

## Engineering Joint Seismic Monitoring with Sparse Networks: Progress Toward Providing Seismic Information to Operators

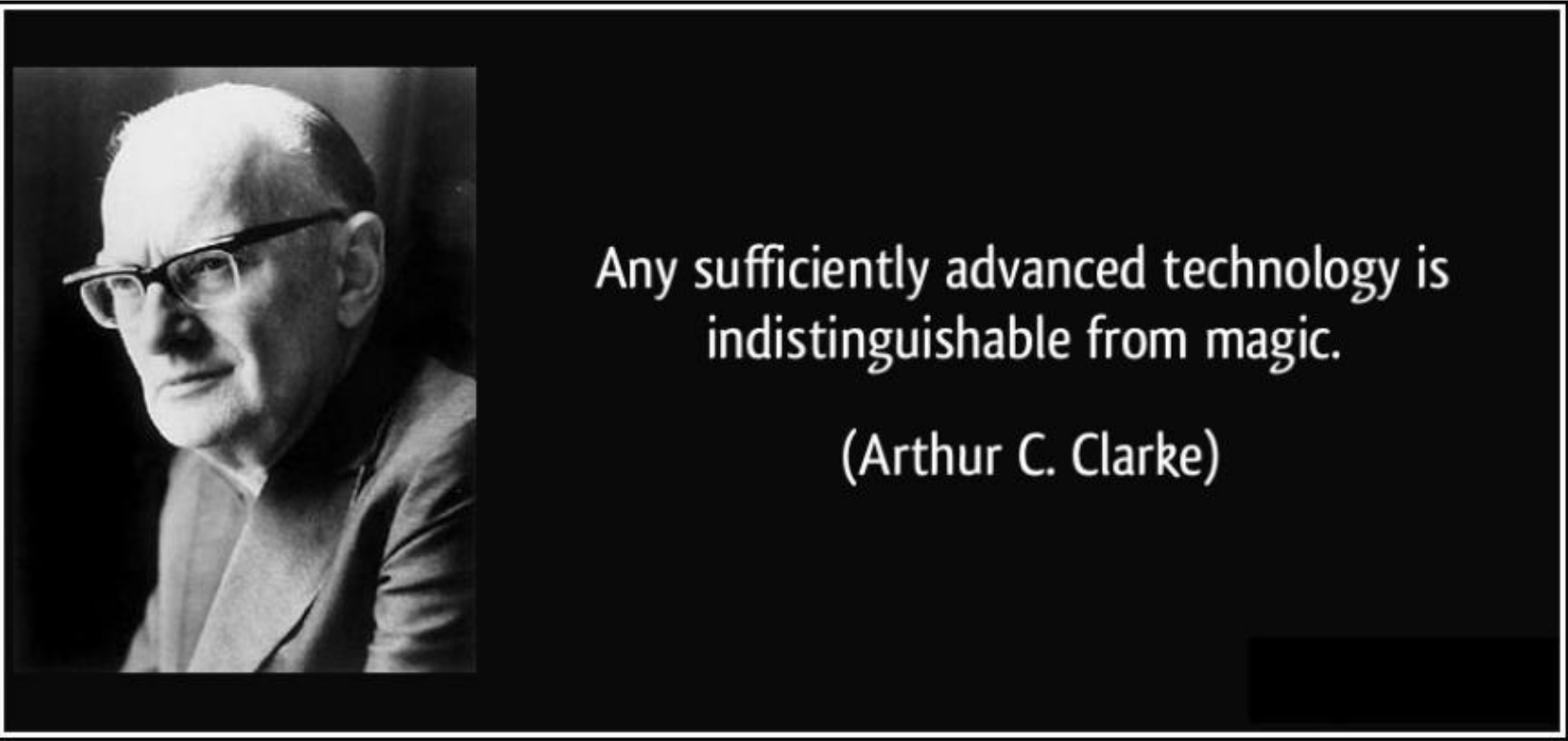
*Paul A. Nyffenegger<sup>1</sup>, K. D. Hutchenson<sup>1</sup>,  
Brendan Kolkman-Quinn<sup>3</sup>, D. Quigley<sup>1</sup>, Elige B.  
Grant<sup>1</sup>, J. Yelton<sup>1</sup>, Mike Dahl<sup>2</sup>, Marie Macquet<sup>3</sup>*

*<sup>1</sup>Geospace Technologies, <sup>2</sup>Geospace  
Technologies, Ca.*

*<sup>3</sup>Carbon Management Canada*



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# Introduction

*You have selected your site, lined up CO<sub>2</sub> sources, and need to finish your Measurement Monitoring and Verification (MMV) plan to file for your Class VI permit or equivalent*

- Induced seismicity monitoring is a regulatory requirement
  - (Class VI, Directive 65/MMV)
- Sparse networks of SADAR compact volumetric phased arrays proven for
  - **passive** microseismic monitoring (TRL 8)
  - **active** source survey imaging functions (TRL 7)
- Seismic ***information*** delivered to field operations – just in time??

Seismic information has value if it can affect a decision (operations), prove a status (regulatory), validate a model (regulatory), or disprove an allegation (liability), provide confidence in ongoing risk assessments (operations)

# Engineered Integrated Seismic MMV

Q: How do we engineer the sparse network of SADAR arrays system to deliver seismic information efficiently and effectively for both seismic monitoring functions?

A: The same way we engineer any complex system :  
***formal systems engineering***

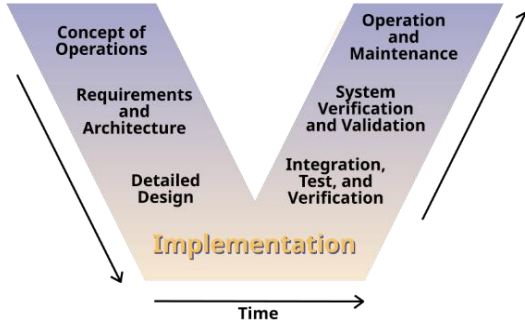
- Systems Engineering  
*Management* Processes
- Systems Engineering  
*Technical* Processes
  - Conceptual system
  - Physical system

## TASK:

Engineer a sparse joint seismic MMV network as one integrated system for providing seismic information using formal systems engineering processes

# Total Seismic MMV Systems Engineering

## Systems Engineering Technical Processes / Activities



Applying systems engineering discipline exposes:

**Trade-offs**      **Limitations**  
**Mandates**

- Identify system scope and operational concepts
- Identify products, consumers, and stakeholders
- Requirements analysis
- Functional Analysis
- System architectures and subsystems design
- Risks: Identify, assess, and manage
- Detailed design
- Test and evaluation master plan (TEMP)
- Development, deployment, and integration
- Verification, evaluation
- System operations

# Requirements (... drive everything)

## Passive Seismic Monitoring

- (Initial) Area of review
- Depth of reservoir and caprock, area of review
- **Magnitude of completeness (locatable events)**
- Allowable footprint / siting restrictions
- Design frequency and band
- Array gain and directivity
- Maximum tolerable reporting latency
- Automated processing bulletin report interval
- State-Of-Health / Noise / Performance updates
- Data/information storage
- Output seismic information stream and interface

## General System

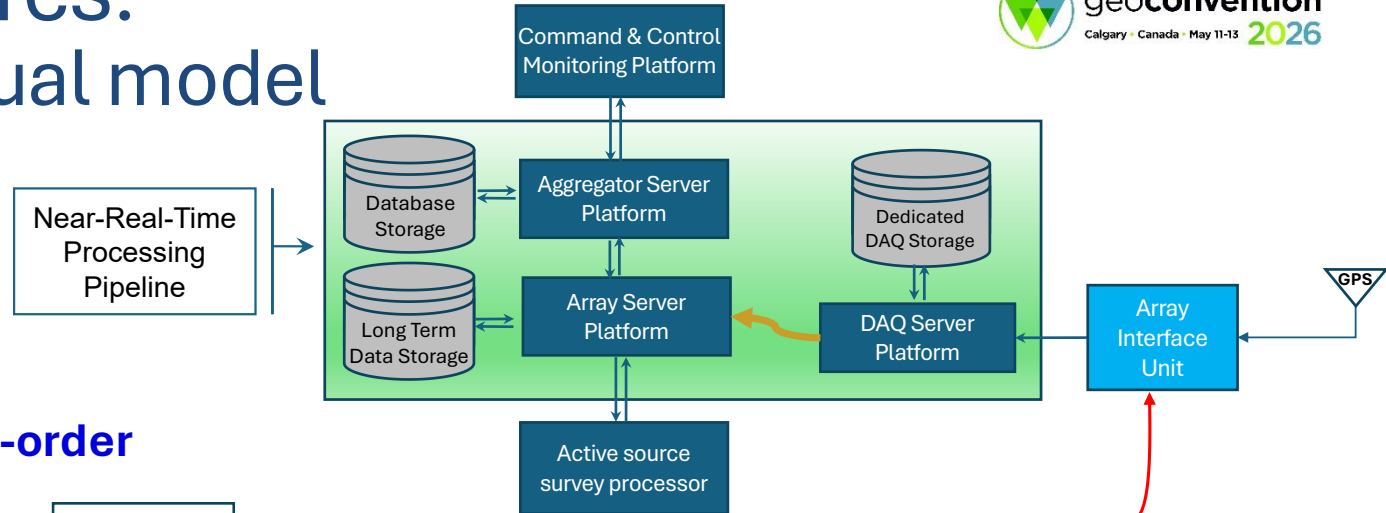
- **Reliability: Permanent components robust to attrition over 20-year-lifetime**
- System scalable / adaptable for AOR growth
- Environmental requirements
- LRU components robust to 5-year lifetime
- Mean time between failures

## Active Source Imaging

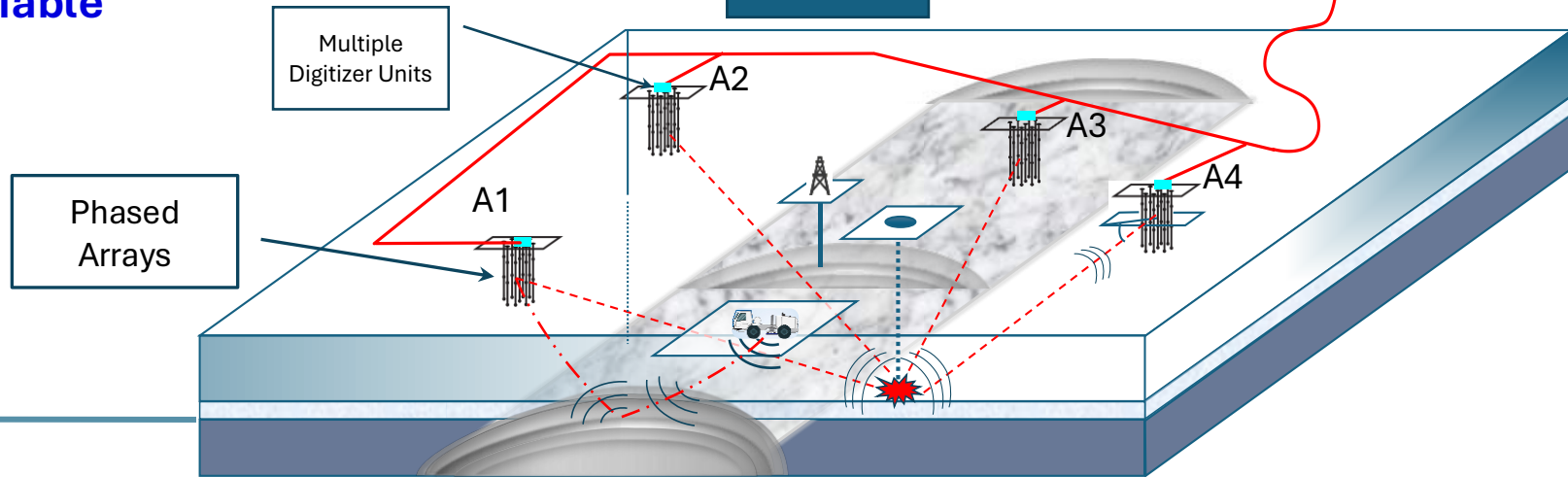
- **Identify desired subsurface volumes, patches, profiles, points for repeated interrogation**
- Identify overlap areas with VSP
- Specify frequency band
- Identify source hardware
- Propose processing sequence

***Stakeholder level requirements  
must be quantified and explicit***

# Architectures: conceptual model



**Network and Array  
architecture is a first-order  
design variable**



# Active Source Imaging Architecture

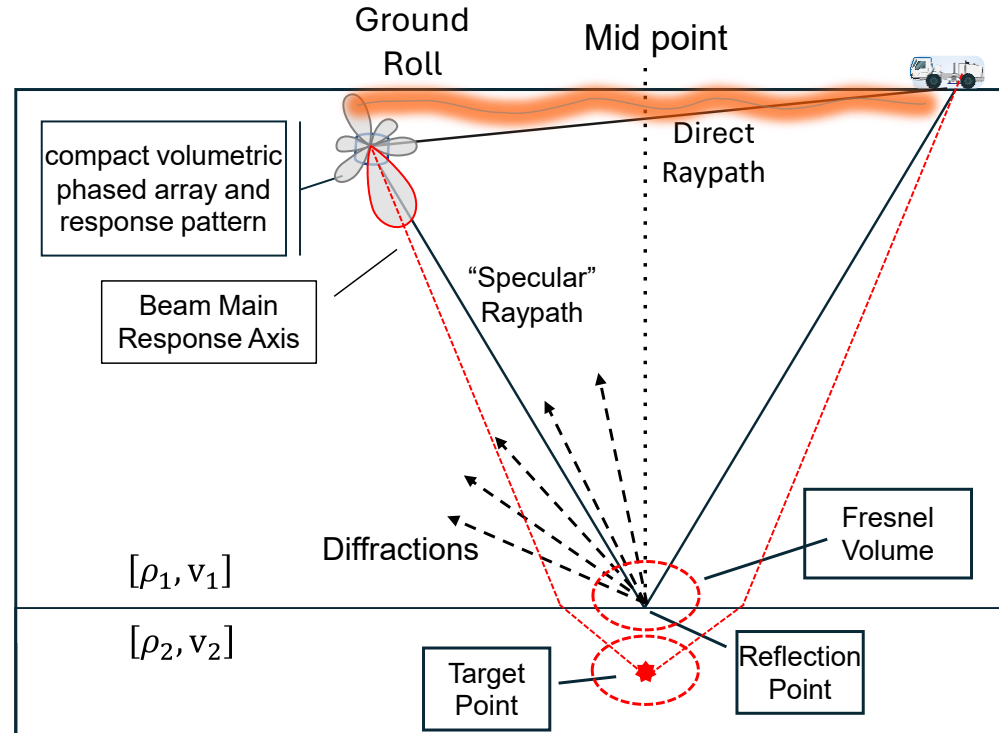
## Architecture / Detailed Design

- CMC-FRS VSP survey plan existed prior to SADAR sparse network installation
- SADAR imaging TRL-6 at installation
- Limited to optimum offset geometries

## Conventional Beamforming

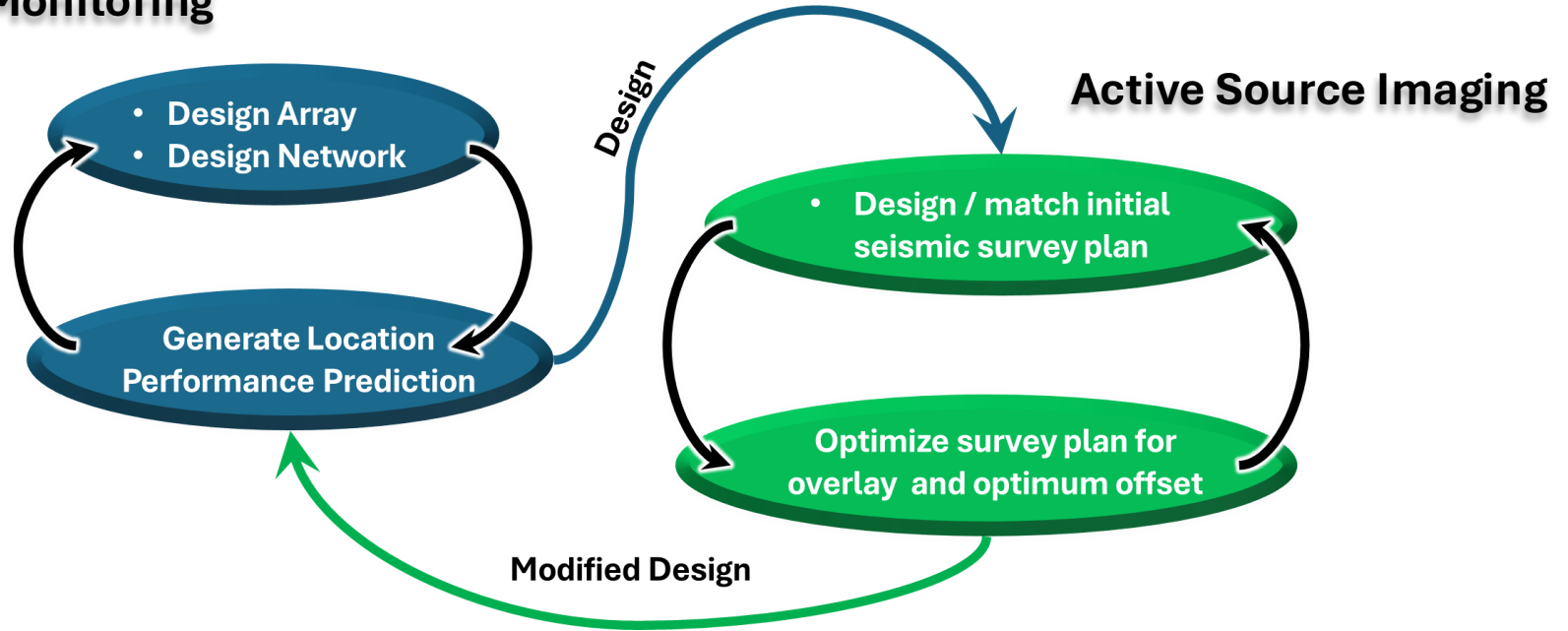
- Applies phase shifts to single element data aligning signals arriving along common wavenumber
- Suppresses random / coherent noise
- Improves SNR of received signal

SADAR array processing sequence including beamforming produces a superior starting-point image



# Array and Network Physical Design

## Passive Monitoring



**Passive monitoring and active imaging designs must be jointly optimized**

# System Specific Risk Analysis

*All technical risks carry financial risk either directly or indirectly*

- Identify / quantify technical risks that exist in the seismic monitoring systems  
Examples: loss of power, loss of sensor, loss of communications link, loss of data from one or more reasons
- Choose to accept risks and mitigate, or transfer risks  
Examples: mitigate power loss with redundant large capacity UPSs, transfer via outsource installation & communications, large circular buffers, mitigate with permanent source piles

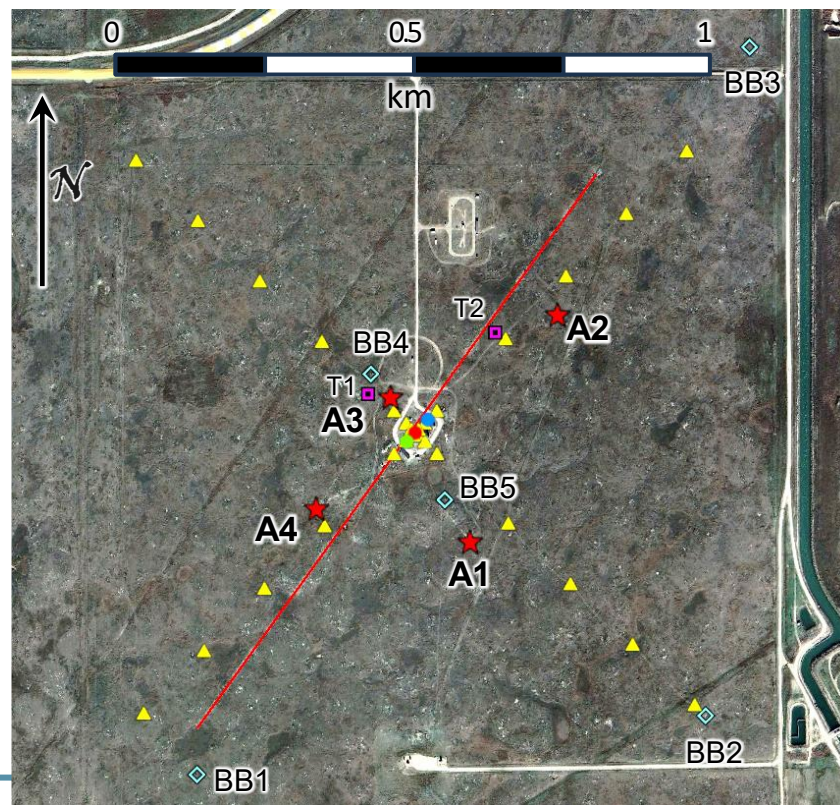
*Sparse networks of permanent SADAR arrays performing both passive microseismic monitoring and active source imaging reduce technical risks (Nyffenegger et al., 2025 IMAGE).*

# Detailed Plan

- Array / Network designs for mitigating technical risks (Mc requirement)
- Permanent installation of sensor components (reliability: robust emplacements)
- Wired network power and communications (low risk of interruption)
- Central control and data logging (least expensive)
- Minimize surface footprint (cost / management)
- No penetration of any strata critical to operations (no risk to reservoir containment)
- All equipment out of the critical path for operations (no risk to standard operations)

**Product: detailed system installation plan with a work breakdown structure and schedule.**

- ★ SADAR array
- 1m deep trench – DAS
- ◆ Broadband Seismometers
- ▲ Permanent 3C Geophones @ surface
- Tensora DSS



# Test and Evaluation Master Plan

Series of acceptance tests and structured performance tests centered around the requirements verification matrix

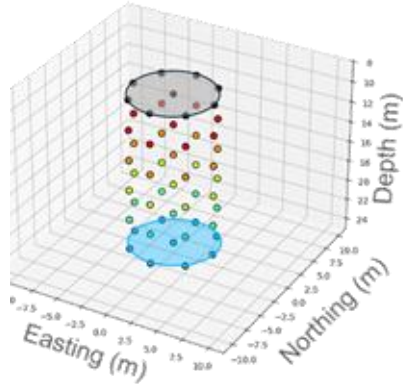
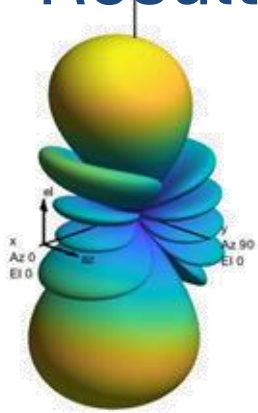
- Ideally, from fabrication onward
  - Starts with factory acceptance tests
  - On site functionality tests prior to installation
  - Deployed system functionality test
- Structured testing  
*(requires a controlled source)*
  - Initial noise assessment
  - Array gain and directivity assessments
  - Detection performance
- Initial and Ongoing continuous performance assessment
  - System state-of-health (continuous)
  - Data quality / noise analysis
  - Periodic reports versus prediction
    - Noise spectra and analysis
    - Array gain examples

**Without controlled sources  
positionable in 3D,  
performance verification  
cannot end after installation**

# Results: what did / did not work

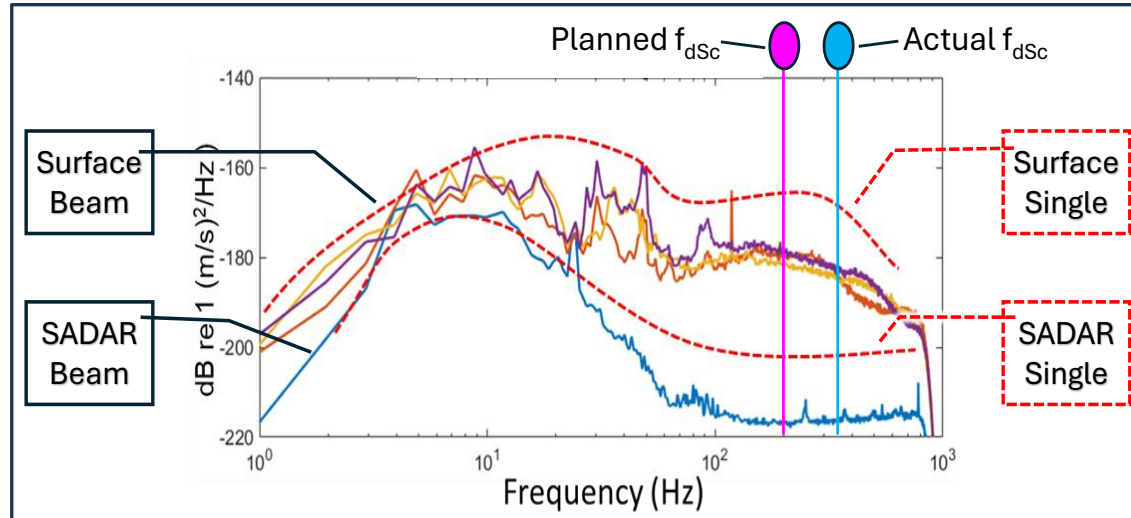
Grade	Engineering Element	Explanation
B+	Array and Network Design	Assumptions on local velocity, unknowns (noise level), other design priorities. Risk mitigation resulted in shrinking monitoring volume, additional array would have improved coverage
A-	Risk Management	Effectively identified Mc risk and adjusted network and array design
A+	Deployment	Planned, efficient, and effective. All systems running in 1 week.
A-	Architecture	Near real time prototype architecture is sufficient but not adaptable. Engineered system architecture under development is flexible, adaptable, scalable, efficient
C+	Test and Evaluation Master Plan	After the FAT and the Deployed System Functionality Tests, additional evaluation depends on “sources of opportunity”
B+	Ongoing Operations	Now behind by several months, due to loading and staffing.

# Results: Array Design vs. Emplaced



- Emplaced: upper corner  $f_{dSc} = [330, 580]$  Hz  
 gain:  $\sim 8-20$  dB (c.f. Zhang et al., 2023 *TLE*)

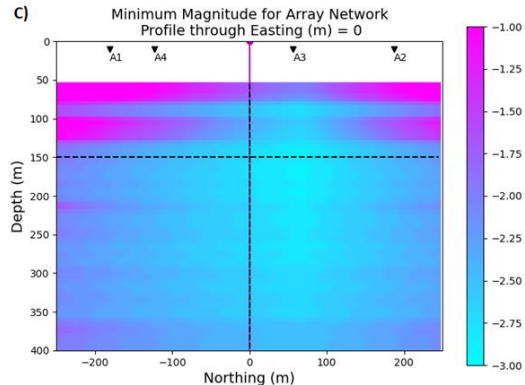
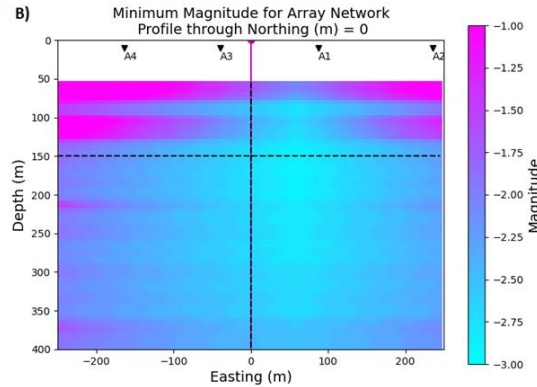
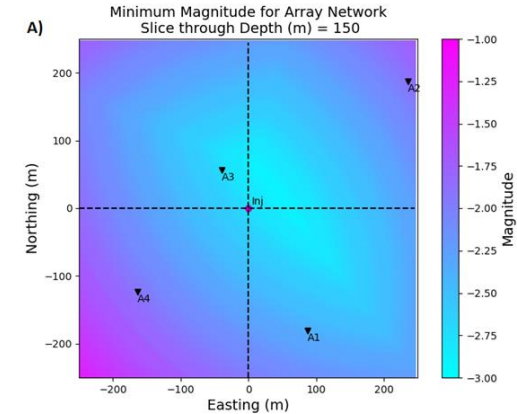
## A3 vs. S-GCL3 Noise



- Directivity @  $f_{dSc} = 200$  Hz
- Under-estimating  $V_d$  increases  $f_{dSc}$
- At  $f \ll f_{dSc}$  the arrays lose gain and directivity
- Design:  $f_{dSc} = [200, 260]$  Hz  
 gain:  $\sim 17$  dB estimate

**Underestimating Local Velocity  
 Directly Impacts Array Performance**

# Results: Network Performance Prediction

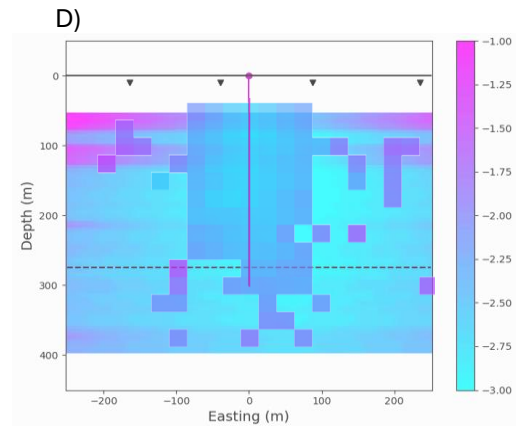
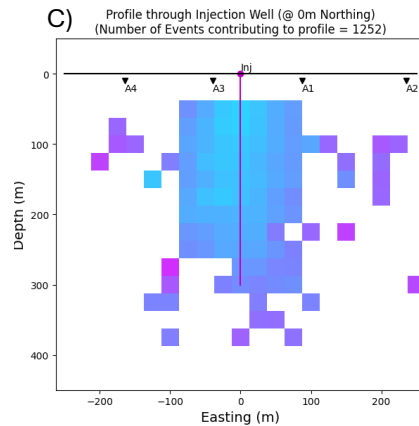
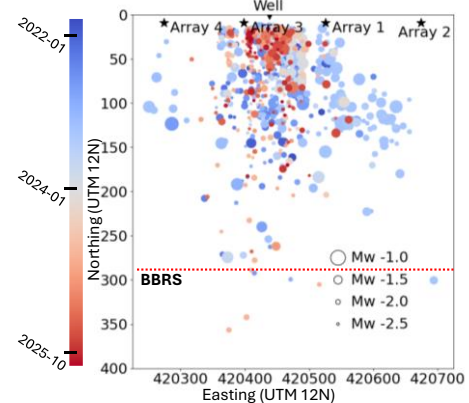
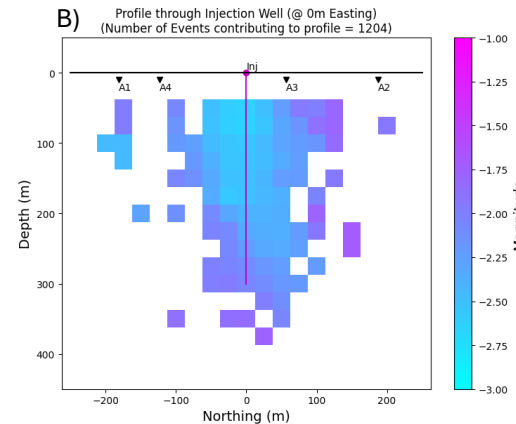
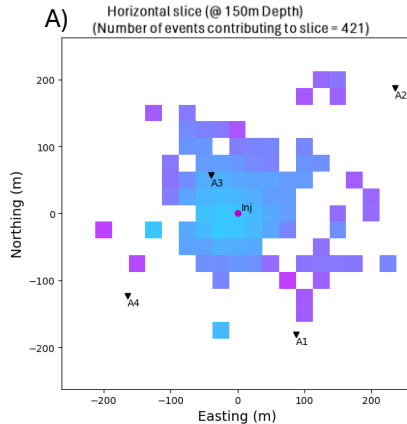
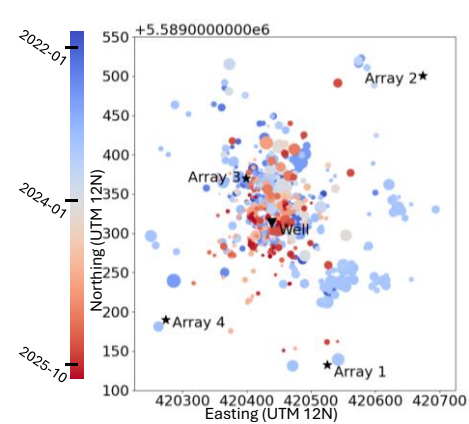


- Late-stage planning process
- Systems engineering approach based on the passive sonar equation -- *Decomposition of SNR*
- As presented in Grant et al. (2026)

- Predicts minimum magnitude locatable events about -3 Mw
- $M_c$  predicted about -2.5 Mw within 165m from injection well, -2 Mw across the AOR

- Provides performance-based map from conceptual system to physical system
  - Supports requirements traceability to physical system
- Physics and engineering-driven, not empirical guesswork**

# Results: Network Prediction vs. Measured



## Validation of the model

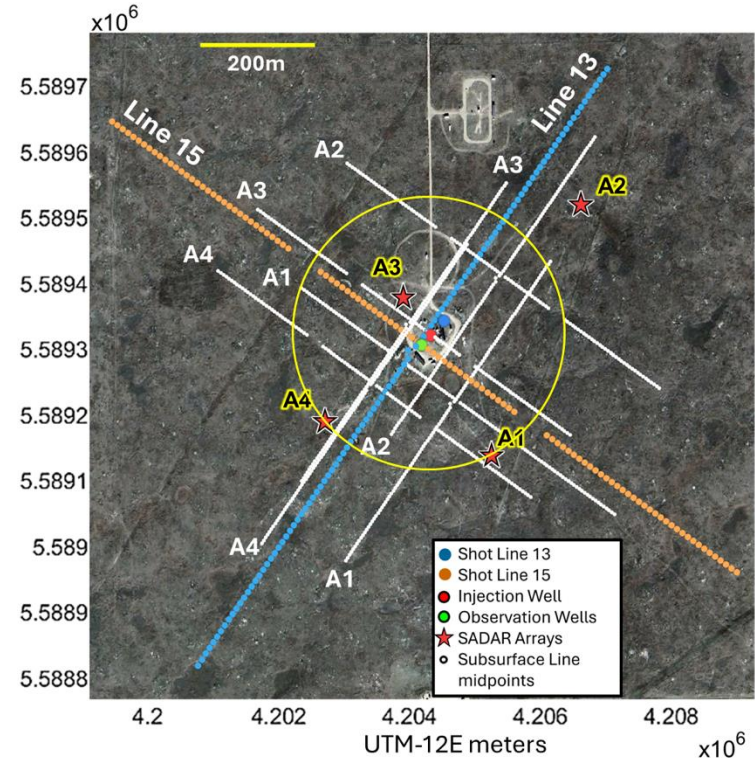
- Conformance of the system performance
- On going continuous evaluation
- Called out in TEMP
- Four years of results:
  - 14,073 events total
  - (left) 741 events  $z > 15m$ ,  $ndef=4$
  - (right A-D) 3486 events  $z > 25m$
  - AOR  $M_c = -2.5$  Mw

**Four Years of Data  
Validate the  
Engineering Model**

# Active Source Imaging Results

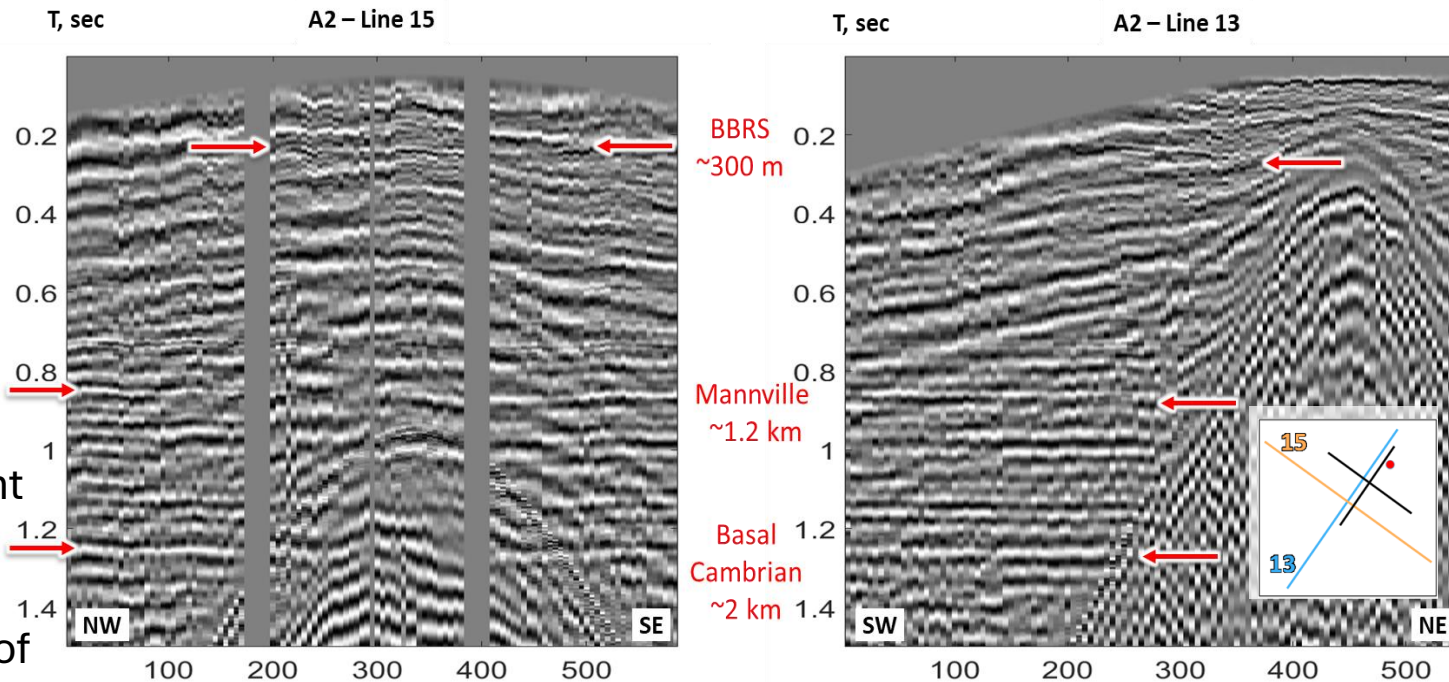
- Basic Procedure:
  - Preprocess, cut into shot record segments per array element,
  - Cross correlate with sweep,
  - Average repeated shots per shot point,
  - Beamforming to targeted depth points,
  - Sort into “common receiver gather” cross-section,
  - Normal moveout correction, data scaling, enhancements
- Main conclusions:
  - Basic targeted beamforming suppresses ground roll and increases the optimum offset window
  - Strata down to Basal Cambrian can be easily imaged
  - Offsetting the shot line from the array provides a better optimum-offset image

SADAR array optimum offset imaging beyond TRL-7.  
SADAR array time-lapse imaging still in POC.



# Optimum Offset Imaging Example

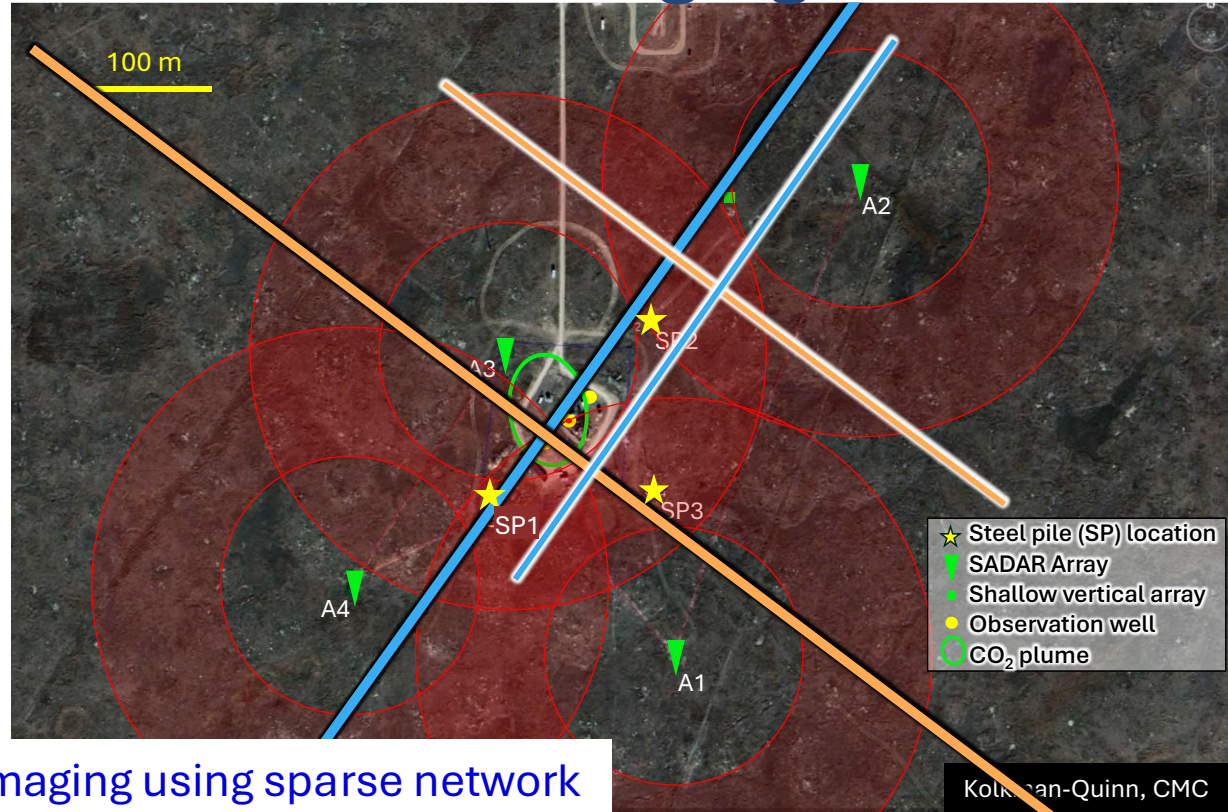
- Most basic image using targeted beamforming
- Each shot point yields a single targeted beam trace
- X-axis is offset along the midpoint line
- Line 15 shows superior imaging of the BBRs



Optimizing optimum offset imaging using a sparse network of  
SADAR arrays requires non-standard survey planning

# Engineering Optimum Offset Imaging

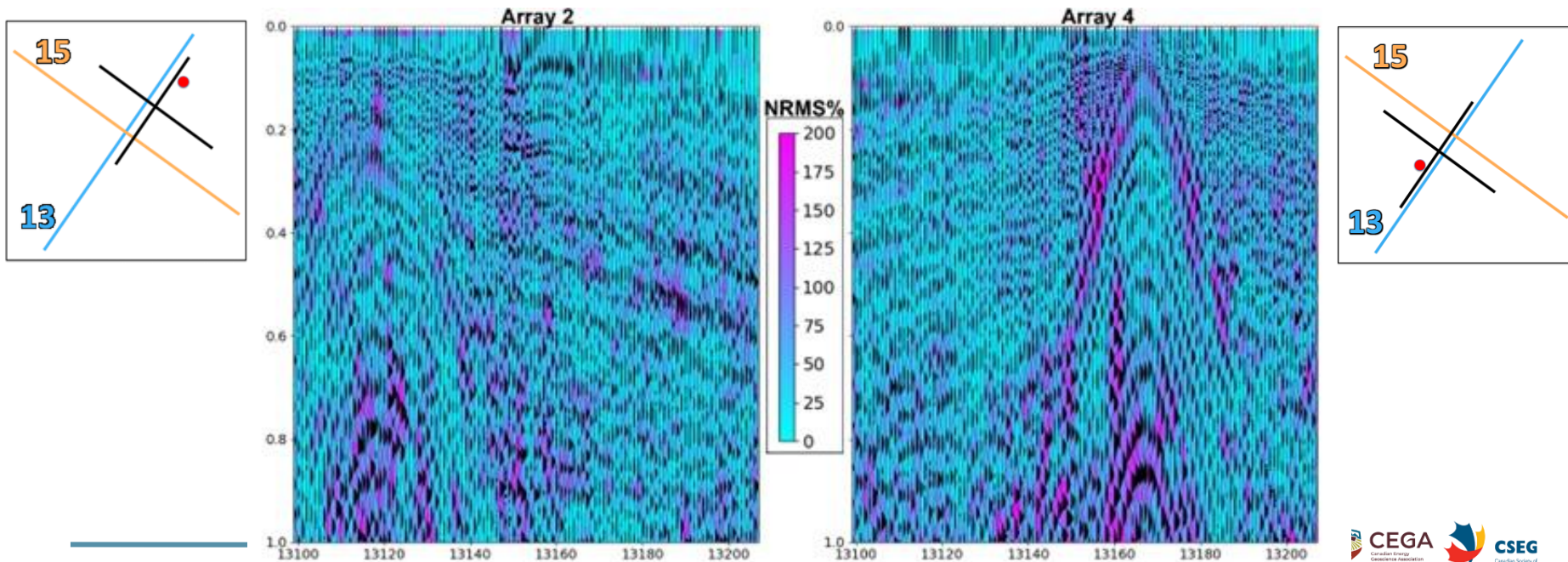
- Optimum offsets for SADAR arrays shown as red donuts
- Overlap between SADAR and VSP imaging of the BBRs is achieved from A3
- Permanent source shots at SP1 result in an optimum offset sample at A1, A4, A3.
- Permanent sources provide more frequent, automated seismic sampling.



Optimizing optimum offset imaging using sparse network of SADAR arrays requires non-standard survey planning

# Result: Time-lapse Taste

Timelapse difference of Array 2 (left) and Array 4 (right) for targeted beam profiles of the Line 13 October 2024 survey minus the July 2022 survey overlain on NRMS.



# Discussion / Recommendations

## *Systems Engineering Is Not Magic*

Total system engineering technical processes applied to integrated seismic functions will ensure the MMV systems meet requirements, provide transparency, and support public confidence

- We introduced a procedure for total system engineering for integrated seismic MMV
- Partial systems engineering works – but exposes gaps and deficiencies
- Risks were identified, accepted, and mitigated resulting in the network and arrays meeting passive microseismic monitoring requirements
- Continuing evaluation against performance prediction is a workable alternative to structured testing
- Performance evaluation metrics are shared with operations monitoring metrics for the integrated seismic monitoring system.

# Discussion / Recommendations

## Next Steps Are Clear

1. Mature workflows concentration on timelapse analysis
2. Integration and automated processing for permanent sources
3. Migration to more advanced beamforming algorithms
4. Engineering of outputs – seismic information

**Passive seismic monitoring infrastructure can be the backbone for multiphysics node power and information in a sparse MMV network**

## Thanks for sticking with us!



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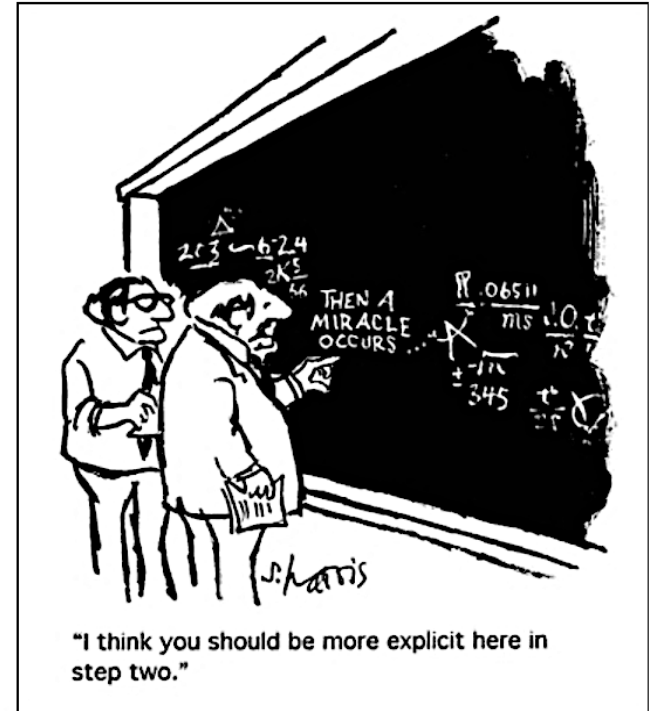
Book Meeting



SADAR

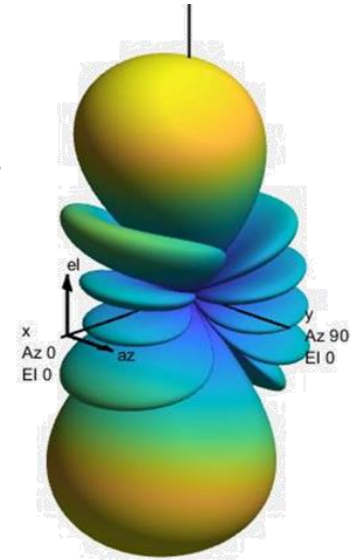
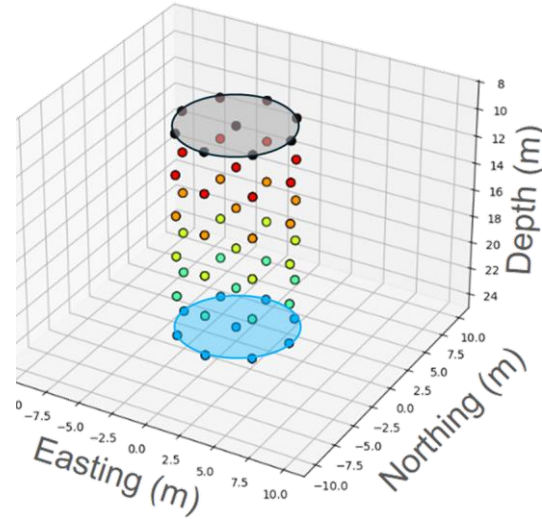
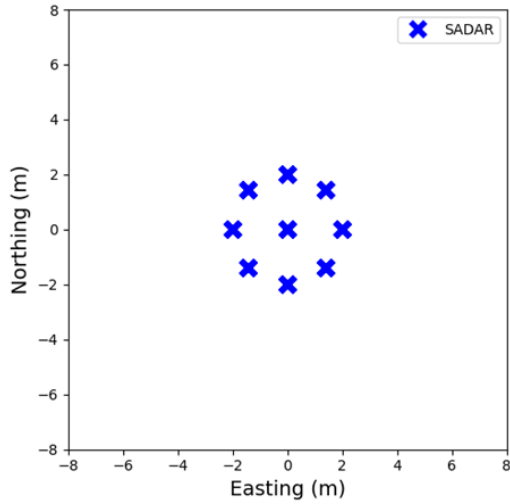
### Acknowledgements

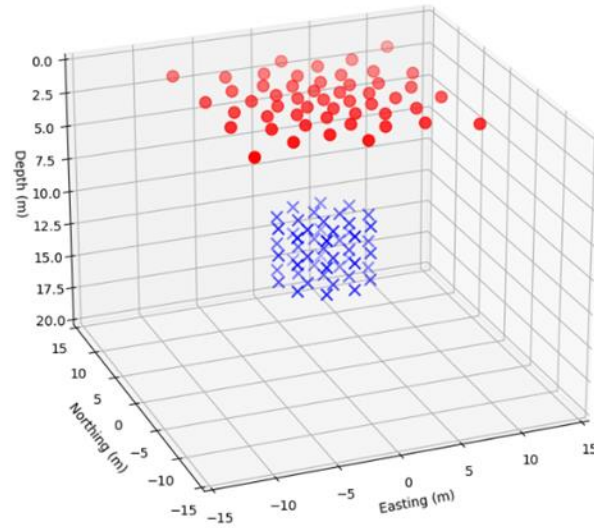
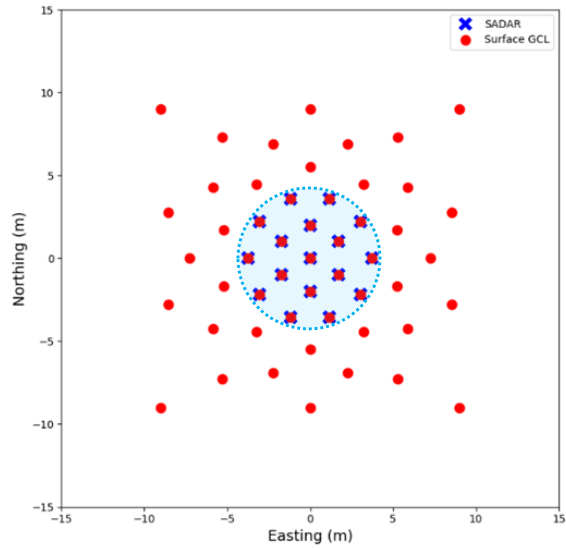
Research and operations at the Field Research Station are supported by the CMC-CaMI Joint Industry Project members. CMC authors also acknowledge financial support from Emission Reduction Alberta (ERA) through the Advanced Multi-Physics Sparse Monitoring (AMPS) project.



<http://www.sciencecartoonsplus.com/gallery/math/index.php#>

# EXTRAS





# What Is The Microseismic Performance?

**Near Range**

2021 Nov 18

16:25:48.465

50.45002N

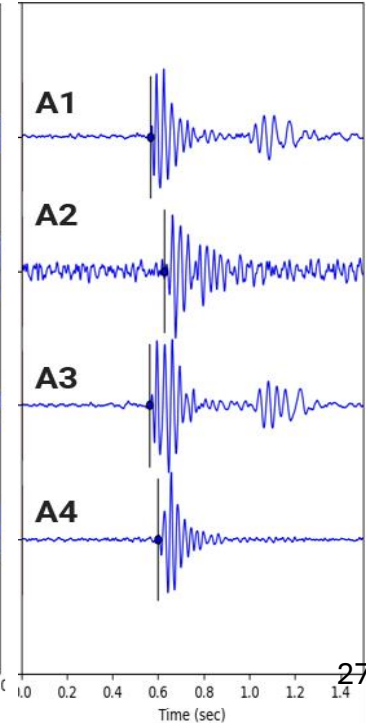
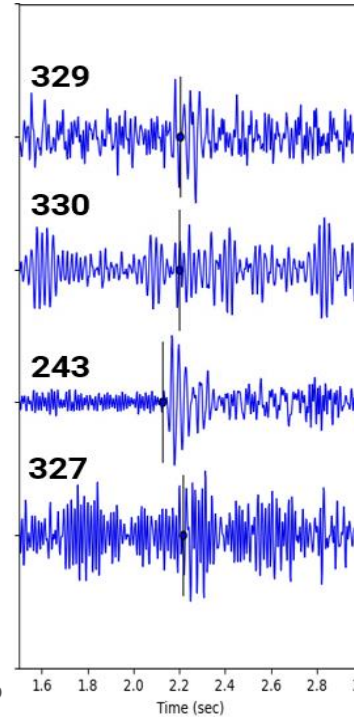
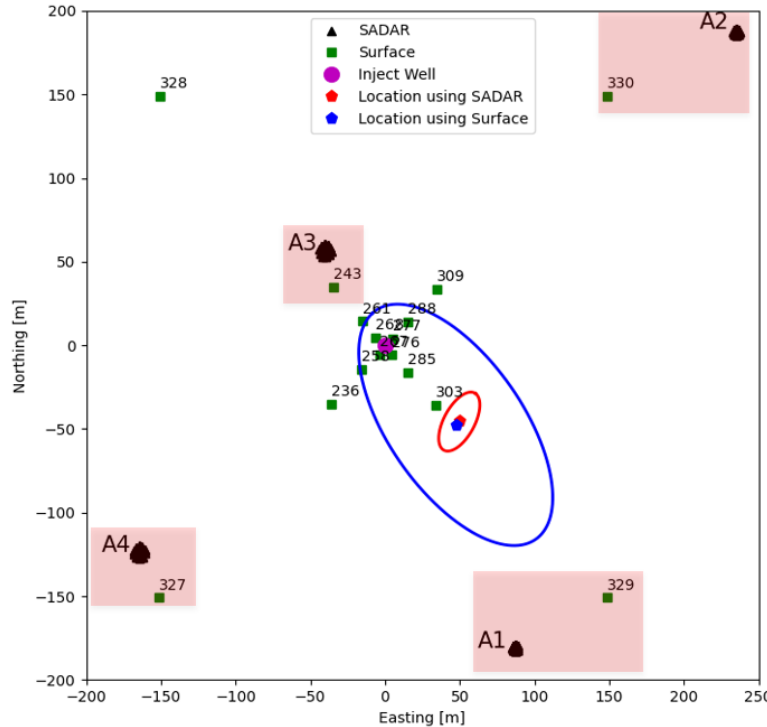
112.11997W

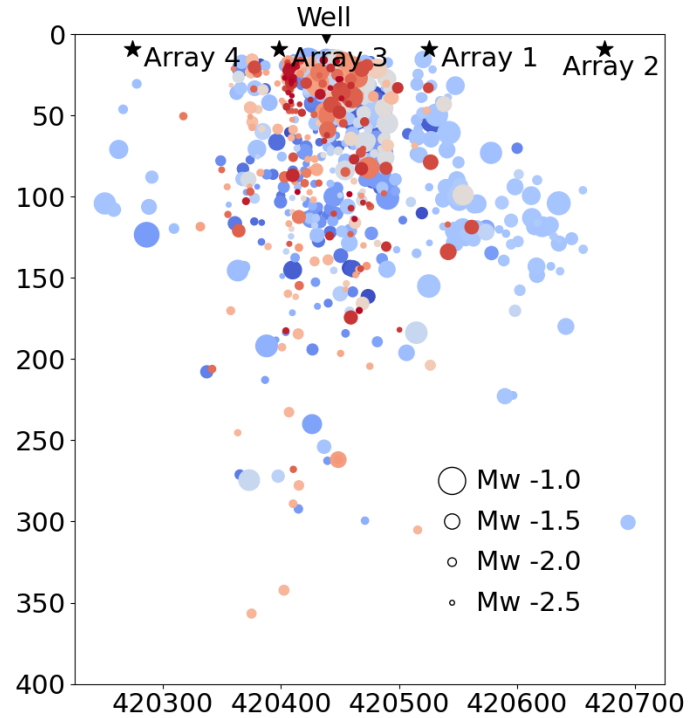
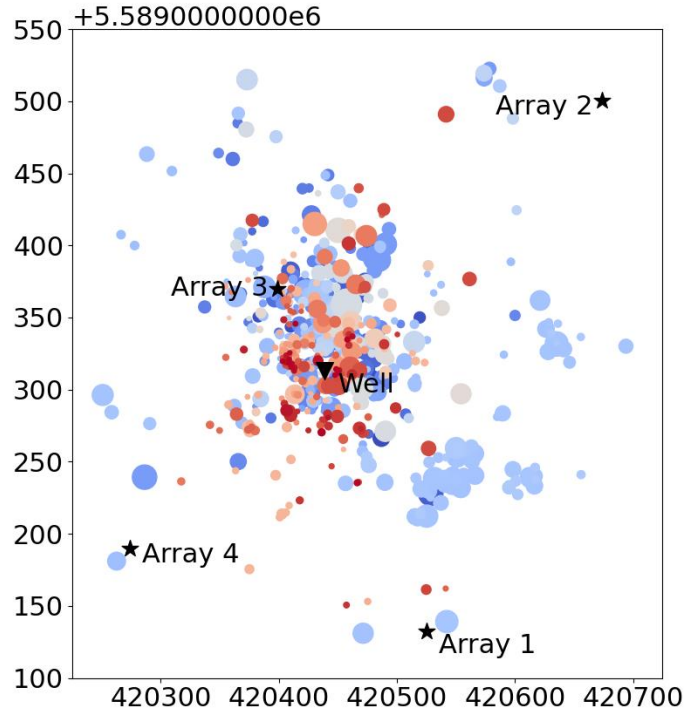
21m

Mw=-1.2

**Far Range**

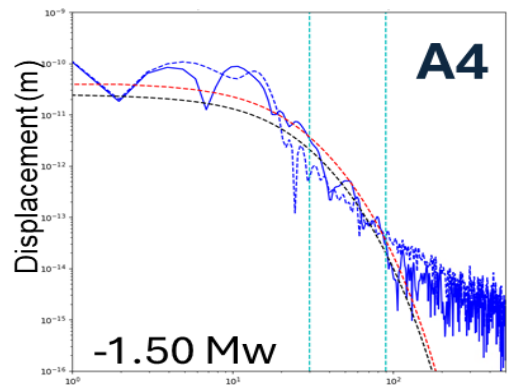
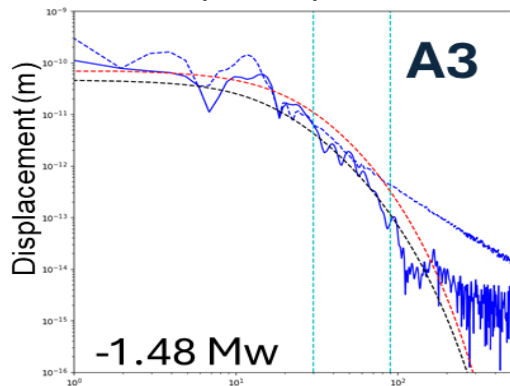
**SADAR**





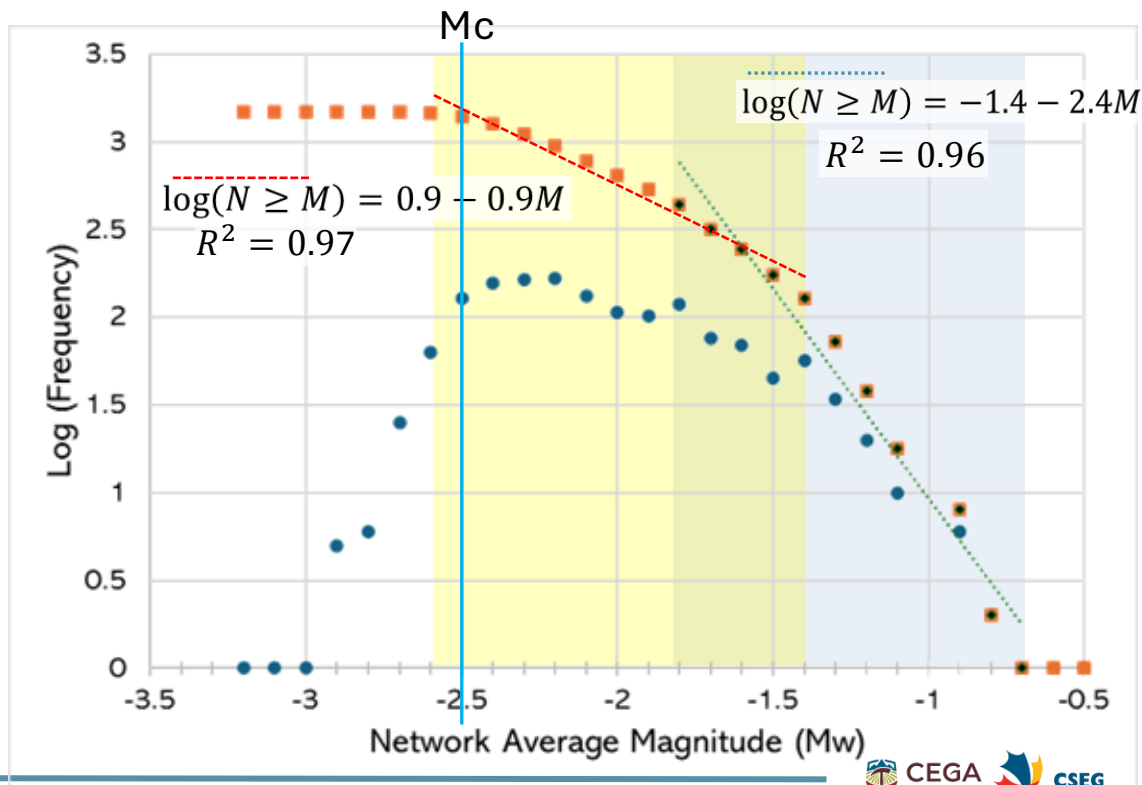
# Moment Magnitude

Brune(1970) method

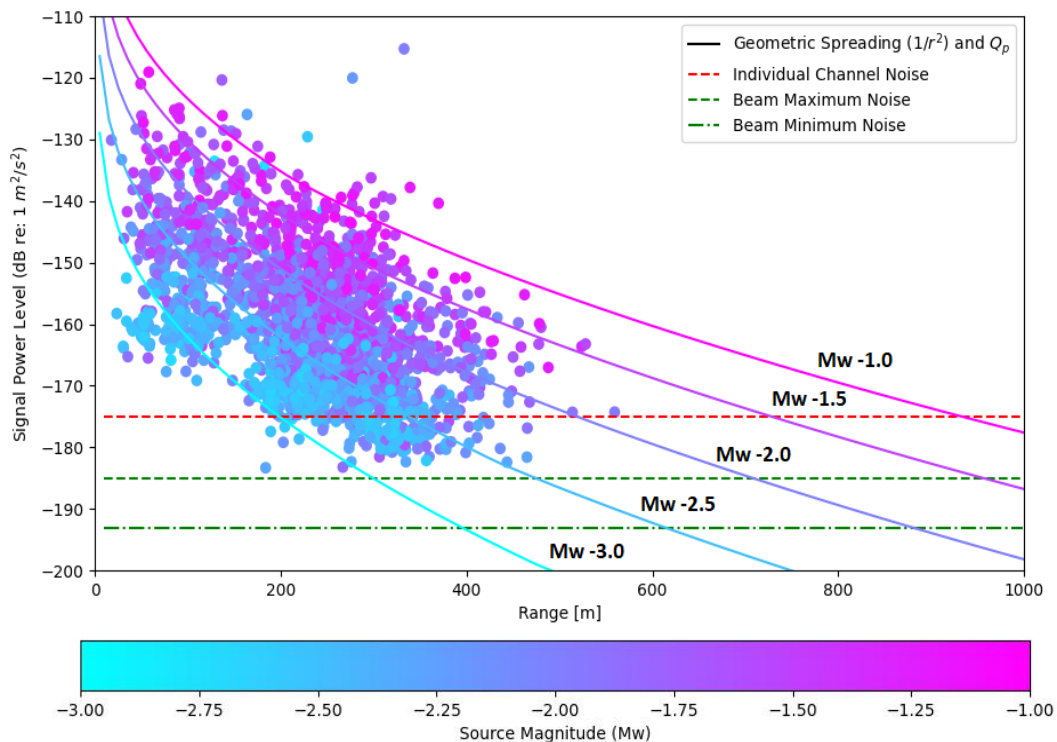


Freq (Hz)

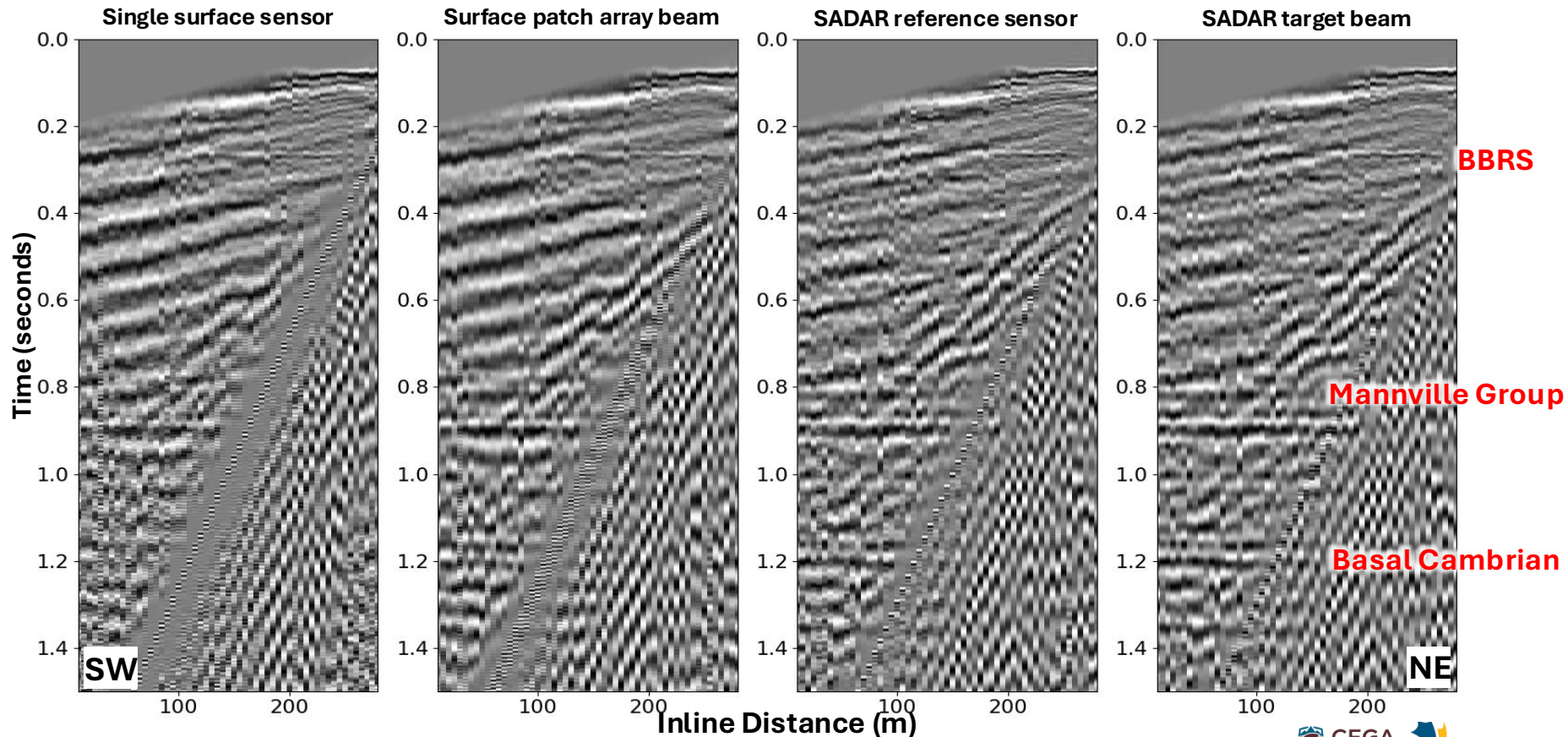
Magnitude frequency distribution for 1583 events



# Received Signal vs Power Distance



# Shot Line13-Array3



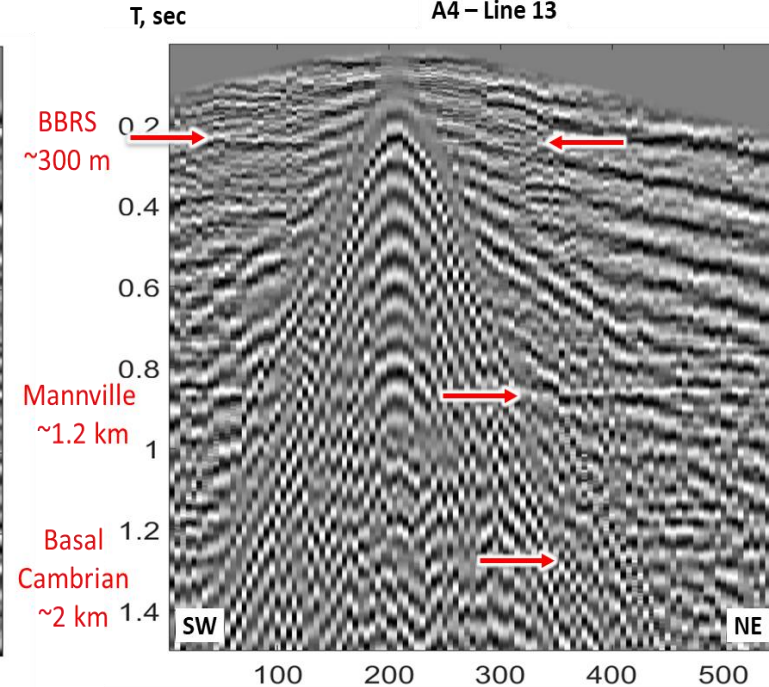
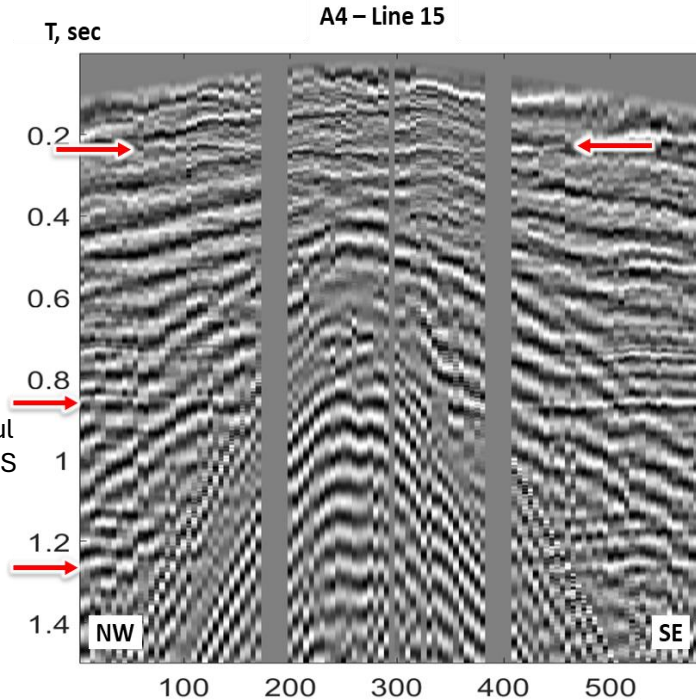
# Application: A4 Active Survey Results

A4: hybrid design,  
72 elements, hemisphere  
approximation,  
Best apertures, best beam  
response patterns

Line 13 is not the best  
geometry for optimum offset  
imaging because of the noise  
cone.

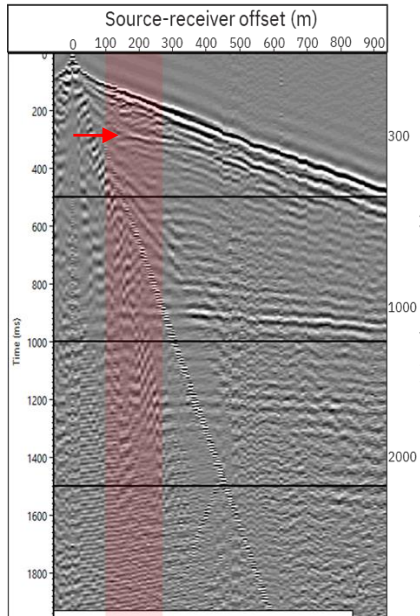
Line 15 provides a more useful  
geometry for imaging the BBRS  
reservoir.

A2 produced better optimum  
offset images of deeper  
horizons.



# Proof Of Concept (Vibe at SP1)

Optimum offset  
(2D vibroseis)



Optimum offset  
(Pile + SADAR)

