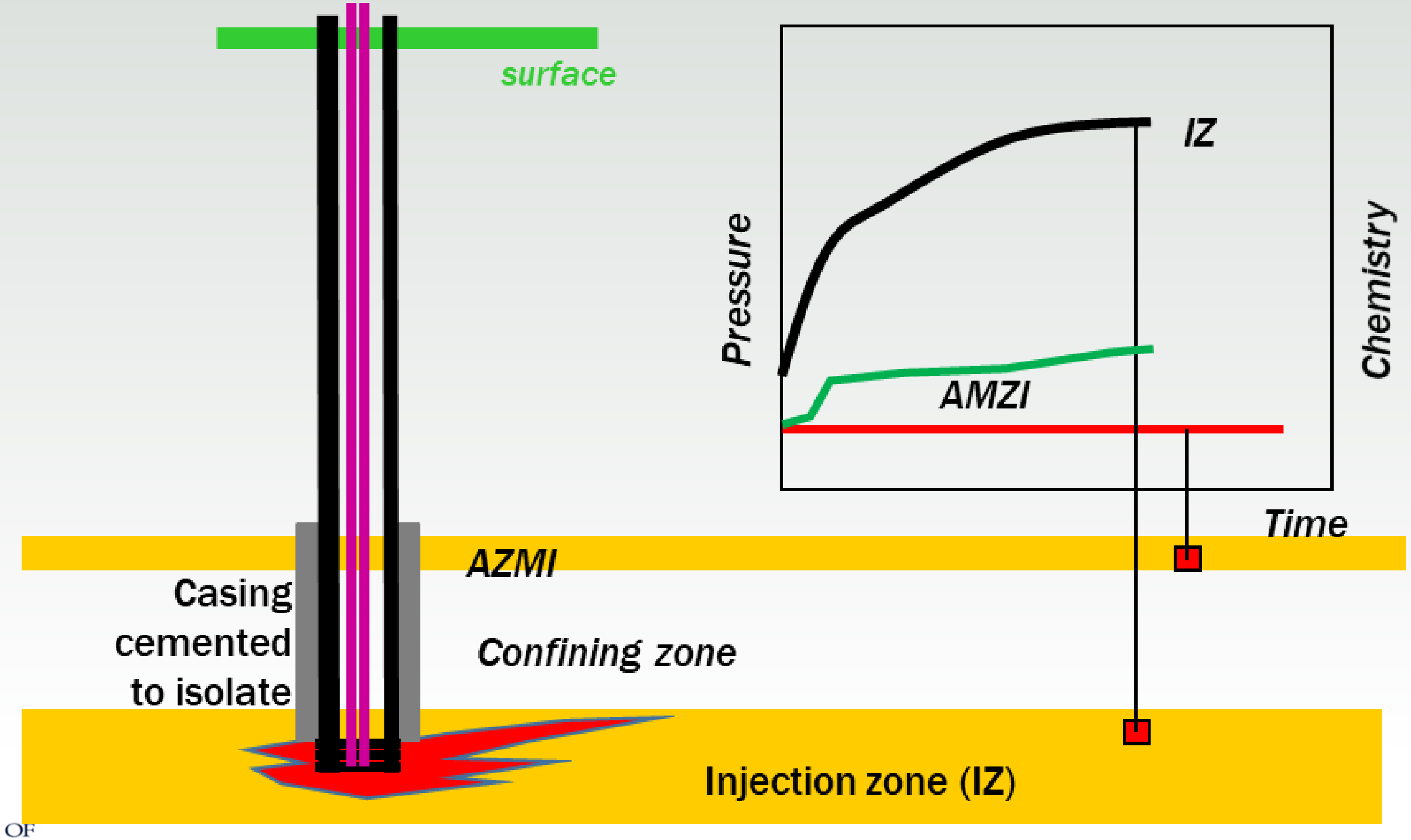
# Example of optimizing leakage detection: above zone monitoring for leakage detection- Pressure or chemistry?

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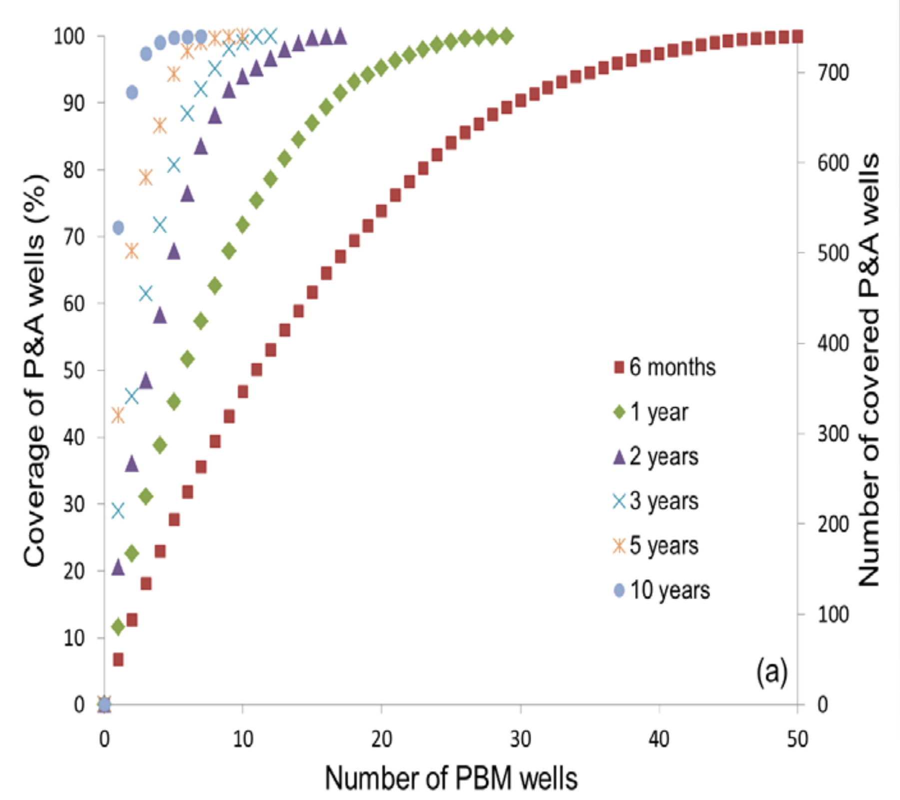
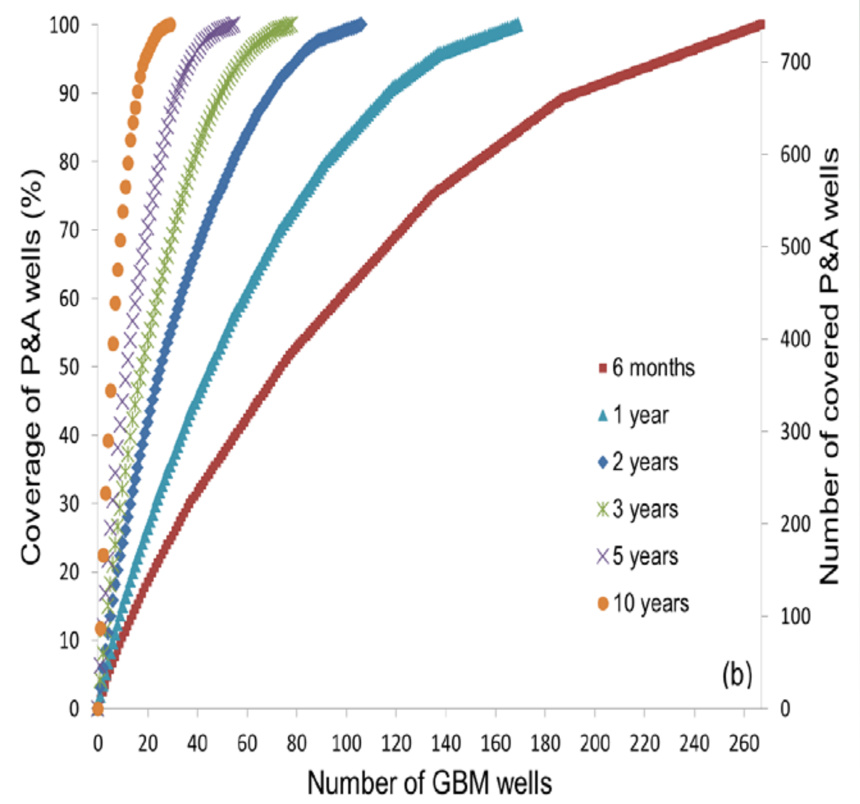
# Sensitivity analysis for leakage detection time in models

## Detecting pressure signal




## Detecting geochemical signal

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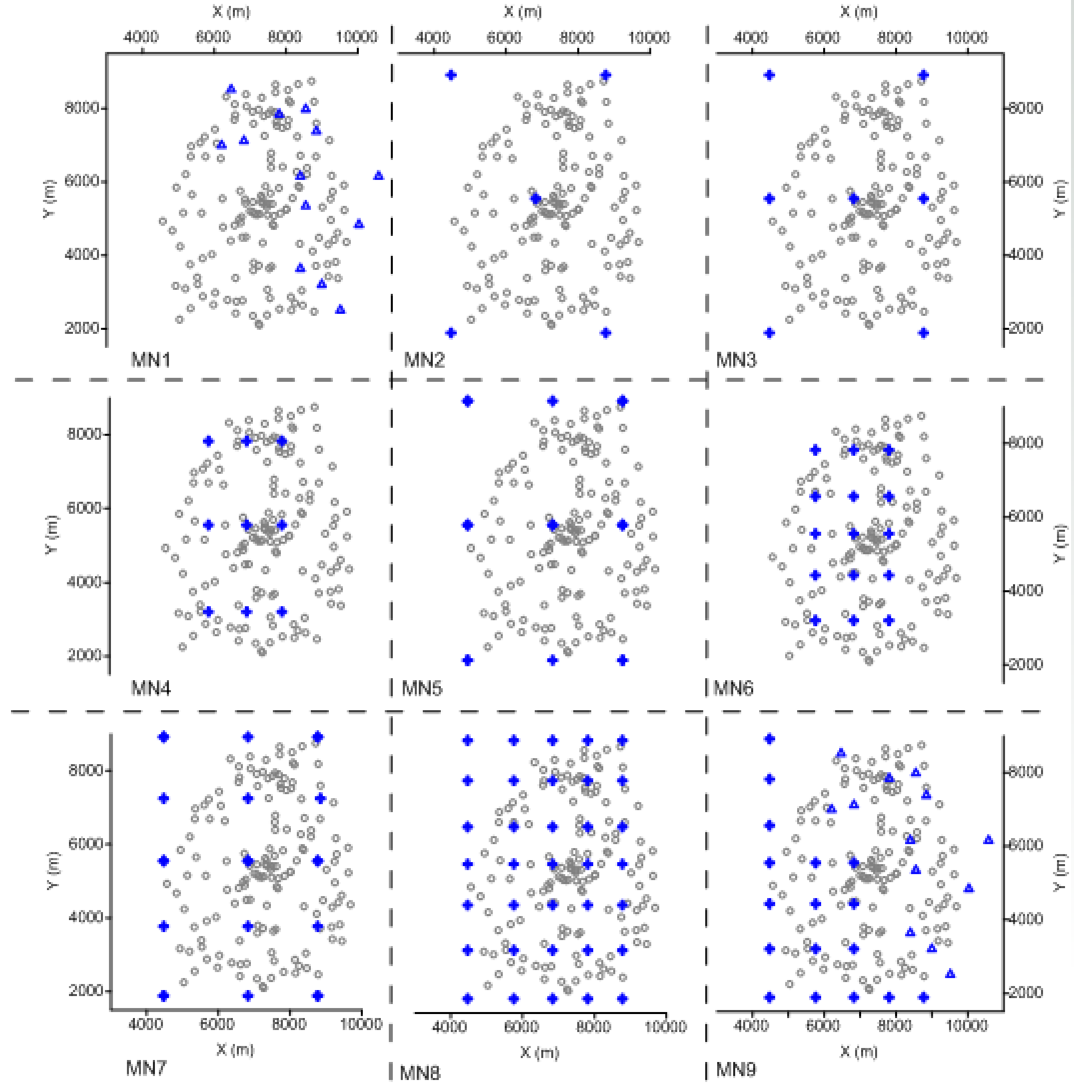
Behni Bollhassani, UT MS thesis

# Groundwater Monitoring Example

- Monitoring Network Efficiency -35 years after leakage to surface




Unit: wells/$km^2$

MN1: 0.322
MN2: 0.124
MN3: 0.173
MN4: 0.223
MN5: 0.223
MN6: 0.371
MN7: 0.371
MN8: 0.866
MN9: 0.742

Yang et al, 2015

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# Value of Information: Leakage Assessments in the Near-Surface

- Cost and effort intensive
- Poor spatial coverage
  - Yang, 2015 - Poor detection coverage in groundwater
  - Controlled releases indicate unpredictable surface expression
  - Need to automate
- High noise
  - Daily, seasonal variability
  - Difficult to define what is leakage and what is natural variability

# Status Quo Thinking on Environmental Monitoring

- Measure “baseline” $CO_2$ for 1 year before project starts to document seasonal variability.
- Monitor $CO_2$ during project and compare to baseline.
- Significant increase from baseline during a project could signal a leak

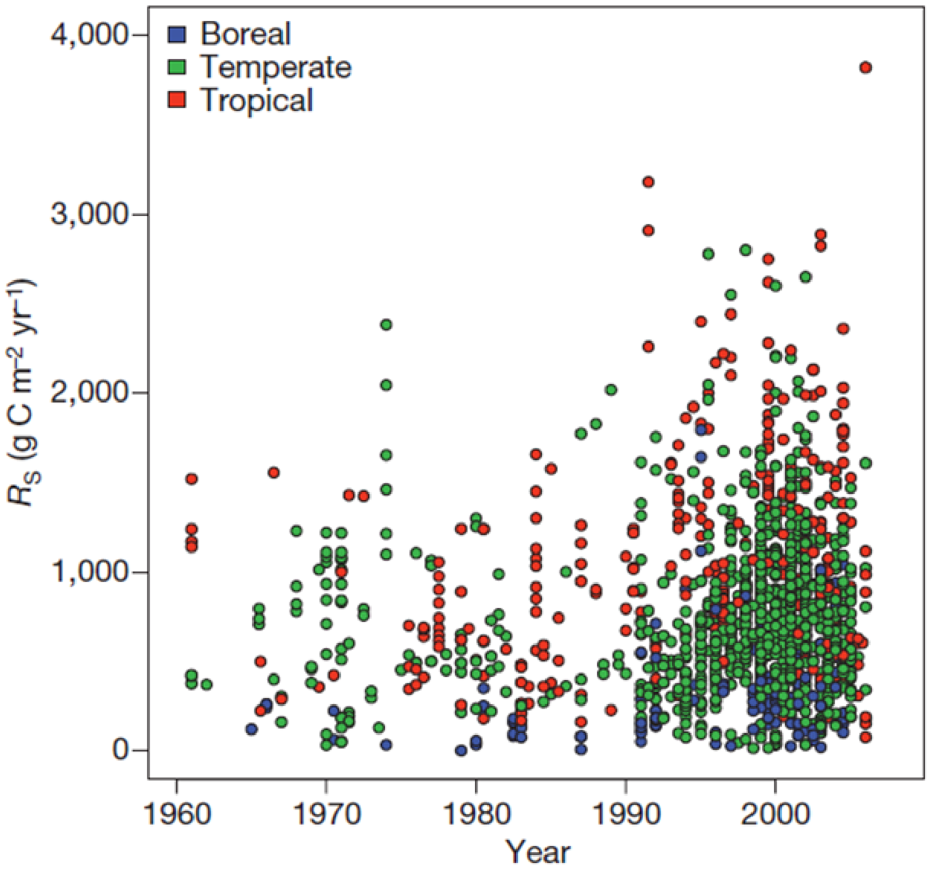
# The Problem with Baselines

## Soil gas $CO_2$ baselines are shifting upward

nature Vol 464 | 25 March 2010 | doi:10.1038/nature08930

**Temperature-associated increases in the global soil respiration record**

Ben Bond-Lamberty[1] & Allison Thomson[1]




RS = the flux of microbially and plant-respired $CO_2$ from the soil surface to the atmosphere,

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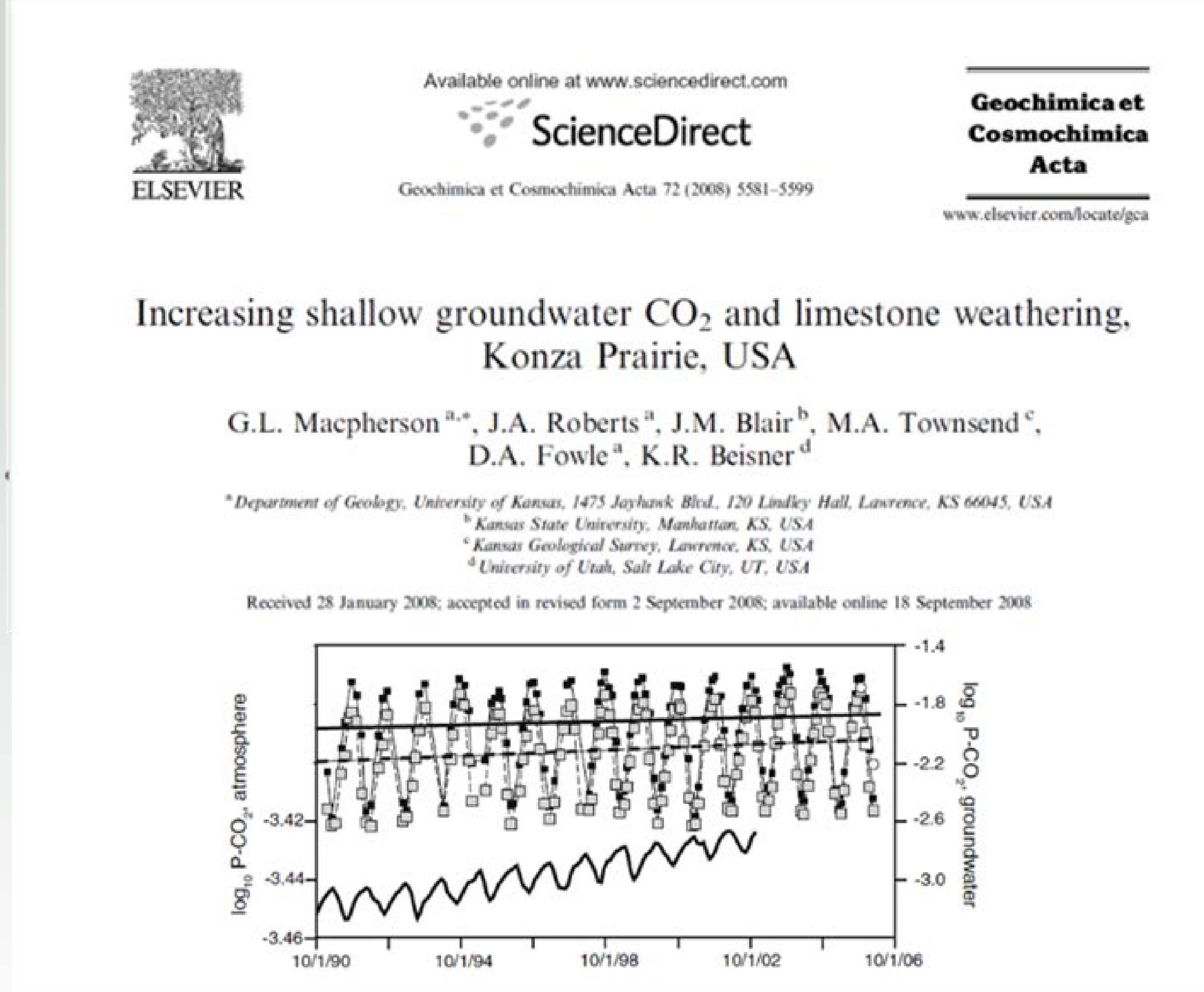
# The Problem with Baselines

Groundwater $CO_2$ baselines are shifting upward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Increasing shallow groundwater $CO_2$ and limestone weathering, Konza Prairie, USA

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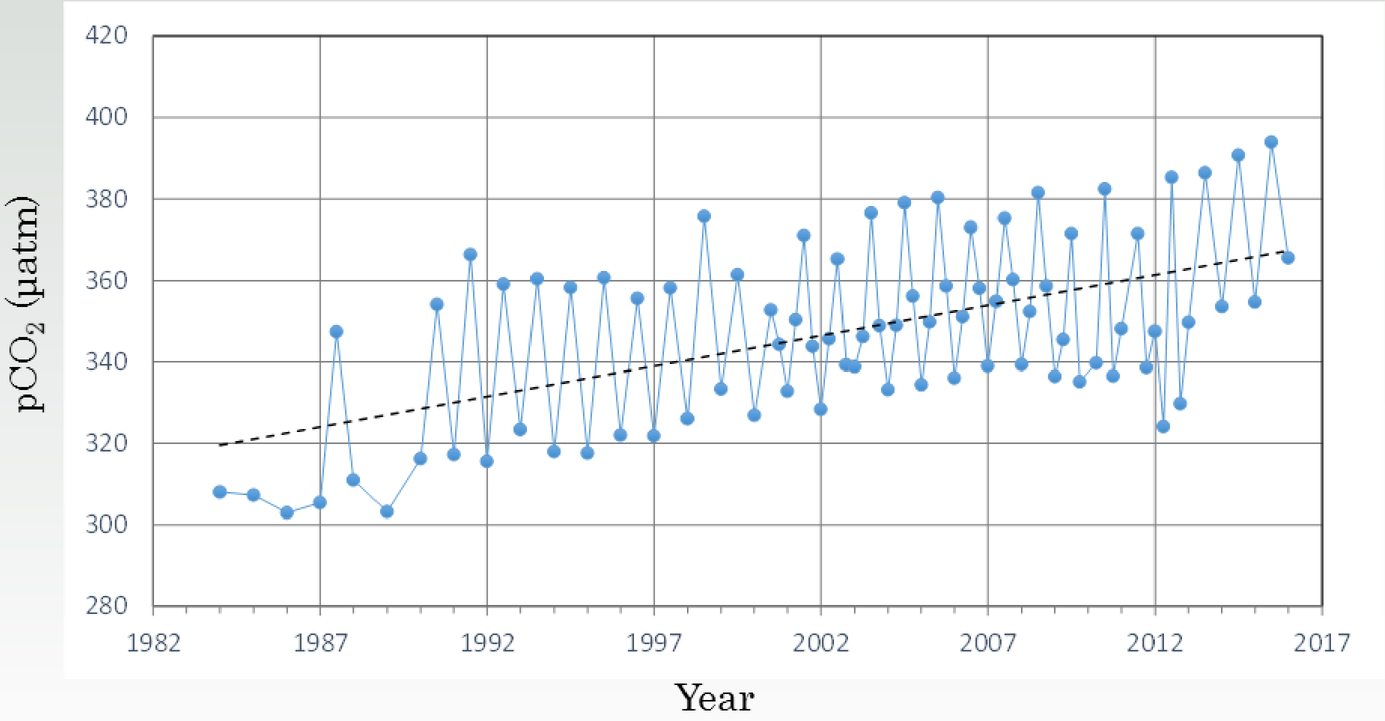
Increased dissolution of $CO_2$ in groundwater and associated mineral dissolution

# The Problem with Baselines

## Seawater $CO_2$ baselines are shifting upward

Surface seawater $CO_2$ level near Japan




Source data by Japan Meteorological Agency

Courtesy of Jun Kita, RITE

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# The #1 risk to CCS projects NOT addressed by risk assessments

- False positives for leakage from baseline-dependent environmental monitoring methods
- The risk of false positives is much greater than the risk of actual leakage.

# False Positive Leakage Assessments

- Landowner leakage claim near the IEAGHG Weyburn-Midale $CO_2$ Monitoring and Storage project
- Saskatchewan Canada


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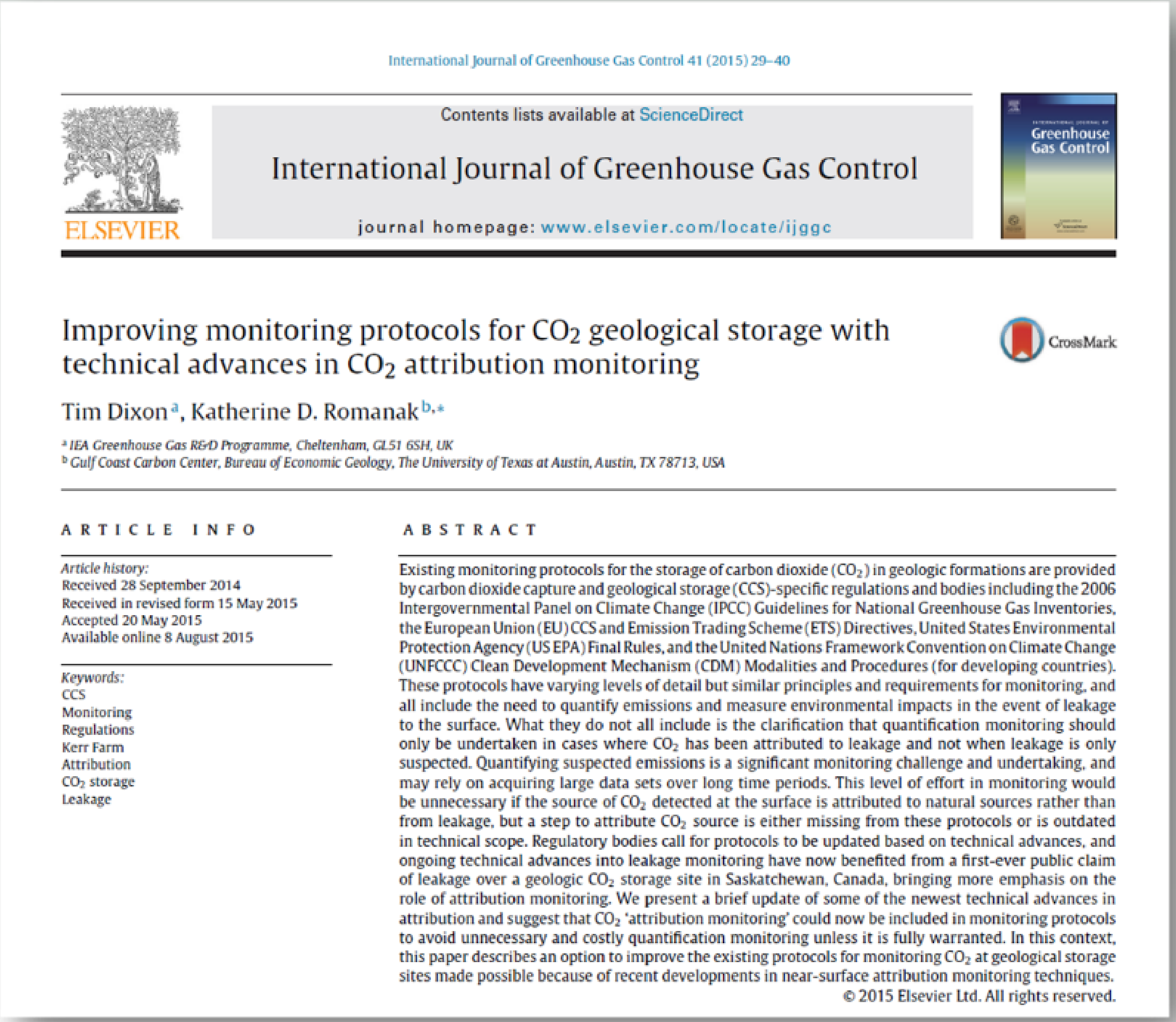
# Source Attribution of Anomalous Signal is Critical

- BEG's experience in attribution: 2 blind anomalies:
  - Kerr Claim at Weyburn
  - Cranfield anomaly
- Very difficult
- Fast accurate attribution is CRITICAL for
  - Public acceptance
  - Project protection
  - Stakeholder protection
  - The way we are doing it with "baselines" and "background sites will not be successful



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Improving monitoring protocols for $CO_2$ geological storage with technical advances in $CO_2$ attribution monitoring

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Leakage

ABSTRACT

Existing monitoring protocols for the storage of carbon dioxide ($CO_2$) in geologic formations are provided by carbon dioxide capture and geological storage (CCS)-specific regulations and bodies including the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories, the European Union (EU) CCS and Emission Trading Scheme (ETS) Directives, United States Environmental Protection Agency (US EPA) Final Rules, and the United Nations Framework Convention on Climate Change (UNFCCC) Clean Development Mechanism (CDM) Modalities and Procedures (for developing countries). These protocols have varying levels of detail but similar principles and requirements for monitoring, and all include the need to quantify emissions and measure environmental impacts in the event of leakage to the surface. What they do not all include is the clarification that quantification monitoring should only be undertaken in cases where $CO_2$ has been attributed to leakage and not when leakage is only suspected. Quantifying suspected emissions is a significant monitoring challenge and undertaking, and may rely on acquiring large data sets over long time periods. This level of effort in monitoring would be unnecessary if the source of $CO_2$ detected at the surface is attributed to natural sources rather than from leakage, but a step to attribute $CO_2$ source is either missing from these protocols or is outdated in technical scope. Regulatory bodies call for protocols to be updated based on technical advances, and ongoing technical advances into leakage monitoring have now benefited from a first-ever public claim of leakage over a geologic $CO_2$ storage site in Saskatchewan, Canada, bringing more emphasis on the role of attribution monitoring. We present a brief update of some of the newest technical advances in attribution and suggest that $CO_2$ 'attribution monitoring' could now be included in monitoring protocols to avoid unnecessary and costly quantification monitoring unless it is fully warranted. In this context, this paper describes an option to improve the existing protocols for monitoring $CO_2$ at geological storage sites made possible because of recent developments in near-surface attribution monitoring techniques.

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Dixon and Romanak, 2015

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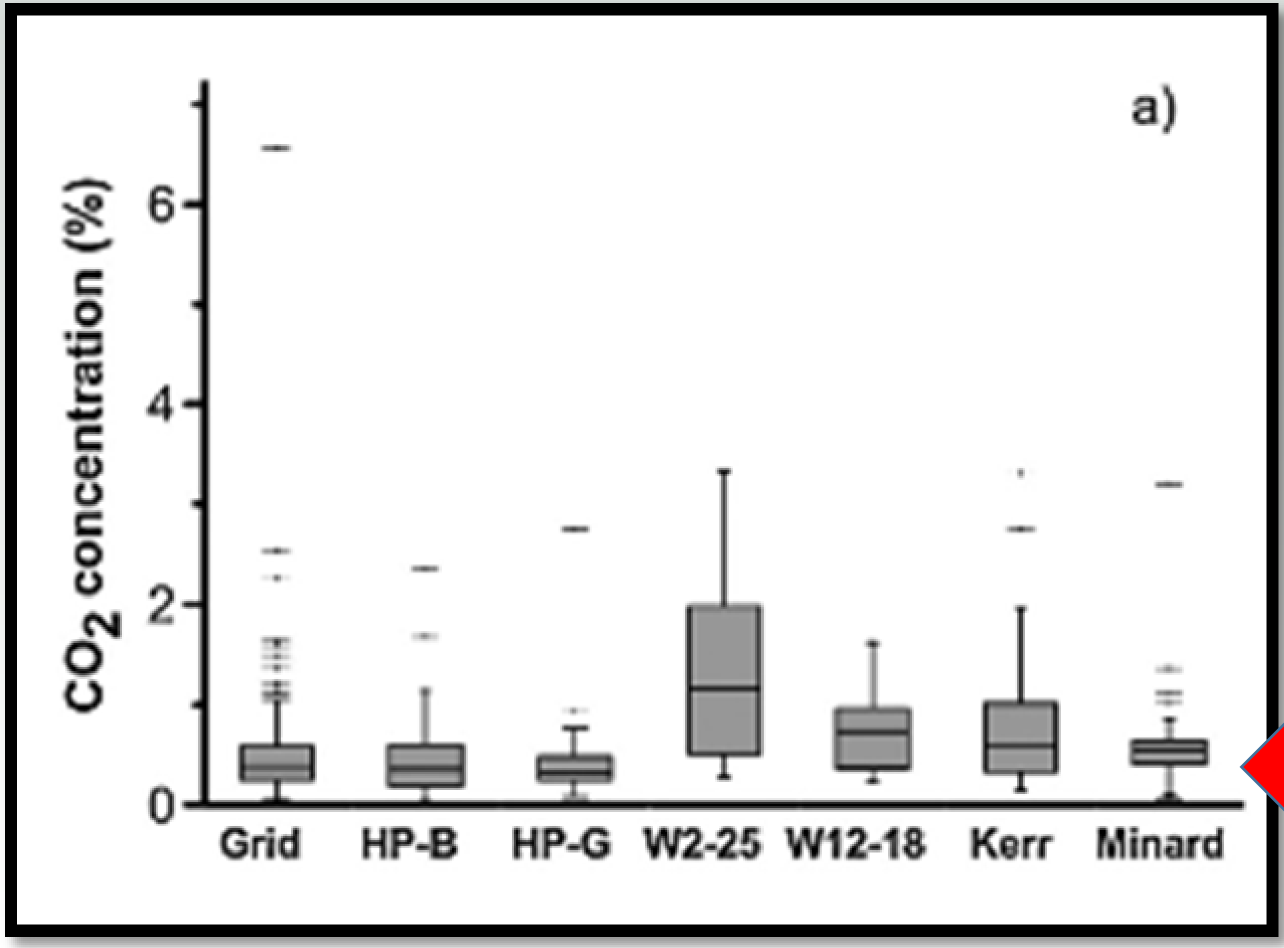
# “Background Reference” site?

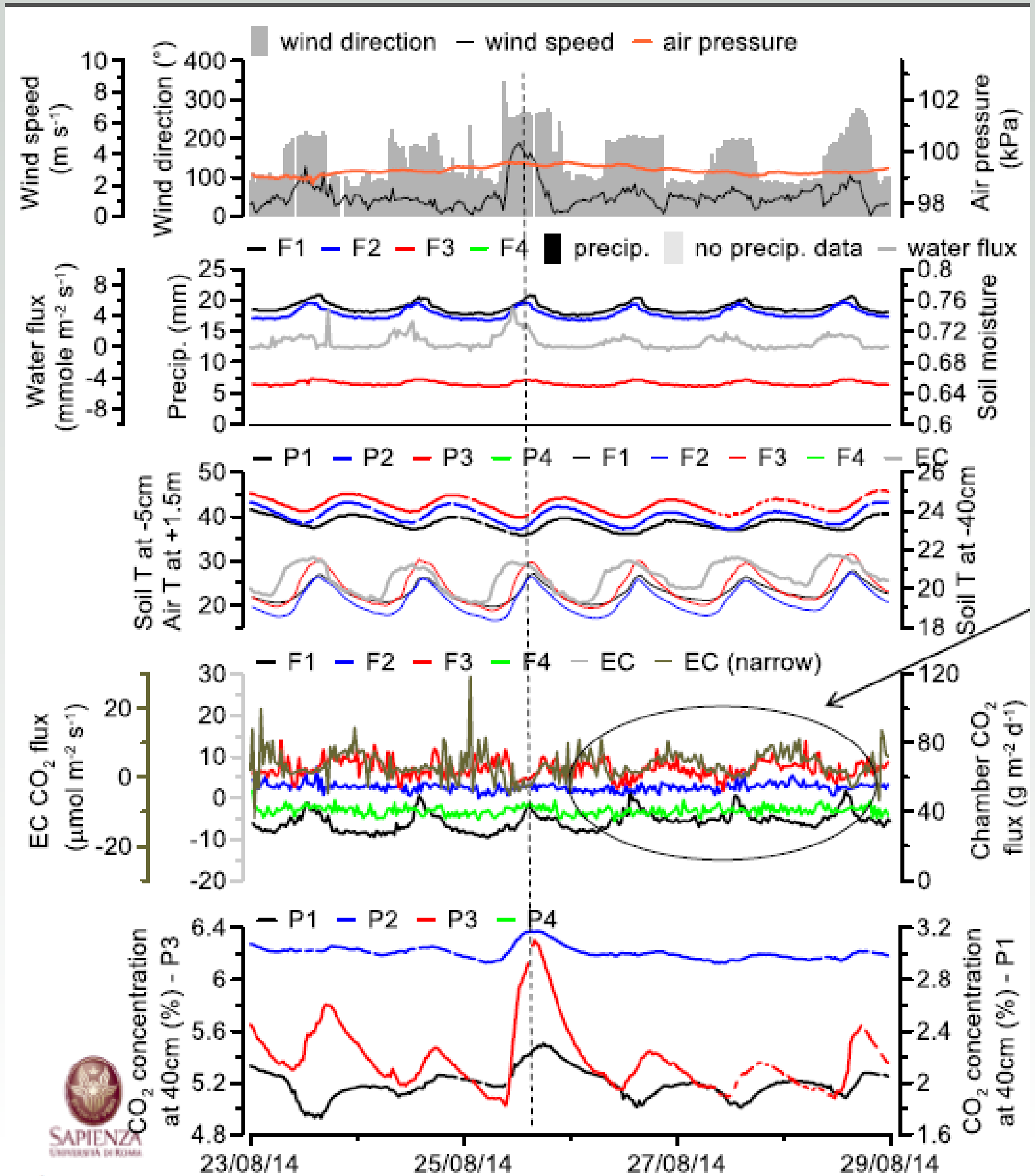



Background Reference Site

Beaubien et al., 2013

# Complexity of $CO_2$ Concentration Variations

- Large datasets over long time periods
- Complex data analysis
- Lack of real-time answer
- Unclear trigger points
- Difficult stakeholder communication
- Rising soil respiration rates due to global warming will cause false positives for leakage.





Dave Jones, British Geological Survey

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# Determining What is “Anomalous”

- What constitutes an “anomaly (e.g. a potential leakage signal)?
- What parameters should be used to indicate leakage?
- When is action required (e.g. thresholds, trigger points) ?
- What action should be taken?

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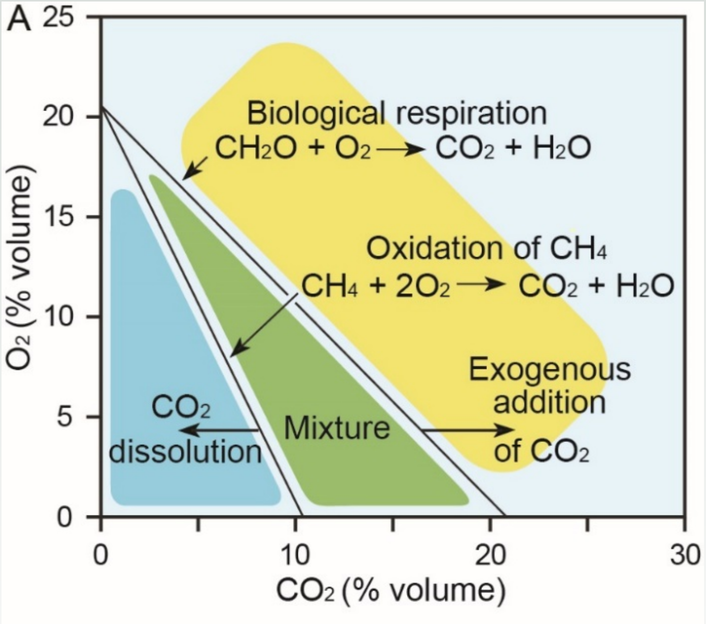
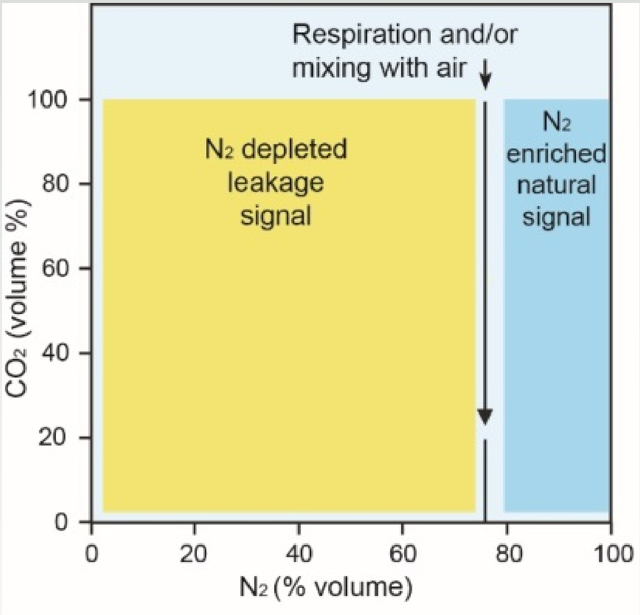
# Developing ratio-based methods

- Process-based approach
  - Define processes based on stoichiometry of reactions
  - Based on 4 simple gases
    - ($CO_2$, $CH_4$, $O_2$, $N_2$)
  - Clear trigger point
    - Respiration line
  - More immediate answer
  - Less data collection
    - No need to measure weather parameters
  - Simple to explain to stakeholders




Romanak et al., GRL, 2012
Romanak et al., IJGGC, 2014
Dixon & Romanak, IJGGC, 2015

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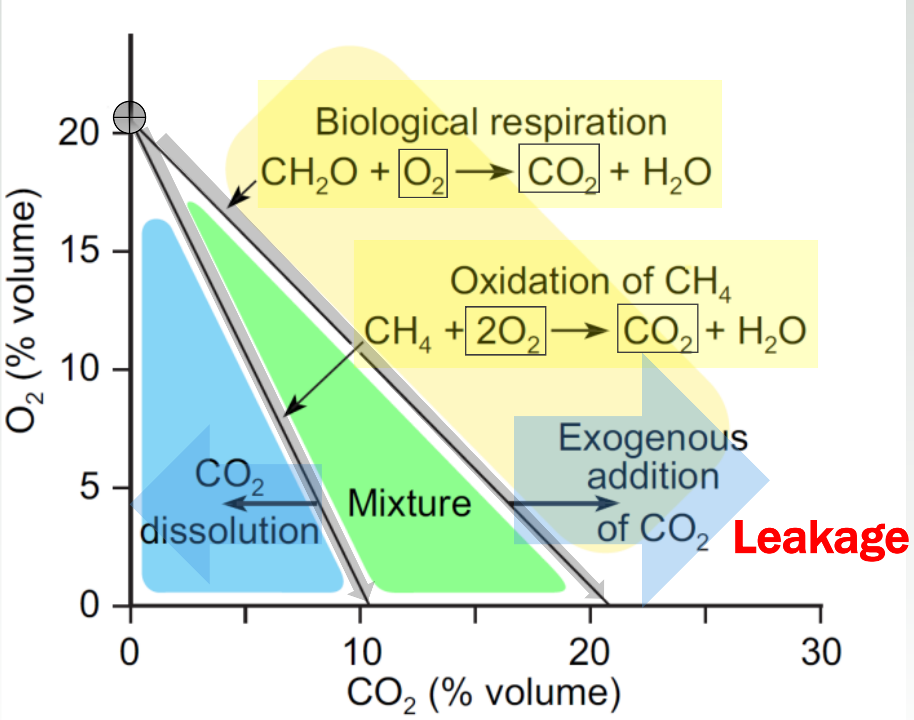
# Process-Based Gas Ratio - 1

$O_2$ vs. $CO_2$

- Indicates natural processes that affect $CO_2$ concentrations
- Distinguishes among respiration, $CH_4$ oxidation and dissolution
- Gives an initial assessment of leakage

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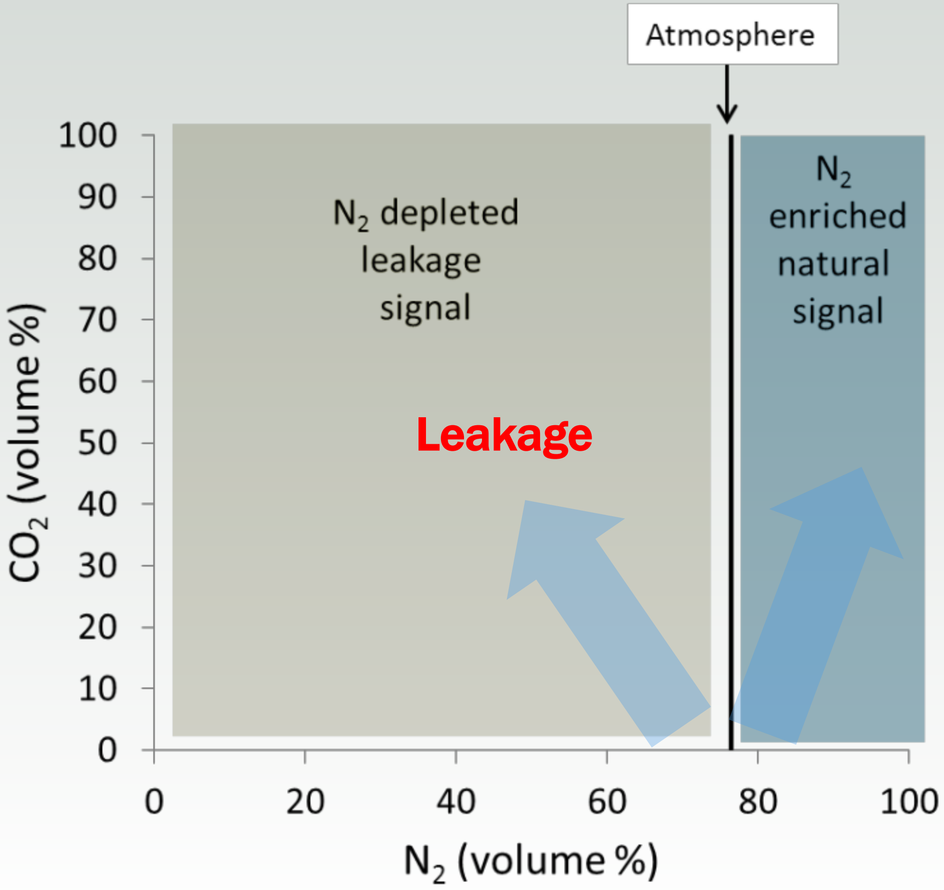
# Process-Based Gas Ratio - 2

$CO_2$ vs. $N_2$

- ıdentifies whether gas has migrated from depth.
- Indicates whether $CO_2$ is being added through leakage or lost through dissolution.

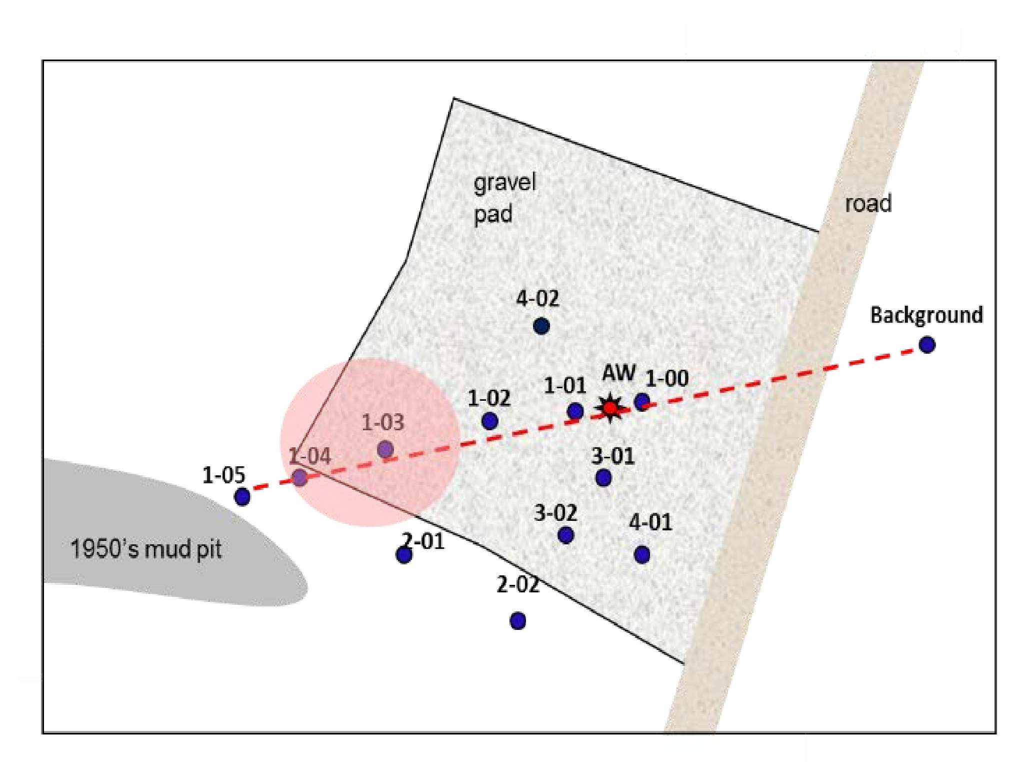


# Motivation

- Rigorous testing of methodology is critical
- Ensure high level of stakeholder confidence
- Must understand signals in a variety of environments
- New learnings from monitoring operational projects
- Reassess the Cranfield surface gas anomaly
- Refine and expand process-based method
  - formerly only aerobic processes
  - Now including anaerobic processes
- Ramifications for identifying industrial signals

# Cranfield Anomaly

- Cranfield $CO_2$-EOR site, Mississippi, USA
- US DOE SECARB RCSP site
- 1950's plugged and abandoned well
- An un-remmediated "mud pit"
- 1124 $m^2$ gravel pad
- 13 multi-depth gas sampling stations as deep as 3 meters
- Near-surface soil gas anomaly
  - 43% $CO_2$, 45% $CH_4$

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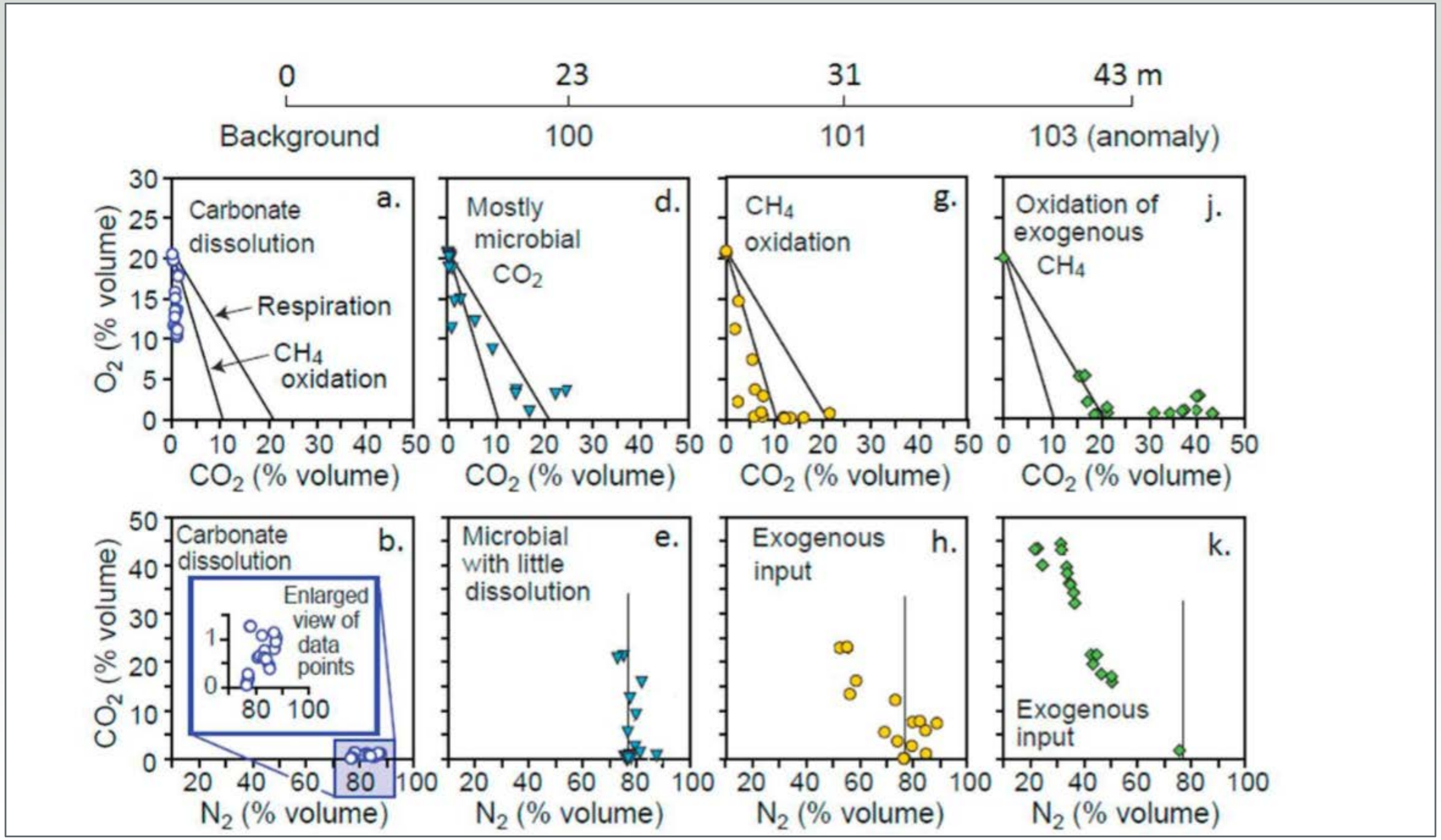
# Process-based assessment

Systematic change towards leakage signal along the transect from background to anomaly

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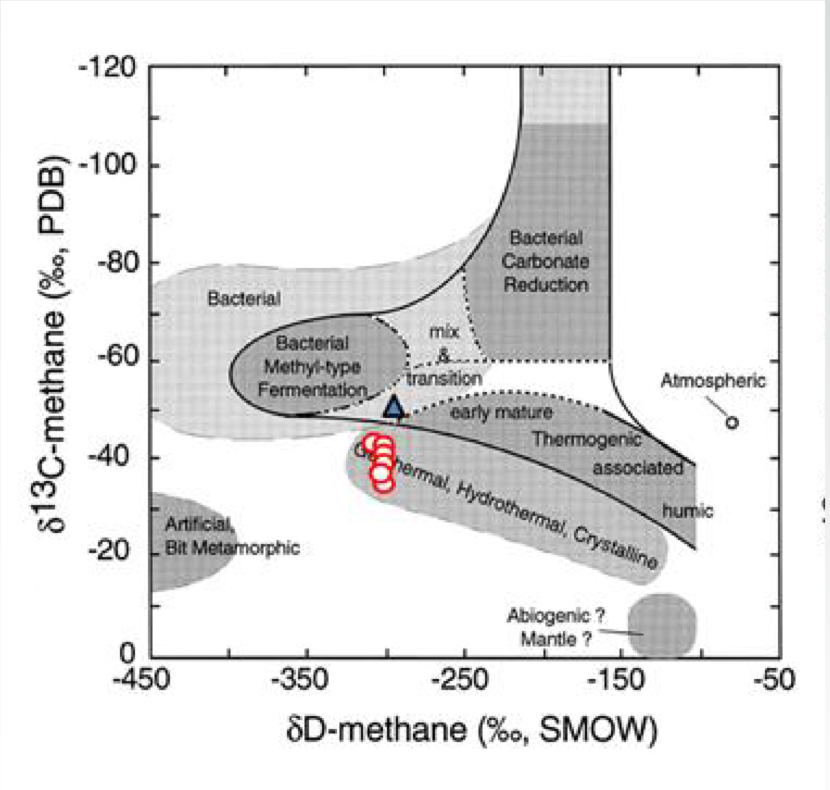
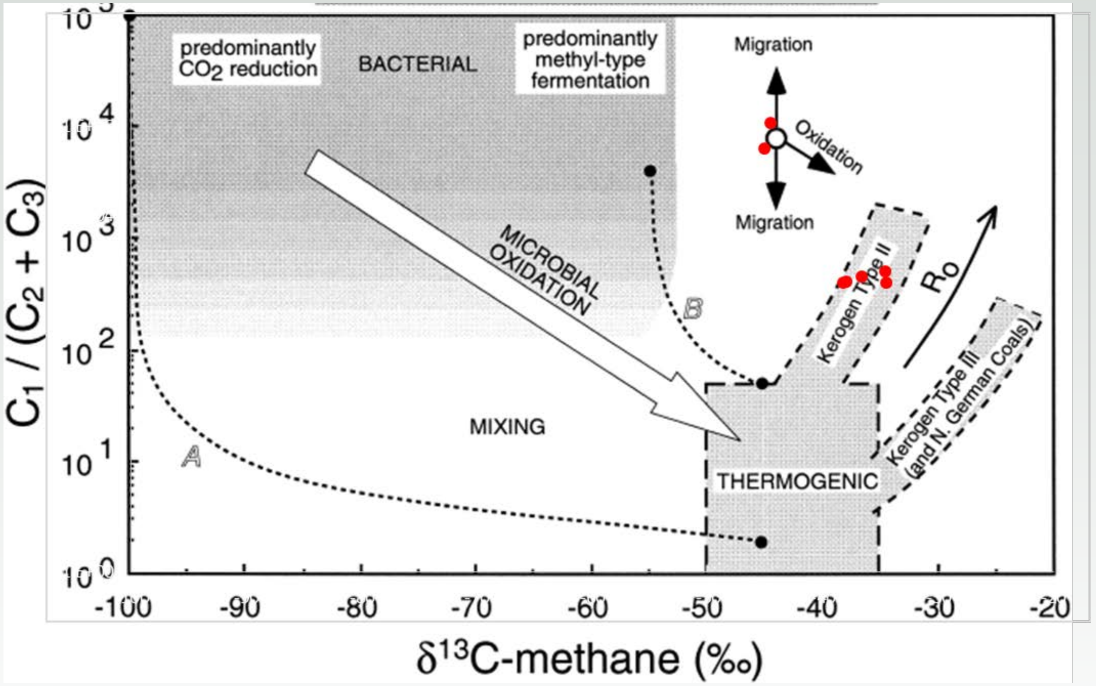
# Ambiguous Isotopic Information




Whiticar, 1999

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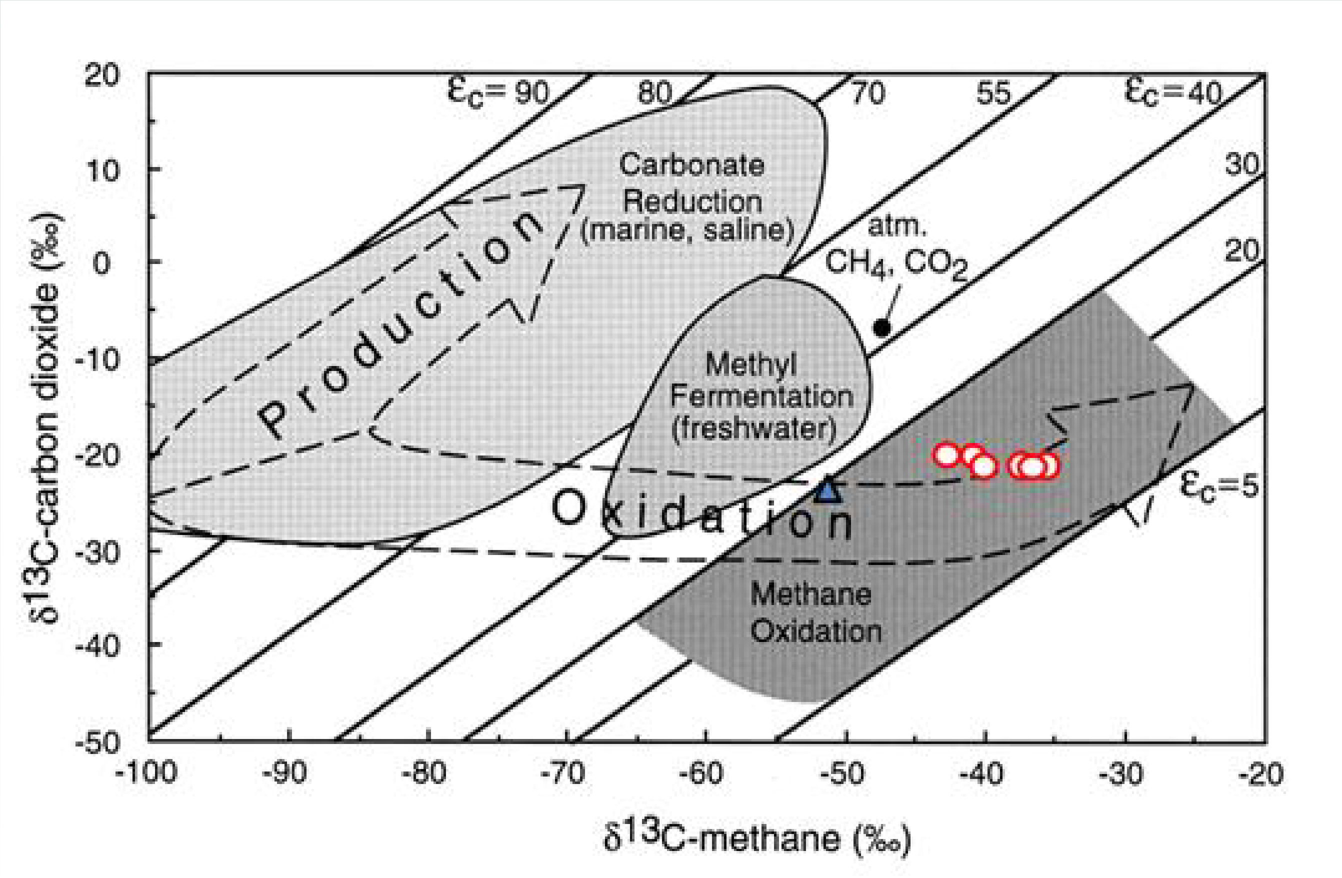
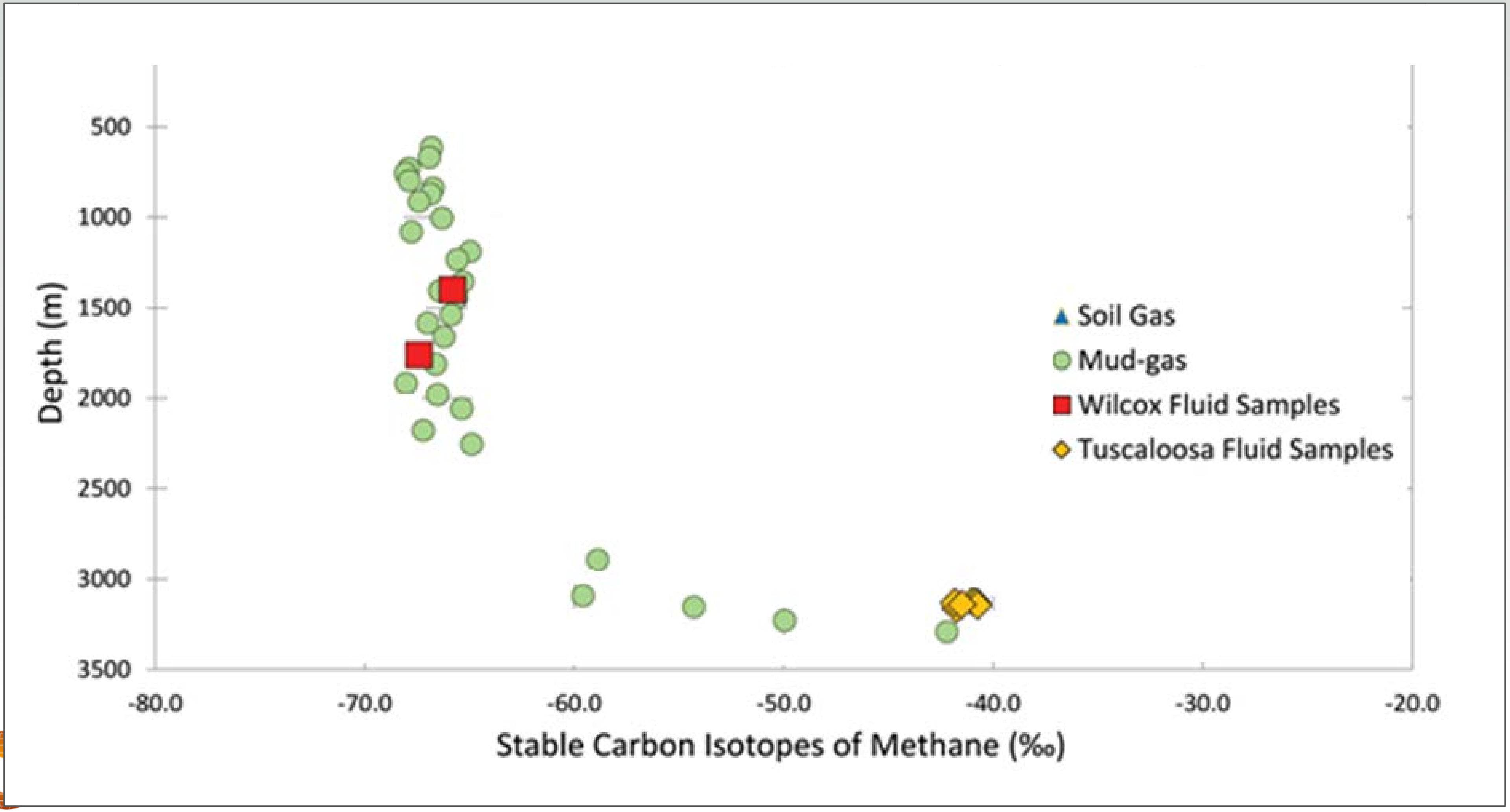
# Ambiguous Isotopic Information




Whiticar, 1999

# Overburden Characterization

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# Summary of Data

- Process-based ratios were consistent with a leakage signal
- Methane isotopes of the anomaly that matched the reservoir
- Stable carbon and hydrogen isotopes that suggested migration from oil and gas reservoir (ambiguous)
- Location near a historic well.

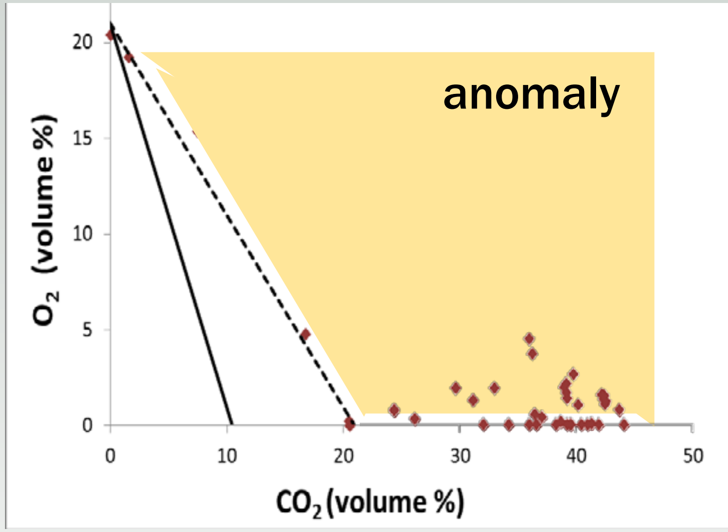
# Surprise

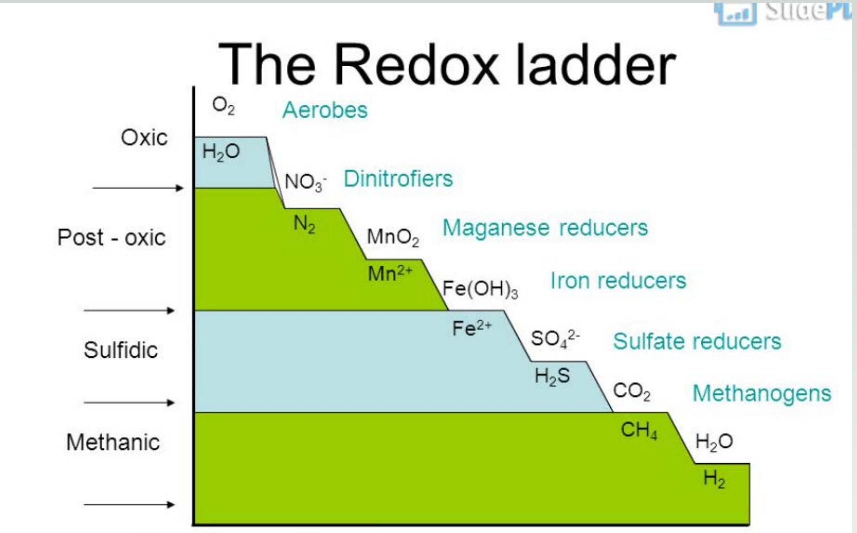
- Modern $^{14}C$ signature of anomaly

Radioactive carbon isotopes of $CO_2$ and $CH_4$.

| Sampling station | $^{14}CO_2$ (pMC) | $^{14}C_1$ (pMC) |
|---|---|---|
| Station 104 – | 105.7 | 109.9 |
| Station 103 – | 106.7 | 109.7 |
| Background – | 102.8 | – |
| Background – | 104.8 | – |
| Ella G Lees #28 | – | 0.2 |

# Process-Based Signature Anomaly




- Anaerobic
- Near equal portions of $CO_2$ and $CH_4$
- Acetoclastic methanogenesis : $CH_3COOH \rightarrow CH_4 + CO_2$
- Denitrification $N_2O + 2H^+ + 2e^- \rightarrow N_2 + H_2O$
  - Nitrogen is included in a process-based assessment

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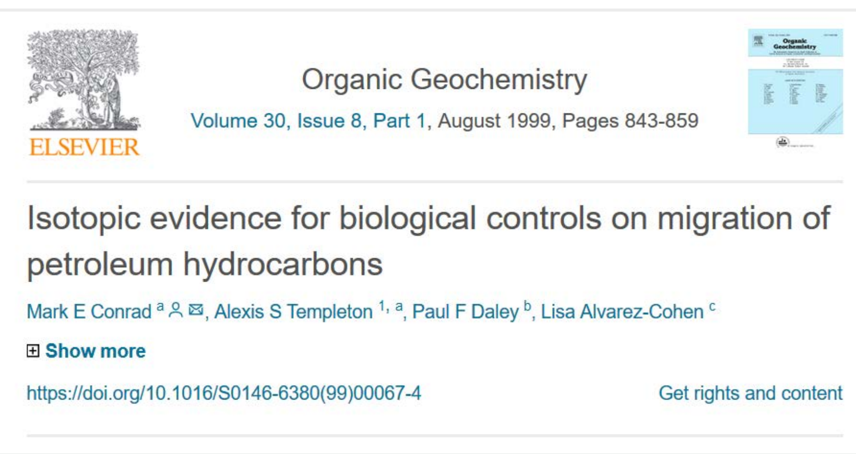
# Published Data on Industrial Spill

- Conrad et al. 1999
- Degradation of an aviation gasoline leaked from storage tanks in 1970s
- Alameda Point, San Francisco Bay.
- Soil gas samples.
  - $CH_4$ 26.4%, and $CO_2$ 21%.
  - $O_2$ 0 to 21%
  - $^{14}C$ from 5.4 to 90.4 % pMC.
- Degradation by acetate fermentation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Organic Geochemistry
Volume 30, Issue 8, Part 1, August 1999, Pages 843-859

Isotopic evidence for biological controls on migration of petroleum hydrocarbons

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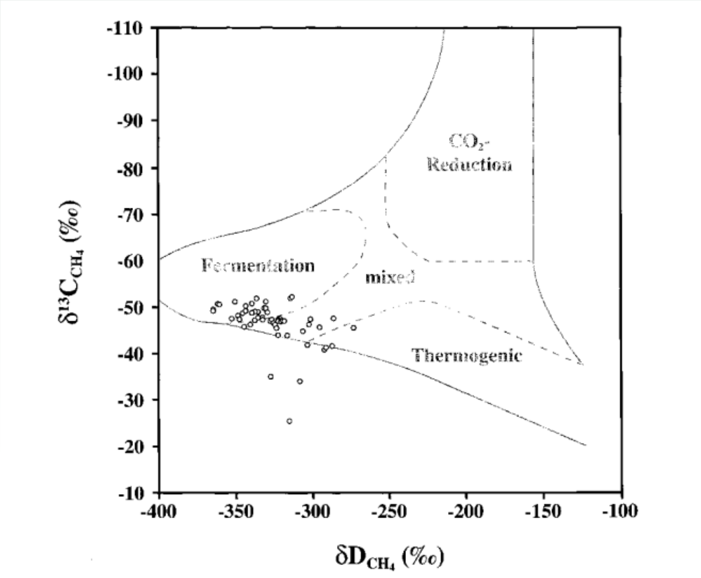
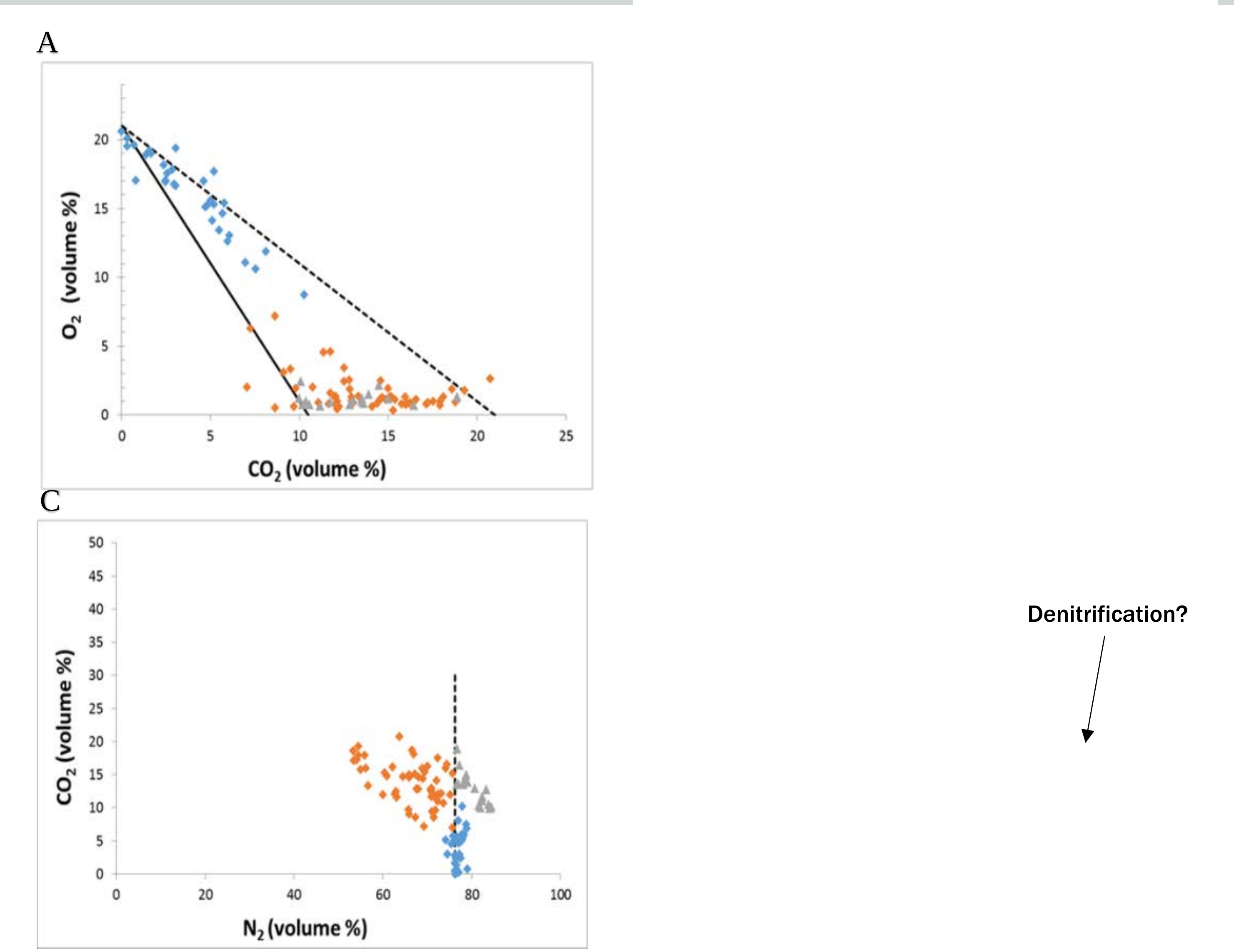


# Process-based Analysis Conrad Data

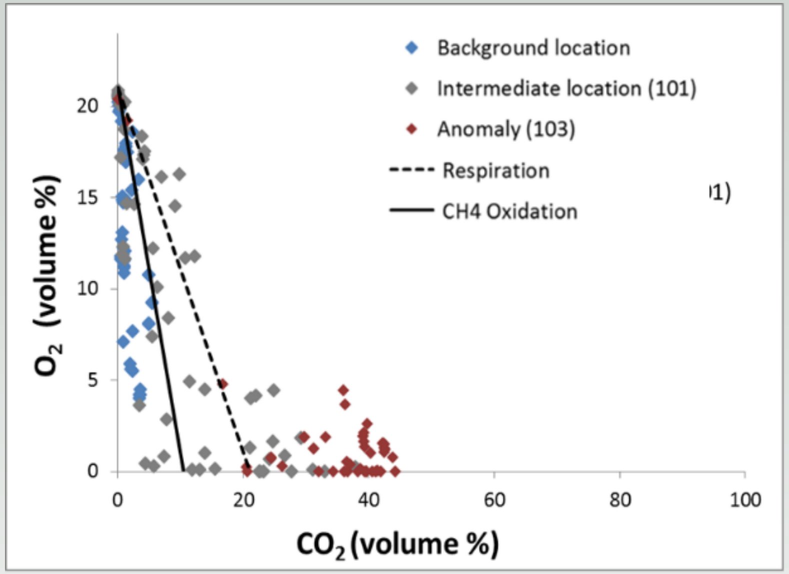
Acetoclastic methanogenesis :

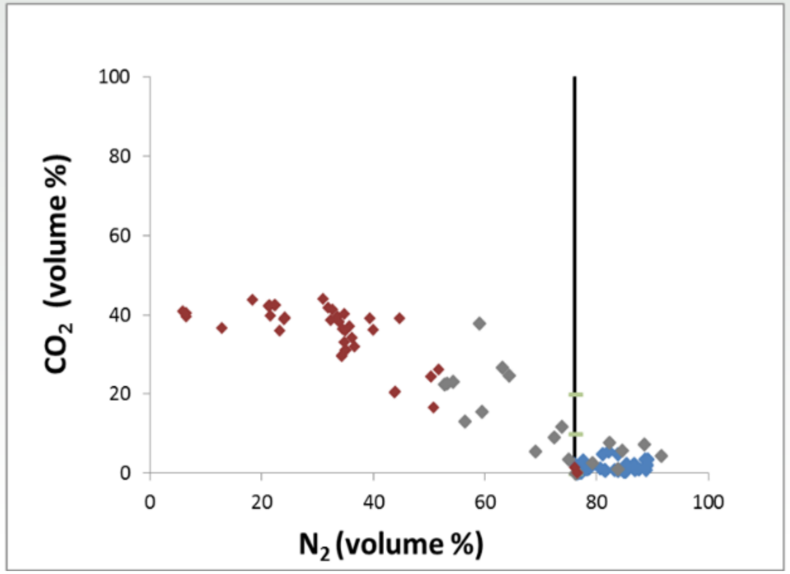
$CH_3COOH \rightarrow CH_4 + CO_2$



# Revisiting the Cranfield Anomaly

- Similar shift

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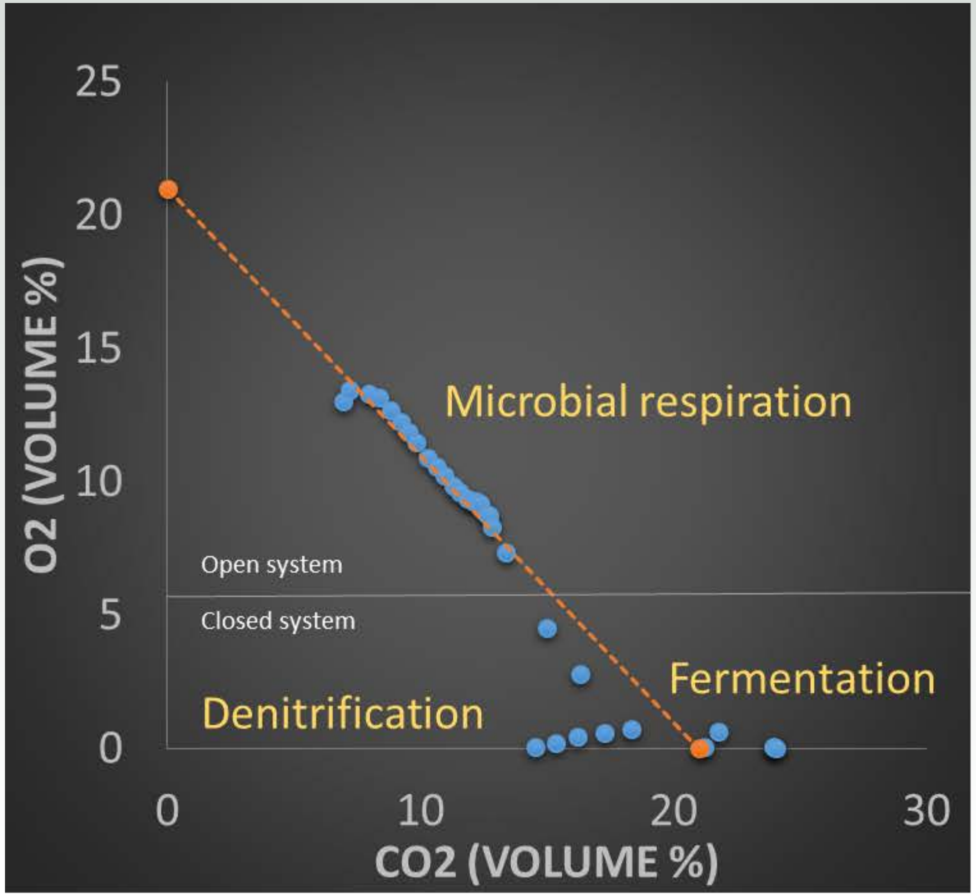
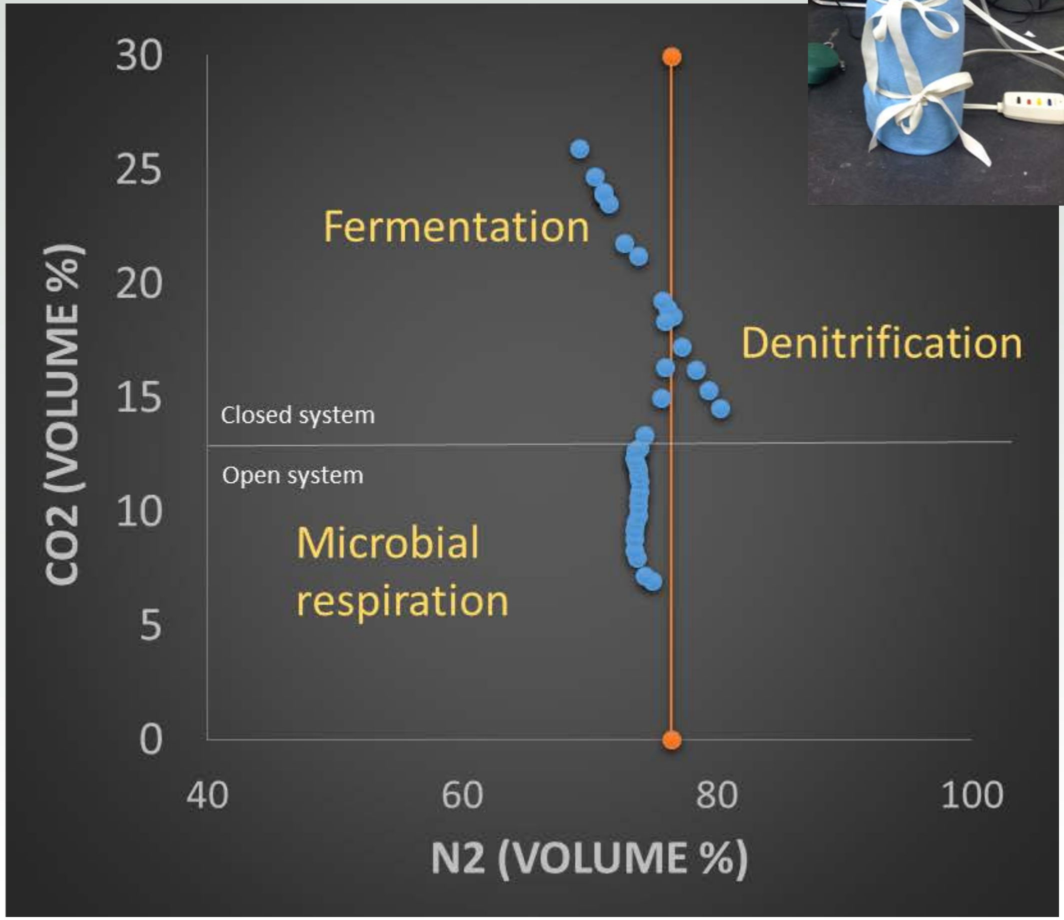
# Laboratory Confirmation

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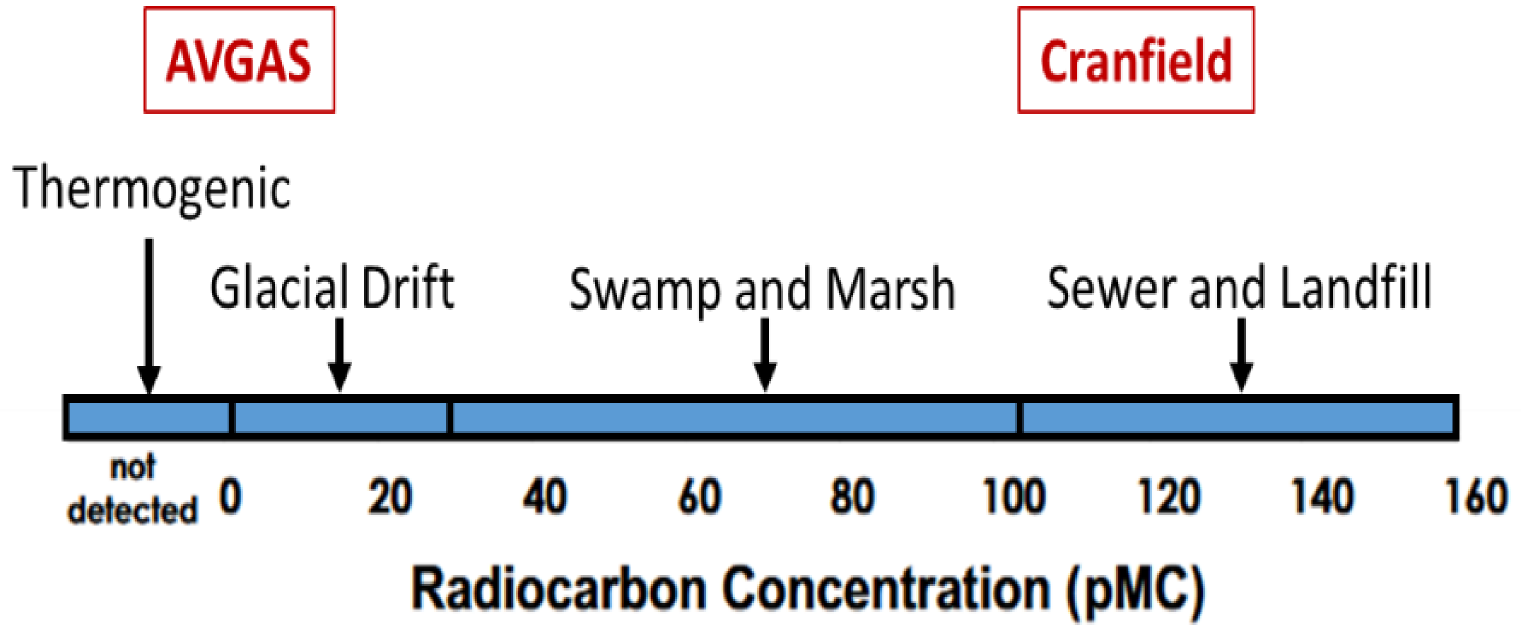
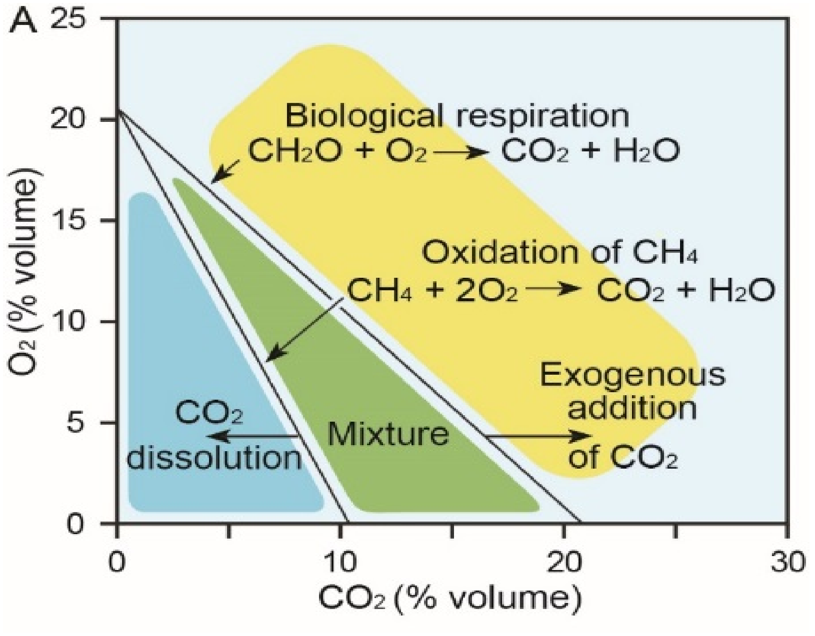
# $^{14}C$




Modified from Coleman, 1994

# Bio-oceanographic Source Attribution

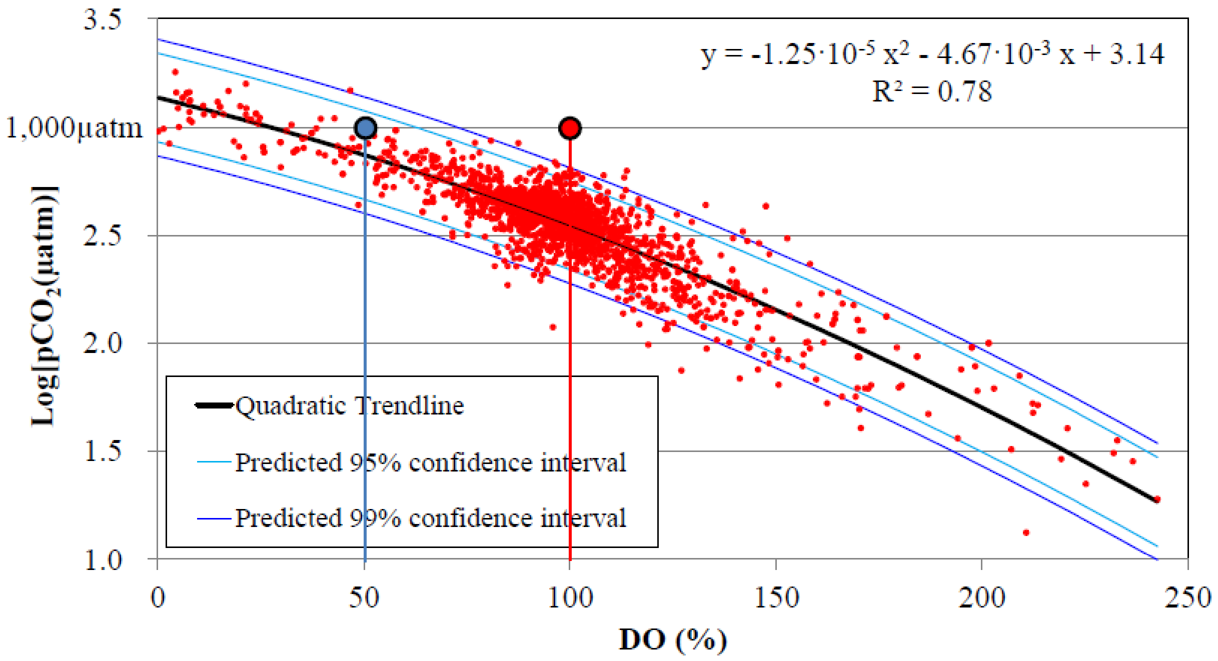
## Onshore:
## Process-Based Method




Katherine Romanak, BEG, USA
Romanak et al., 2012, 2014
Dixon and Romanak, 2015

## Offshore:
## Bio-Oceanographic Method

Relationship between DO (%) and Log[p$CO_2$ (µatm)]
Osaka Bay




Jun Kita, MERI, Japan
Uchimoto et al., 2017

# Tomakomai Environmental Monitoring

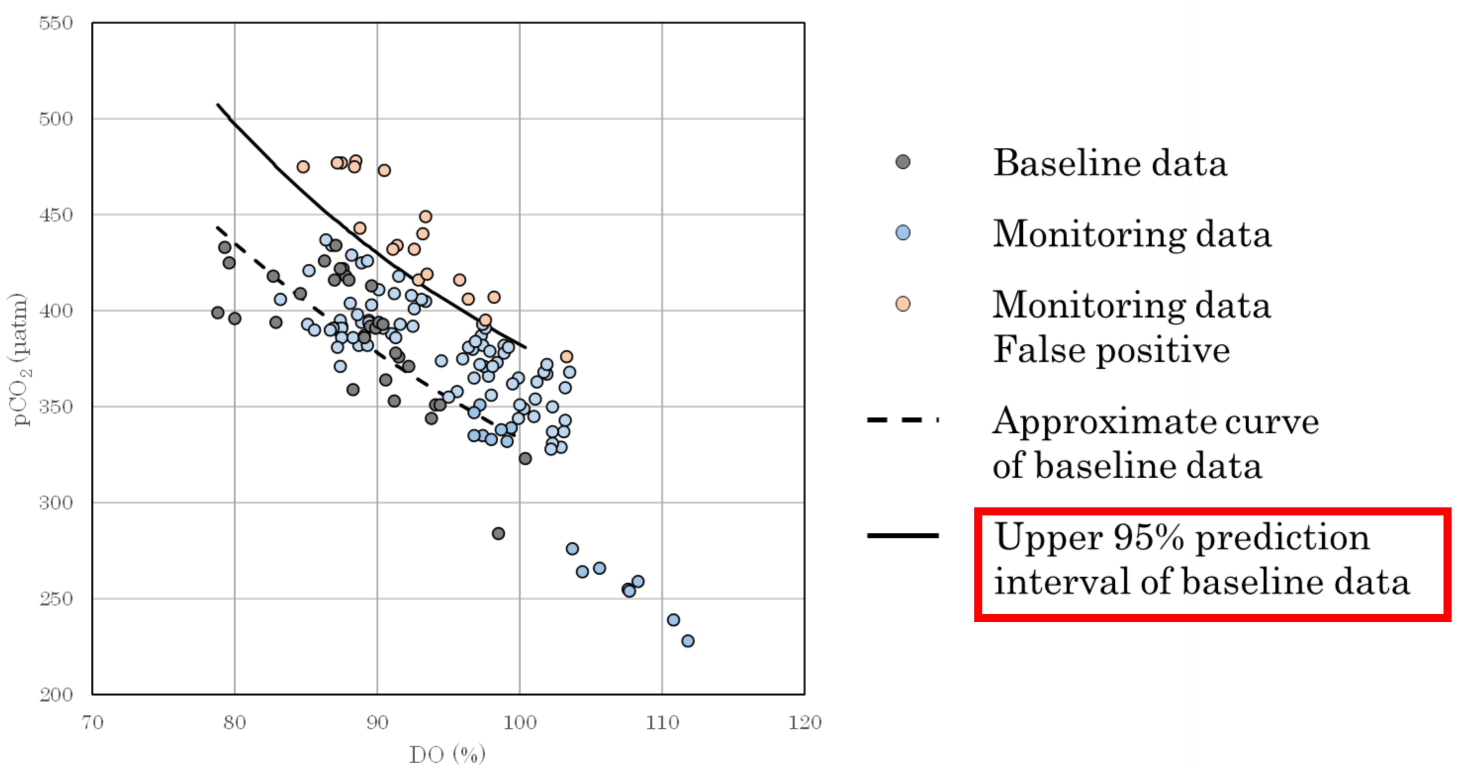
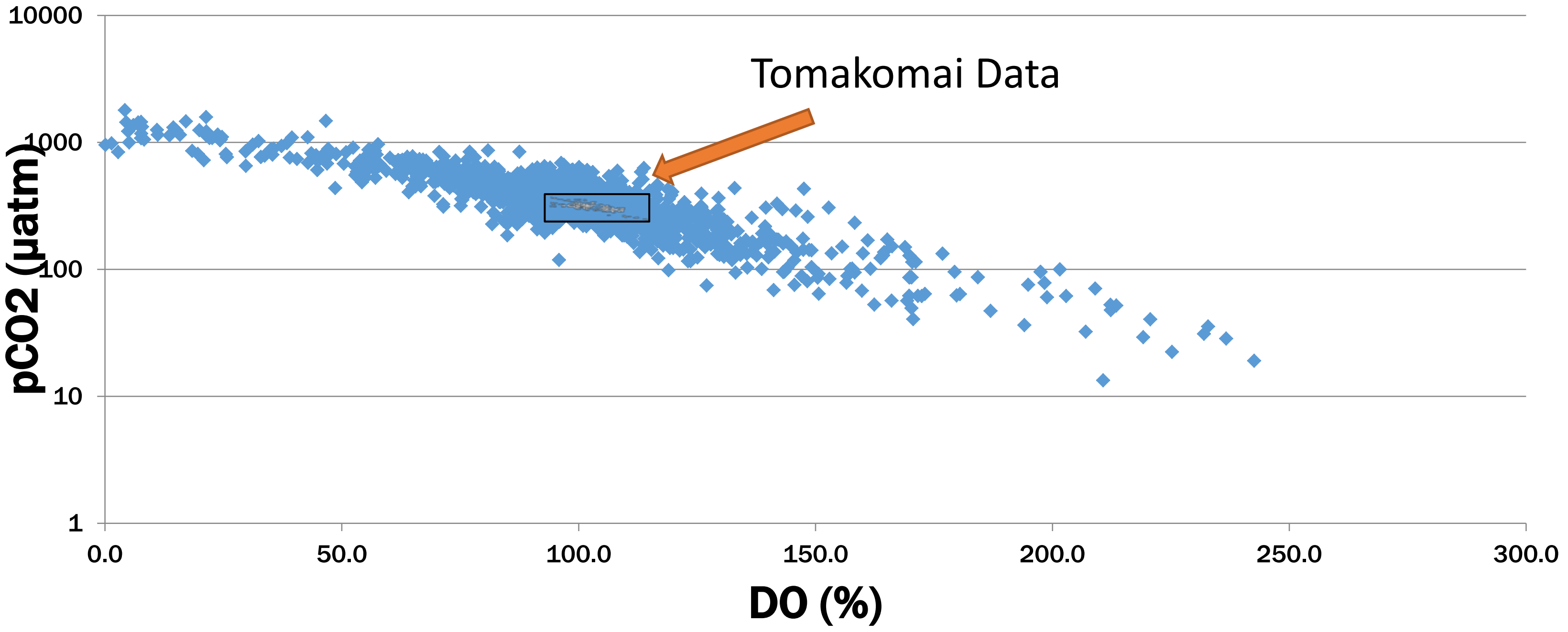



Fig. Relationship between oxygen saturation (DO) and $CO_2$ partial pressure ($pCO_2$) of bottom seawater (2 m above the seafloor).

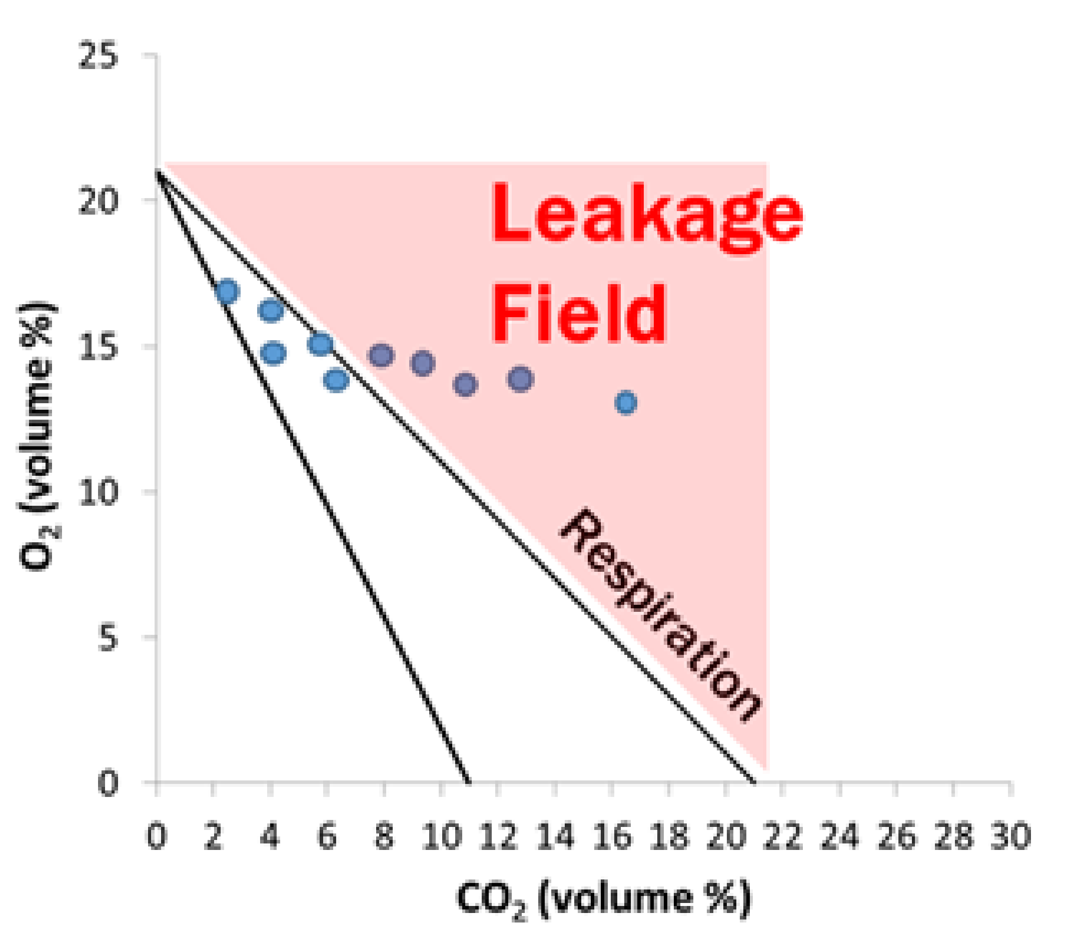
Jun Kita, 2017, 2nd International Workshop on Offshore Geologic CO2 storage

# 1 year Tomakomai Data compared to 10 Years of Osaka Bay Data



# Optimal Attribution Methods

- Simple, accurate, reliable method
- Cost-effective method
- Standardized method with a global trigger points
- Sure protocol for responding to claims
- Minimize false outcomes
- Maximize stakeholder trust
- Method that can be easily and economically implemented at an industrial scale.

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# Main Overarching Points

- Combining an ALPMI process with risk assessment provides for more purposeful monitoring plans targeted to potential impacts.
- ALPMI provides a clear definition for project success.
- Baseline $CO_2$ concentrations in soil, groundwater, and marine environments are shifting upward due to climate change.
- Current methods of attribution which rely on baseline concentrations will result in false leakage claims.
- Sound attribution tools are needed to avoid false positives.
- The #1 risk to projects is not leakage but the shutdown of projects due to false positives for leakage.
- The Cranfield Anomaly required reassessment and the resulting learnings have grown our capabilities for attribution.
- Bio-oceanographic method may be improved by reducing scatter from salinity and temperature differences

# Thank You

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http://www.beg.utexas.edu/gccc/