Development of Novel 3D Acoustic Borehole Integrity Monitoring System

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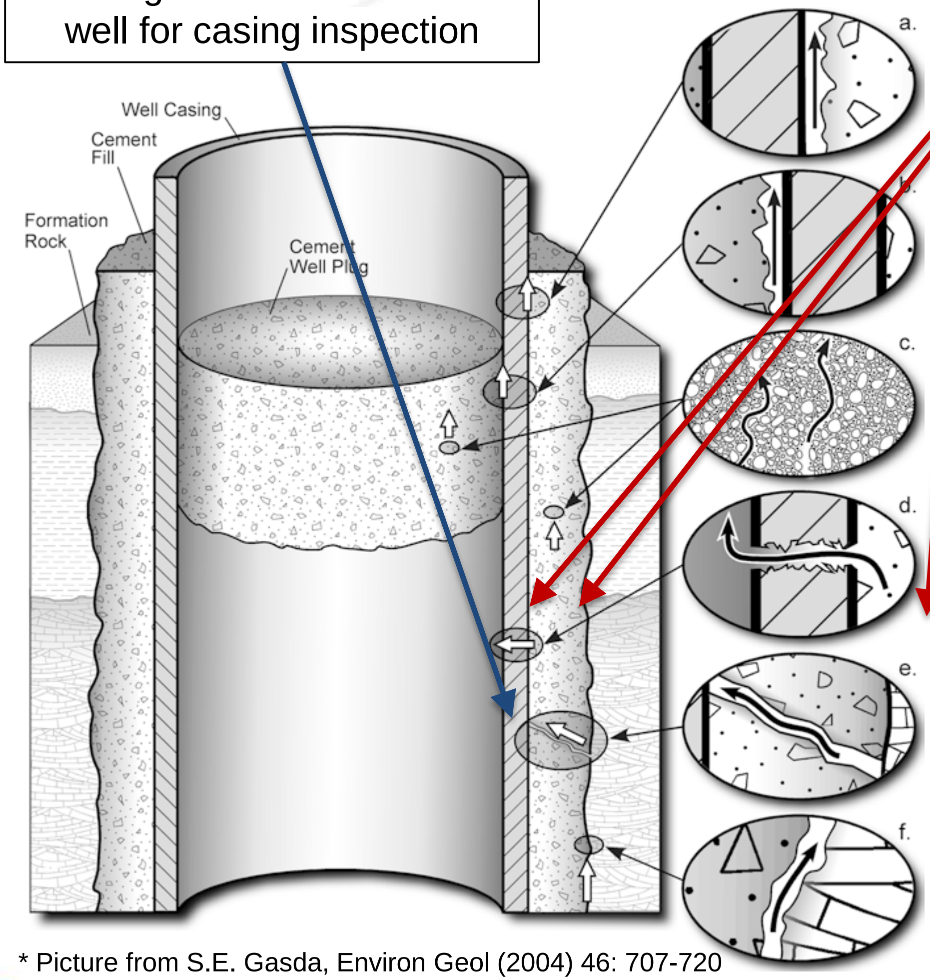
Scope of Work

The Problem:

Defects/fracture detection beyond casing with high resolution. No current techniques.

Existing ultrasonic tools work well for casing inspection

We plan to extend applicability to: (1) casing-cement interface, (2) cement-formation interface, and (3) out in the formation (up to ~ 3 meters).



Comparison of existing techniques and the present approach

Method	Frequency (kHz)	Range (m)	Resolution (mm)
Standard borehole sonic probe, e.g. BARS (Borehole Acoustic Reflection Survey)	0.3-8	15	~ 300
Present approach	10-150	~ 3	~ 5
Ultrasonic probe, e.g. UBI (Ultrasonic Borehole Imager)	>250	casing	4-5

* Picture from S.E. Gasda, Environ Geol (2004) 46: 707-720

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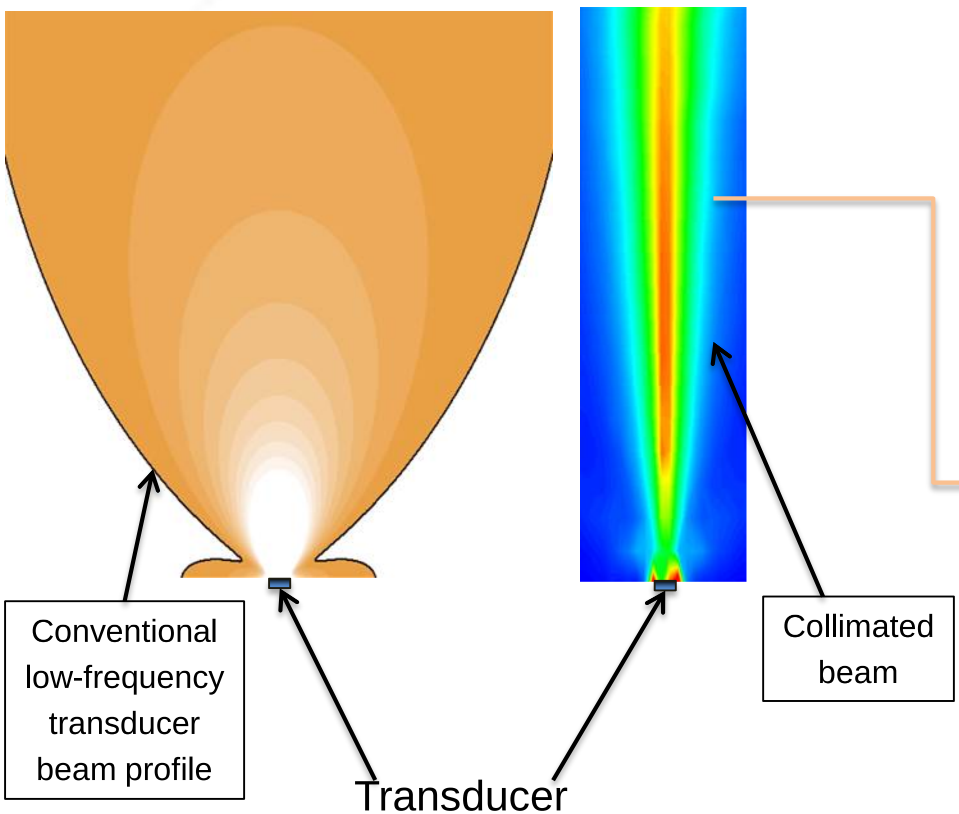
Scope of Work

The Proposed Solution:

Novel technique that fills this technology gap.

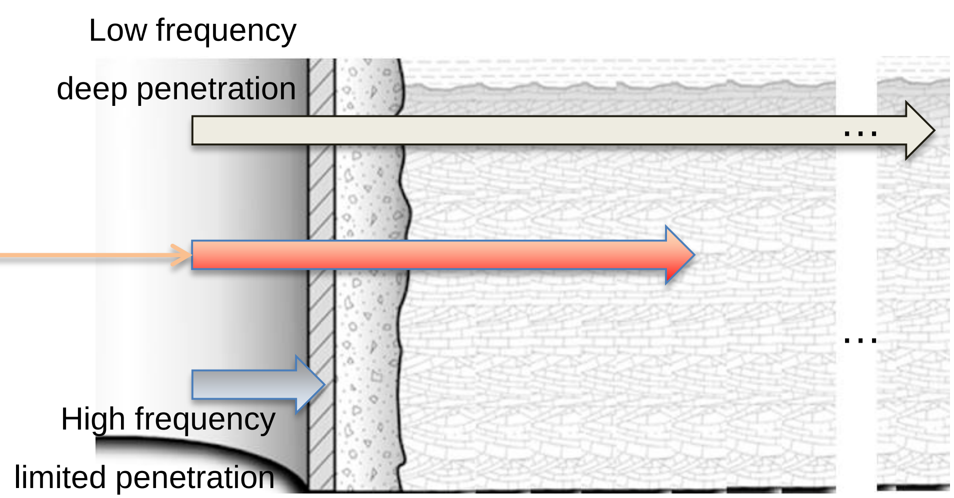
1. Collimated beam for increased resolution



2. Low frequency for deeper penetration

$$Attenuation \sim f^n$$

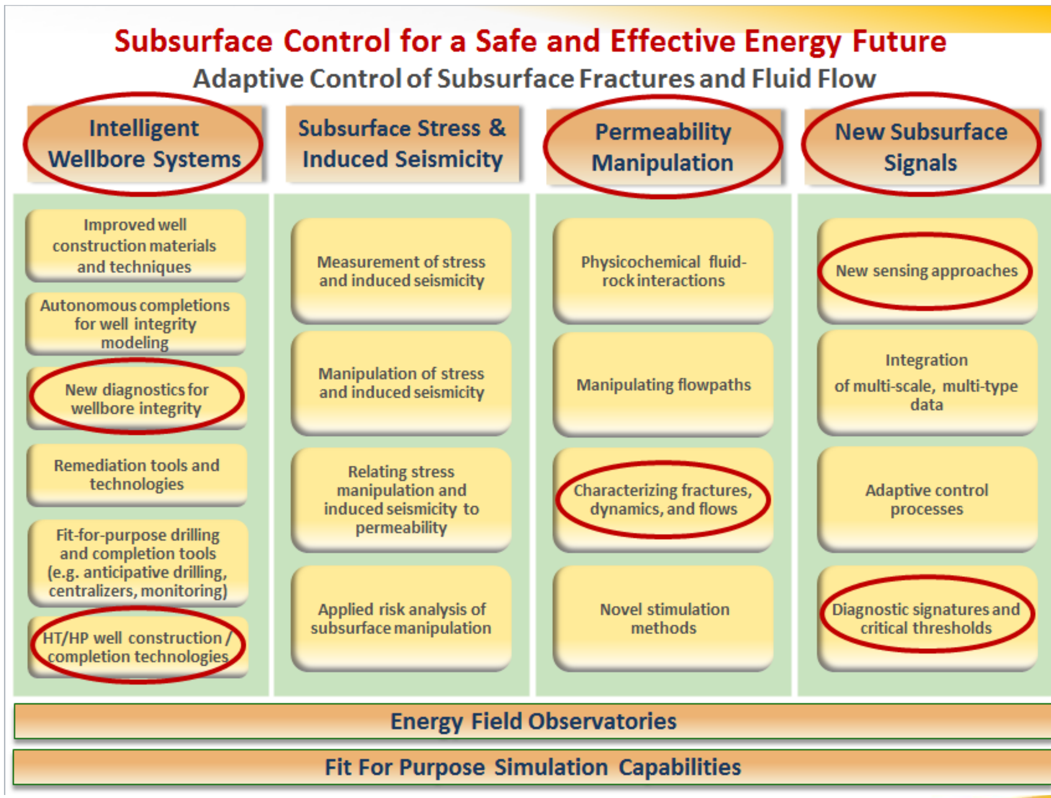
f = frequency, n = 1-2



Scope of Work

Relevance to the SubTER pillars:

Comprehensive solutions to wellbore integrity monitoring and improved near wellbore fracture detection are needed in multiple energy sectors (CO_2 Storage, Geothermal, Oil & Gas, Nuclear).



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Scope of Work

Long-term objectives:

Develop a complete 3D imaging system, based on:

- unique acoustic source (low frequency, highly collimated, broad-band: 10-150 kHz, high power)
- advanced image processing.

Investigate effectiveness of next generation wellbore completion technology such as foamed cements.

Year 1

Develop & demonstrate the method on simple wellbore systems

- Build apparatus — LANL
- Inversion technique development — ORNL
- Image processing — LANL
- Initiate tests in realistic wellbores — SNL/LANL
- Initiate foamed cement test — NETL/LANL

Year 2

Evaluate method on more complex wellbore environments

- Make cement/seal — NETL
- Characterize w/CT — NETL
- Test Acoustics — LANL
- Real wellbore tests — SNL/LANL
- Refine 3D processing — LANL/ORNL

Year 3

Extend method beyond wellbore

- Enhanced sensors — LANL
- Refine algorithm — ORNL/LANL
- Testing of new sensors — SNL/LANL
- Adapt sensors for foamed cements — NETL/LANL

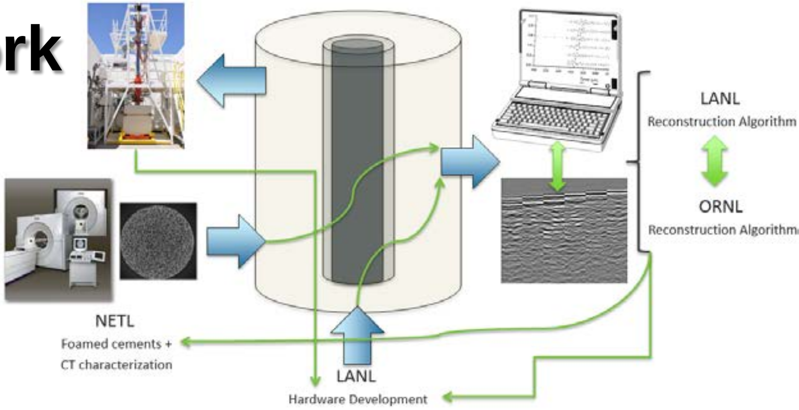
*The target investigation range for the first year:

- wellbore casing and
- casing-cement interface.

Outcome:

- improved imaging resolution around the borehole and
- extended investigation range - beyond the wellbore casing

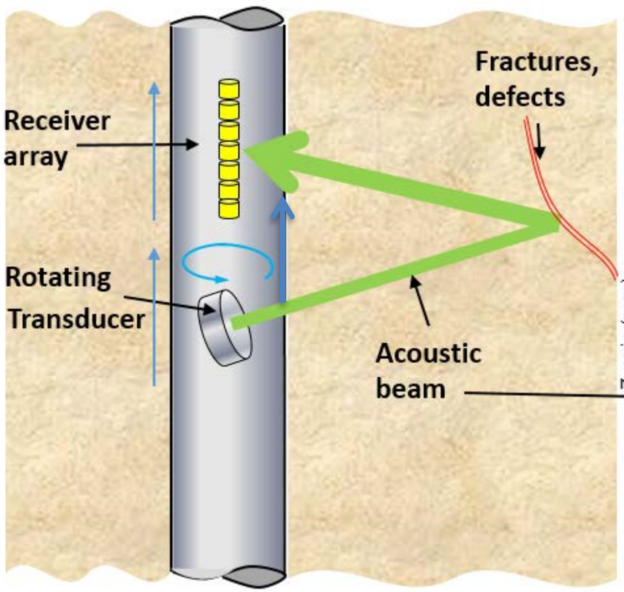
Scope of Work



- Multi-lab project:
  - Develop acoustic source and imaging system (LANL)
    - → Develop imaging system and perform experiments for defects detection
  - Explore different *image processing* approaches (LANL + ORNL).
    - →The best choice (or complementary use) will be selected for future experiments
  - Perform experiments in more realistic boreholes (LANL + SNL)
    - → Incorporate data from realistic borehole and compare resolution with lab experiments
  - Investigate acoustic metrics for *foamed cements* (LANL + NETL).
    - → Incorporate new metrics for wellbores in the field

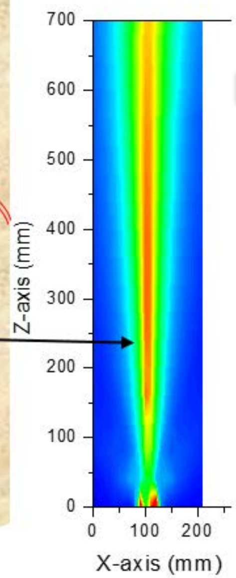
Scientific/Technical Approach

Schematic representation of the 3D imaging system:

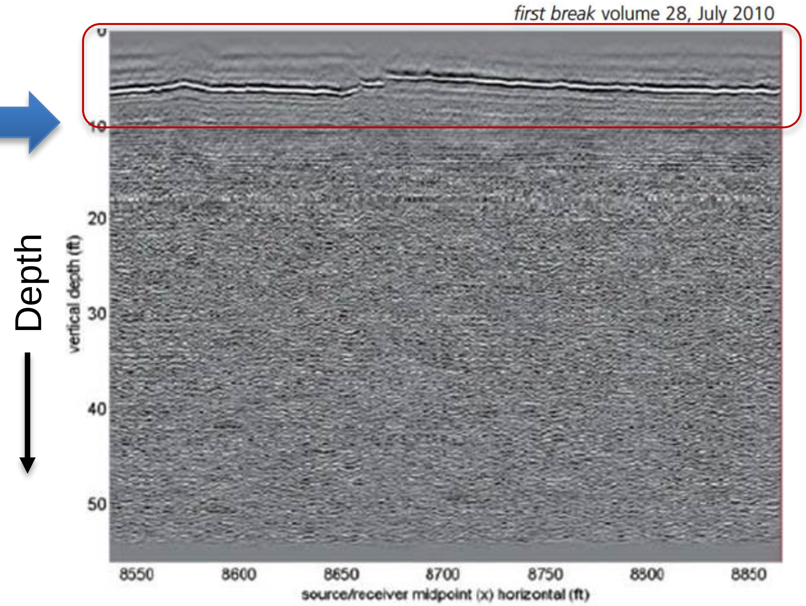


360 degree imaging

Low frequency Collimated beam (10-150 kHz)



No side-lobes



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Project Milestones

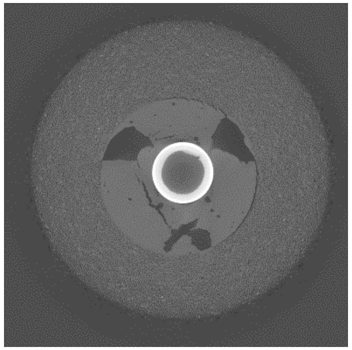
Milestone Summary Table

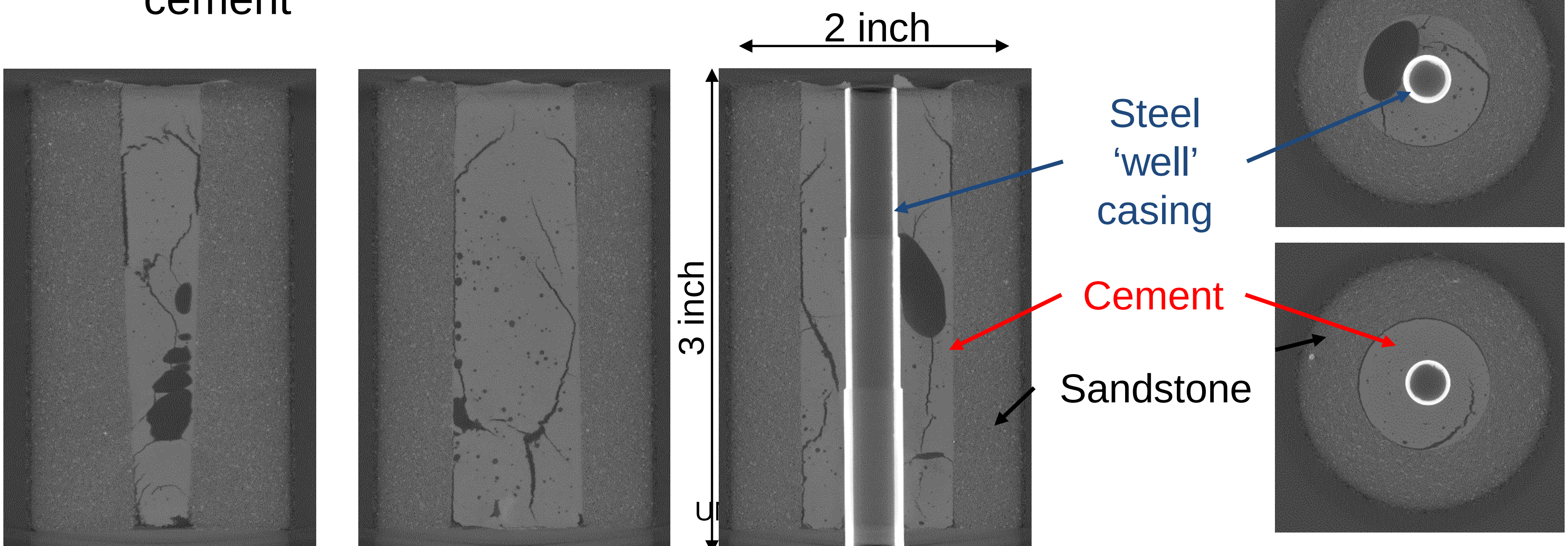
Task No.	Task Title	Milestone Type (Milestone or Go/No-Go)	Milestone No.	Milestone Description	Milestone Verification Process (Who, What, When, Where)	Anticipated Date of Completion
1	Build apparatus					
2	Defects imaging	Milestone	1	Demonstrate imaging capability for casing imperfections.	Thinning Metal loss Eccentricity	09/30/2016
			2	Demonstrate imaging capability for delaminations and cement cracks	Delamination Fractures in cement * w/ sub-cm resolution	09/30/2016
3	Resolution determination					
4	LANL Image processing	Milestone	3	Demonstrate improved resolution	Achieve resolution similar to existing ultrasonic tools (in the order of a few millimeters)	09/30/2016
5	ORNL Image processing	Milestone	3	Demonstrate improved resolution	Achieve resolution similar to existing ultrasonic tools (in the order of a few millimeters)	09/30/2016
6	Foamed cements tests					
7	Realistic wellbores					

GO/NO GO: A go/no go decision will be based on the capability to image the casing-cement interface with a realistically required resolution for applications in the field.

CT Imaging of Well

- **First CT scans acquired of well/cement/rock system in early 2016**
  - Well thickness varied to ensure minimal imaging artifacts during scanning. Scan resolution 27.8 micron.
  - Multiple voids/fractures created in cement during process to test ability to capture imperfections in cement





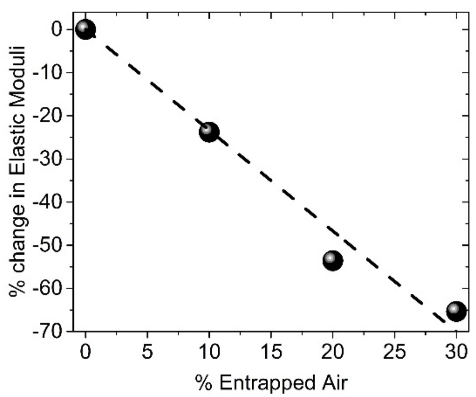
Elastic Properties of Foamed Cement

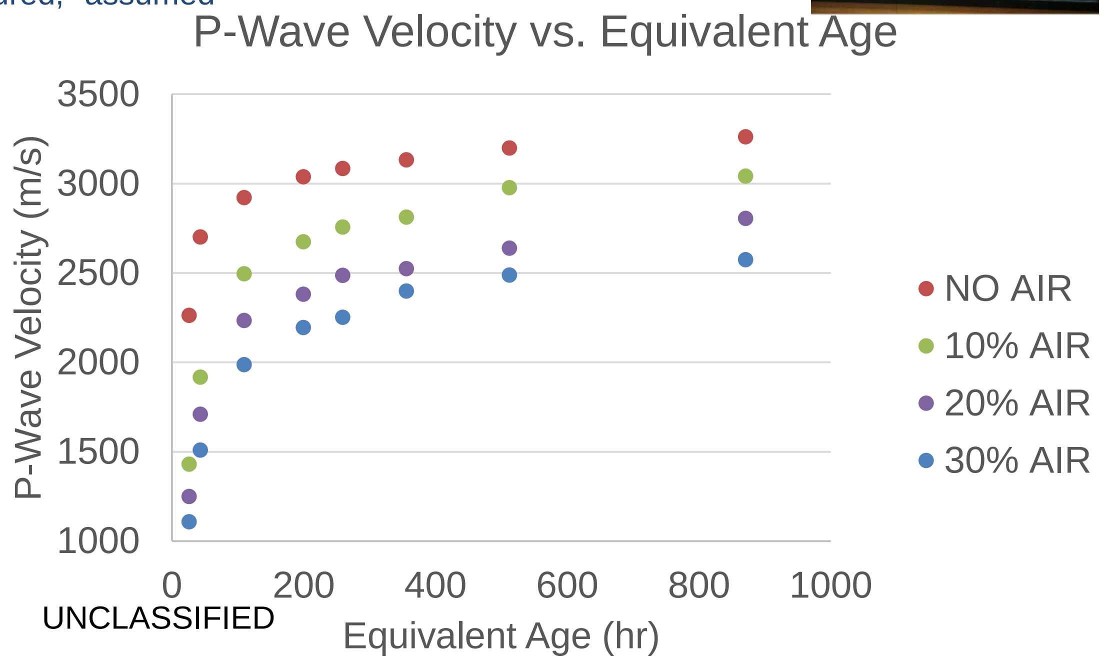
- Ultrasonic testing of Foamed Cement cylinder specimens with size approximately 25 mm (diameter) x 110 mm.
- Equivalent Age was calculated using the Arrhenius equation with an Activation Energy of 35,418 J/mol.

Case (Foam Quality)	0%	10%	20%	30%
P-Wave Velocity+ ($^m/_s$)	3371.5	3060.4	2877.6	2661.8
Mass Density+ ($^{kg}/_{m^3}$)	2120.9	1853.2	1650.3	1468.4
Poisson's Ratio*	0.18	0.18	0.19	0.2
Young's Modulus (GPa)	22.2	15.48	11.9	8.8

+ measured, *assumed

LANL got similar values.
Poisson ratio was determined to be ~0.25, using both longitudinal and shear propagation modes.
Large change in elastic moduli with air content → significant softening





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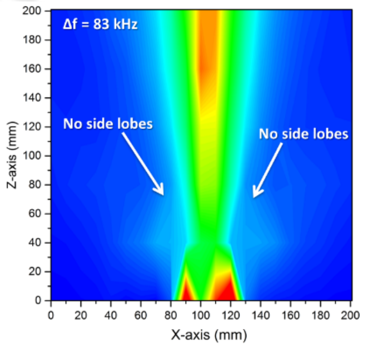
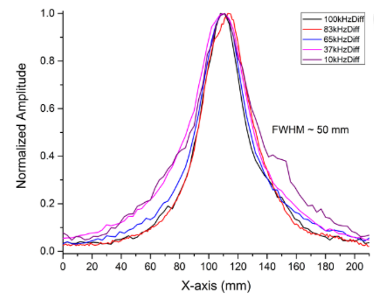
Scientific/Technical Approach
Acoustic Source

- **Parametric Acoustic Source**:
  - Low frequency (10-150 kHz)
  - Large bandwidth (140 kHz)
  - Frequency-independent beam width
  - No side lobes
  - Beam divergence < 6 degrees



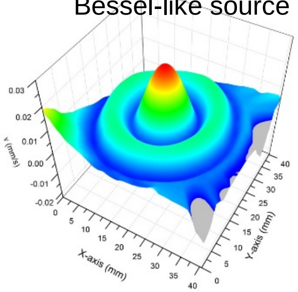
83 kHz difference frequency beam profile in H_2O



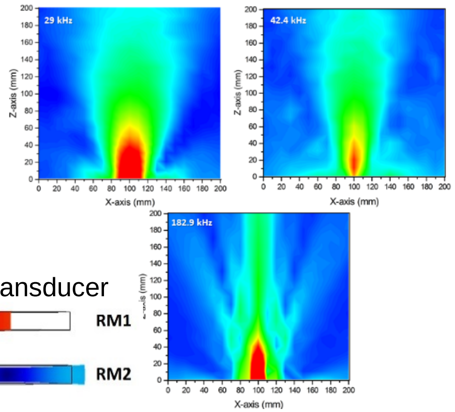
Scans of beam widths at 110 mm from transmitter in H_2O

- **Bessel-like Acoustic Source**:
  - Low frequency (10-150 kHz)
  - Large bandwidth (140 kHz)
  - Limited diffraction during propagation
  - Reduced side lobes

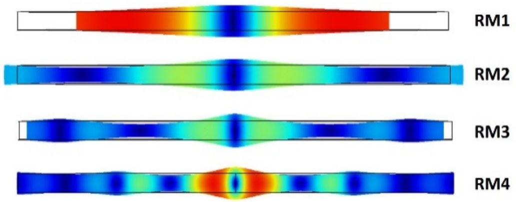
Transducer surface profile of a Bessel-like source



Examples for low-frequency beam profiles in H2O for a Bessel-like source



Radial modes of a Bessel-like transducer

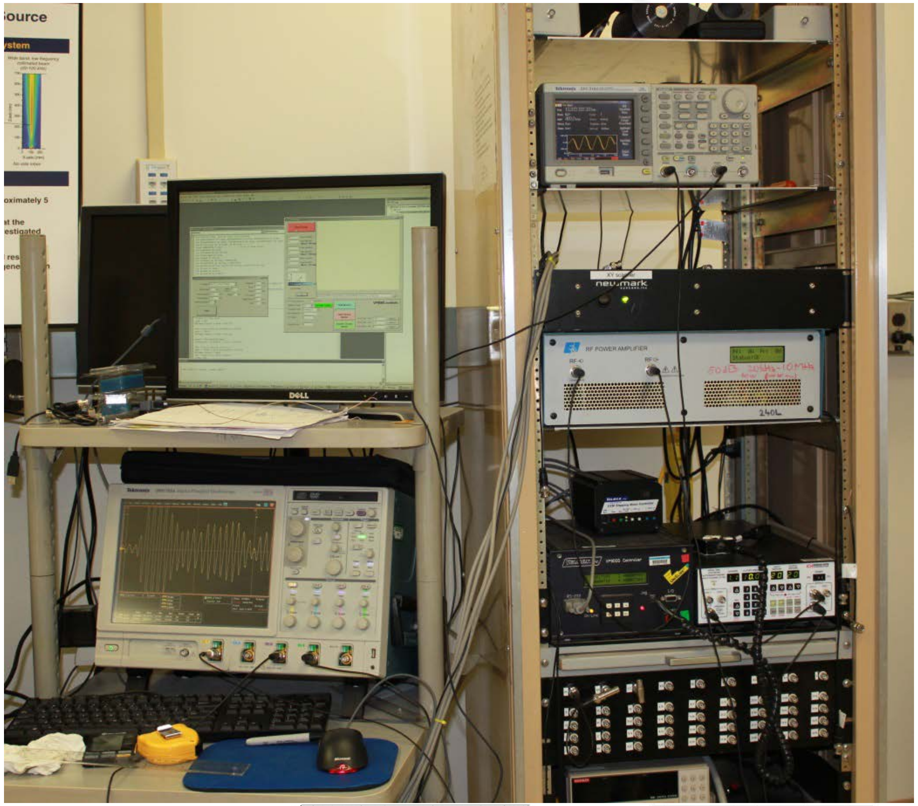


- **Compact Parametric Acoustic Source**:
  - Very compact source; can be fitted in boreholes 1-2 in ID
  - IP process underway

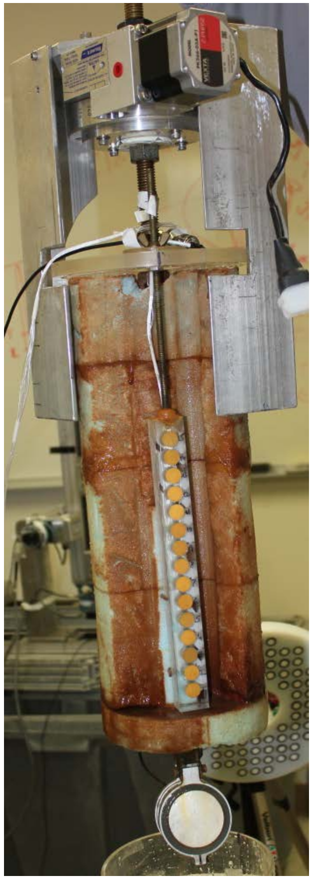
Scientific/Technical Approach
Measurement system

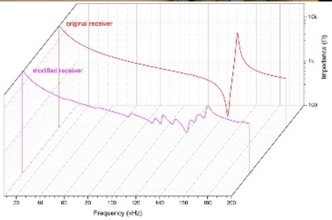
Simulated borehole:
metal casing embedded in cement.

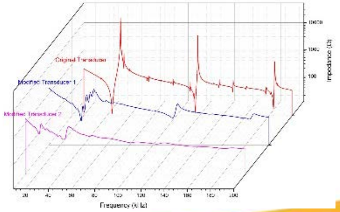
Electronics



Acoustic source
+
receivers array







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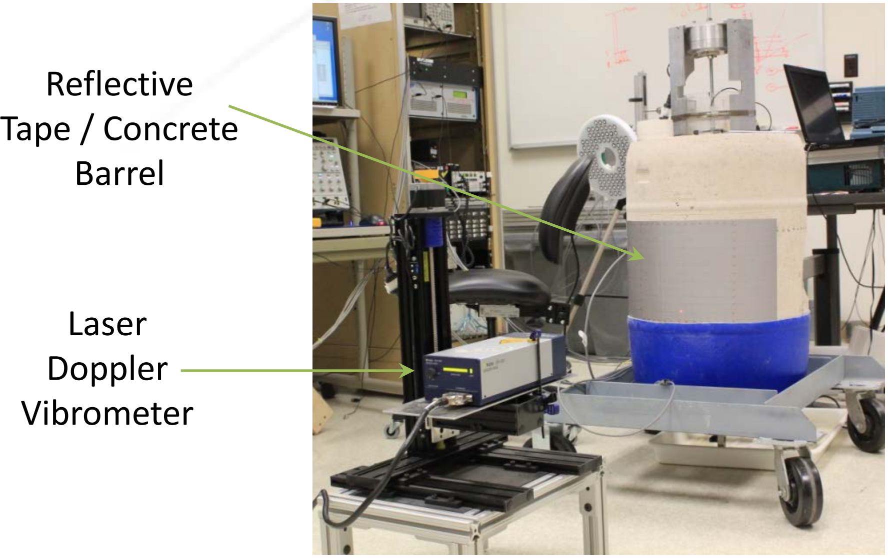
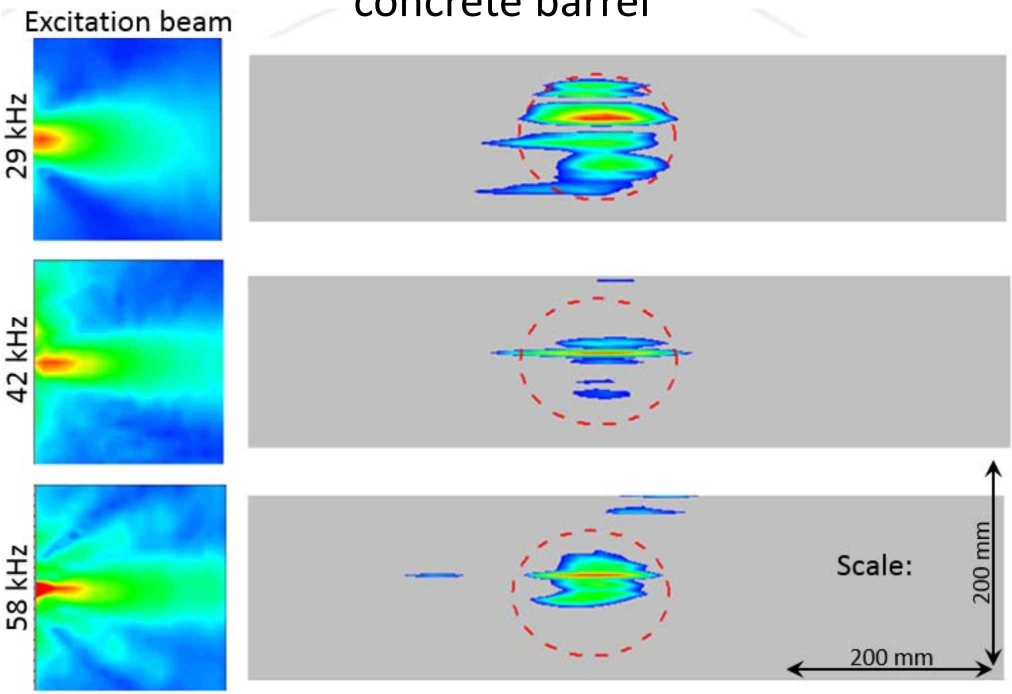
Scientific/Technical Approach
Beam pattern through concrete

Experimental setup for beam pattern determination after propagation through concrete

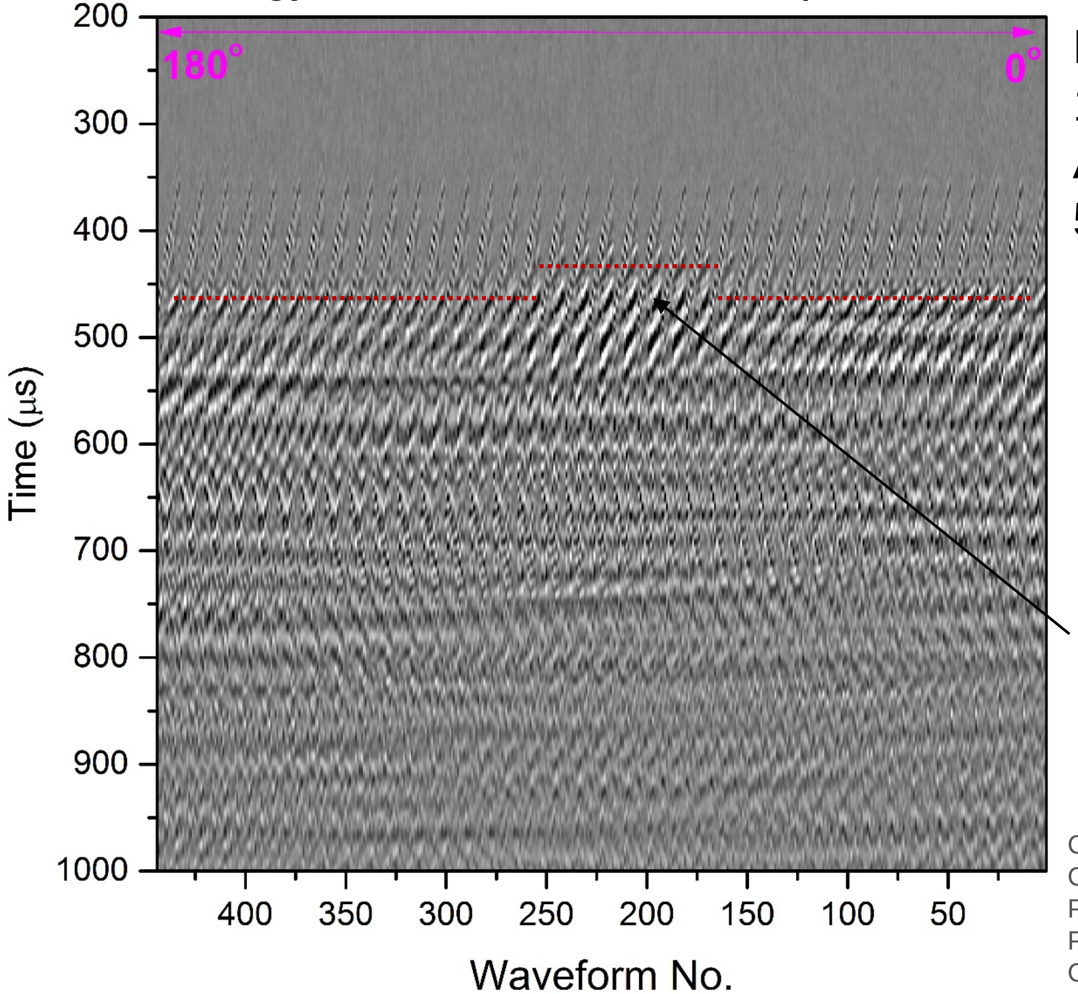


- 6 dB power beam pattern on the face of the concrete barrel

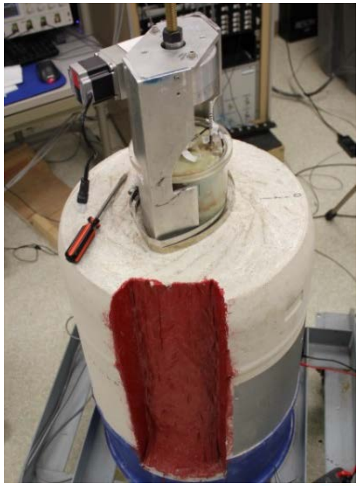


Scientific/Technical Approach
Imaging with parametric source

Open borehole configuration (Plexiglas-lined cement barrel)
Reflection seismology – Common azimuth representation



Excitation:
10-150 kHz Gaussian pulse
Azimuthal data collected every 5 deg, for a 180 deg span.



Cement OD: 477 mm
Cement ID:152 mm
Plexiglas pipe ID: 146 mm
Plexiglas pipe thickness: 3 mm
Groove depth: 50 mm

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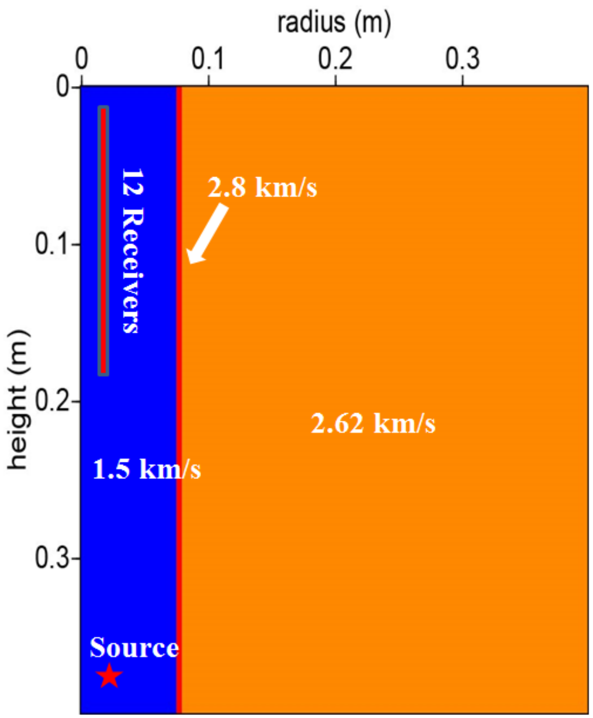
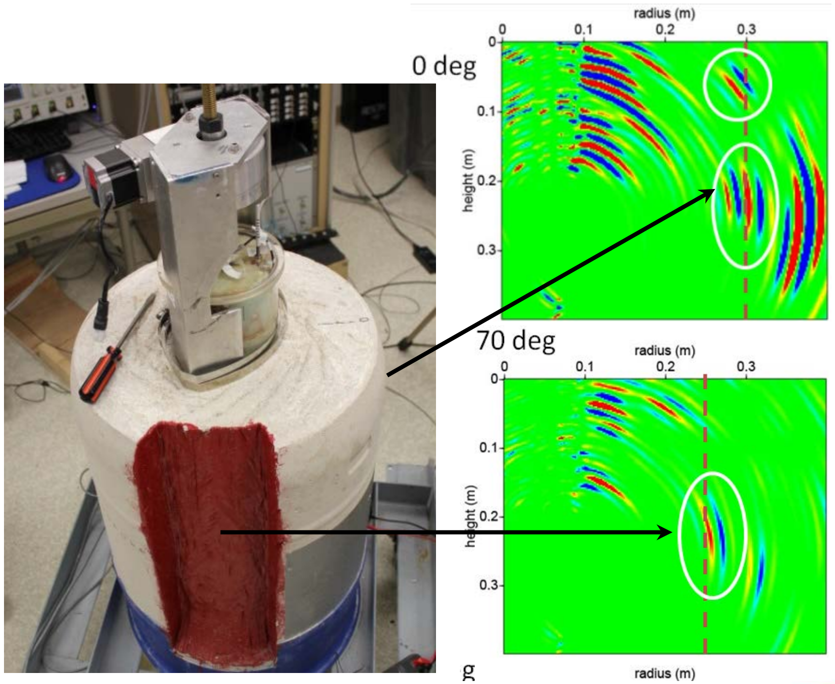
Scientific/Technical Approach
LANL image processing

Open borehole configuration (Plexiglas-lined cement barrel)
Least-squares reverse-time migration

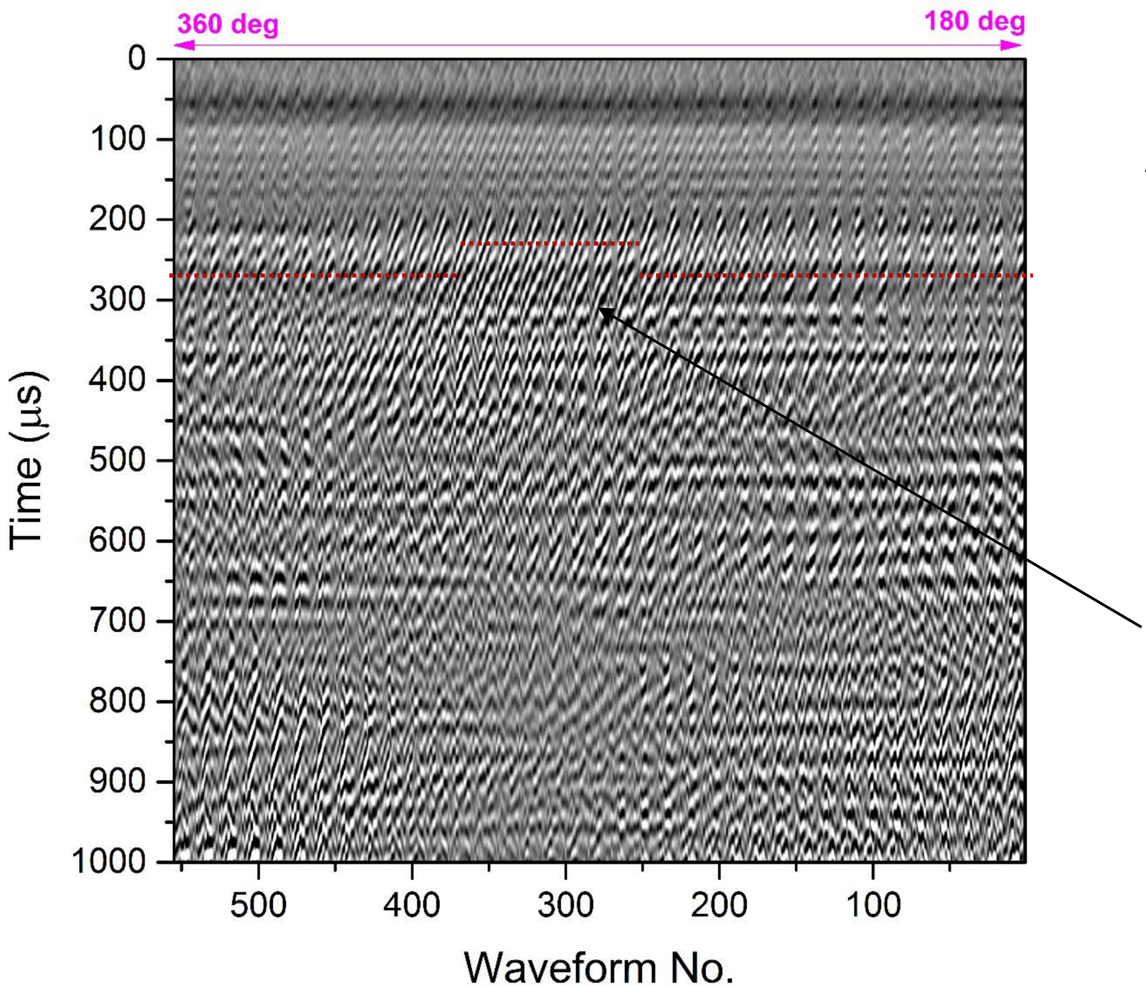
Excitation:
10-150 kHz Gaussian pulse
Azimuthal data collected every 5 deg, for a 180 deg span.



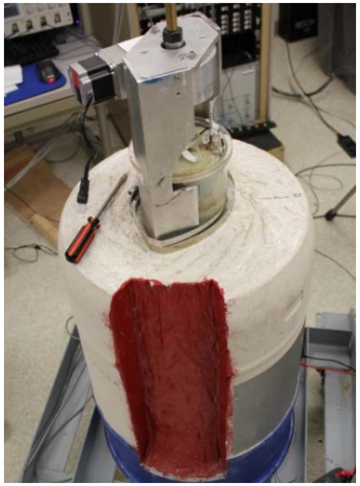


Scientific/Technical Approach
Imaging with Bessel-like source

Open borehole configuration (Plexiglas-lined cement barrel)
Reflection seismology – Common azimuth representation

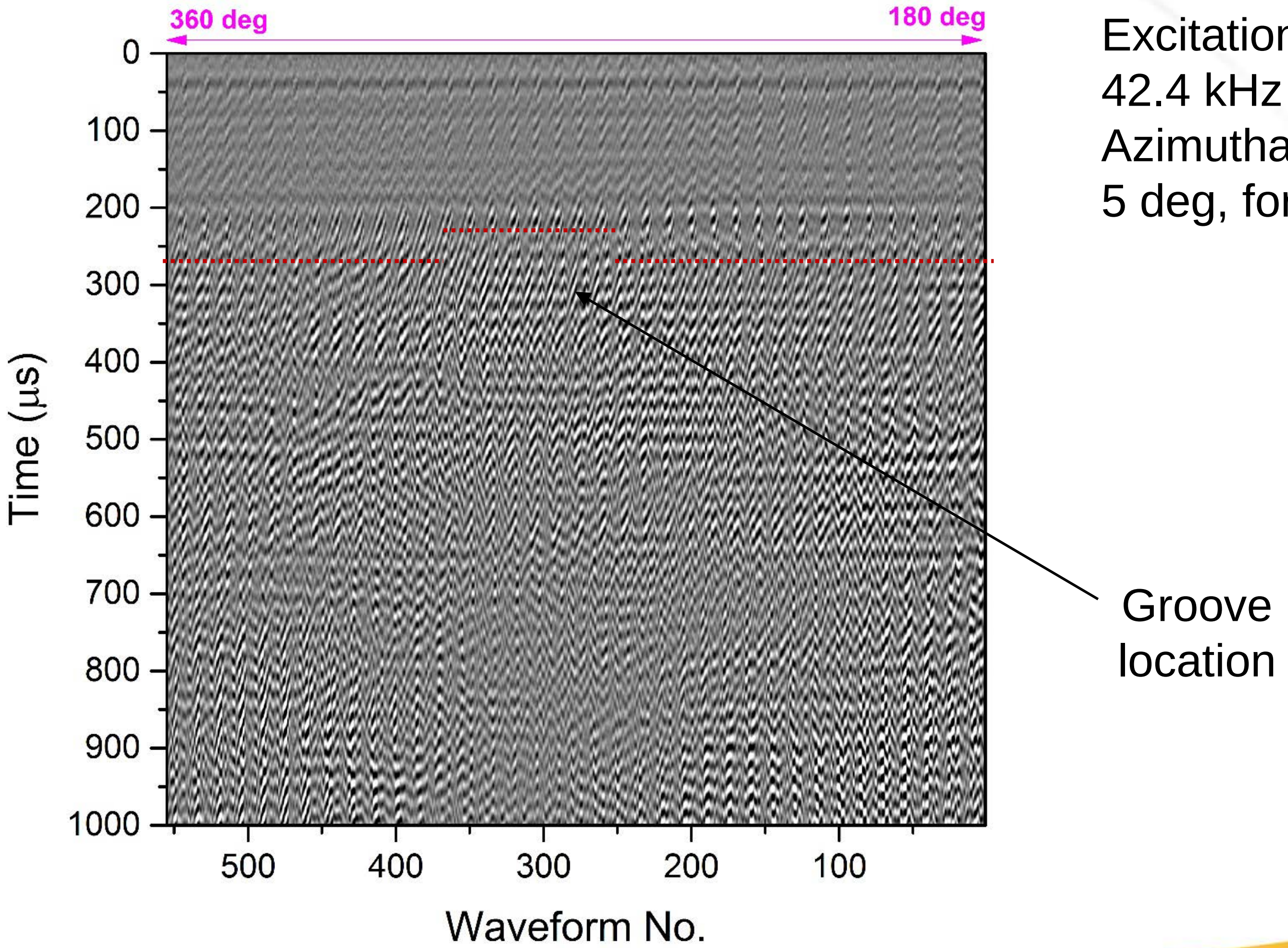


Excitation:
29 kHz shaped pulse
Azimuthal data collected every 5 deg, for a 180 deg span.

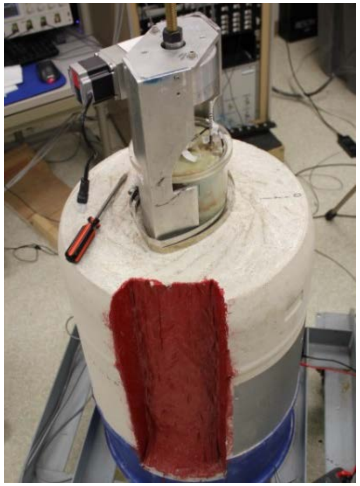


Scientific/Technical Approach
Imaging with Bessel-like source

Open borehole configuration (Plexiglas-lined cement barrel)
Reflection seismology – Common azimuth representation

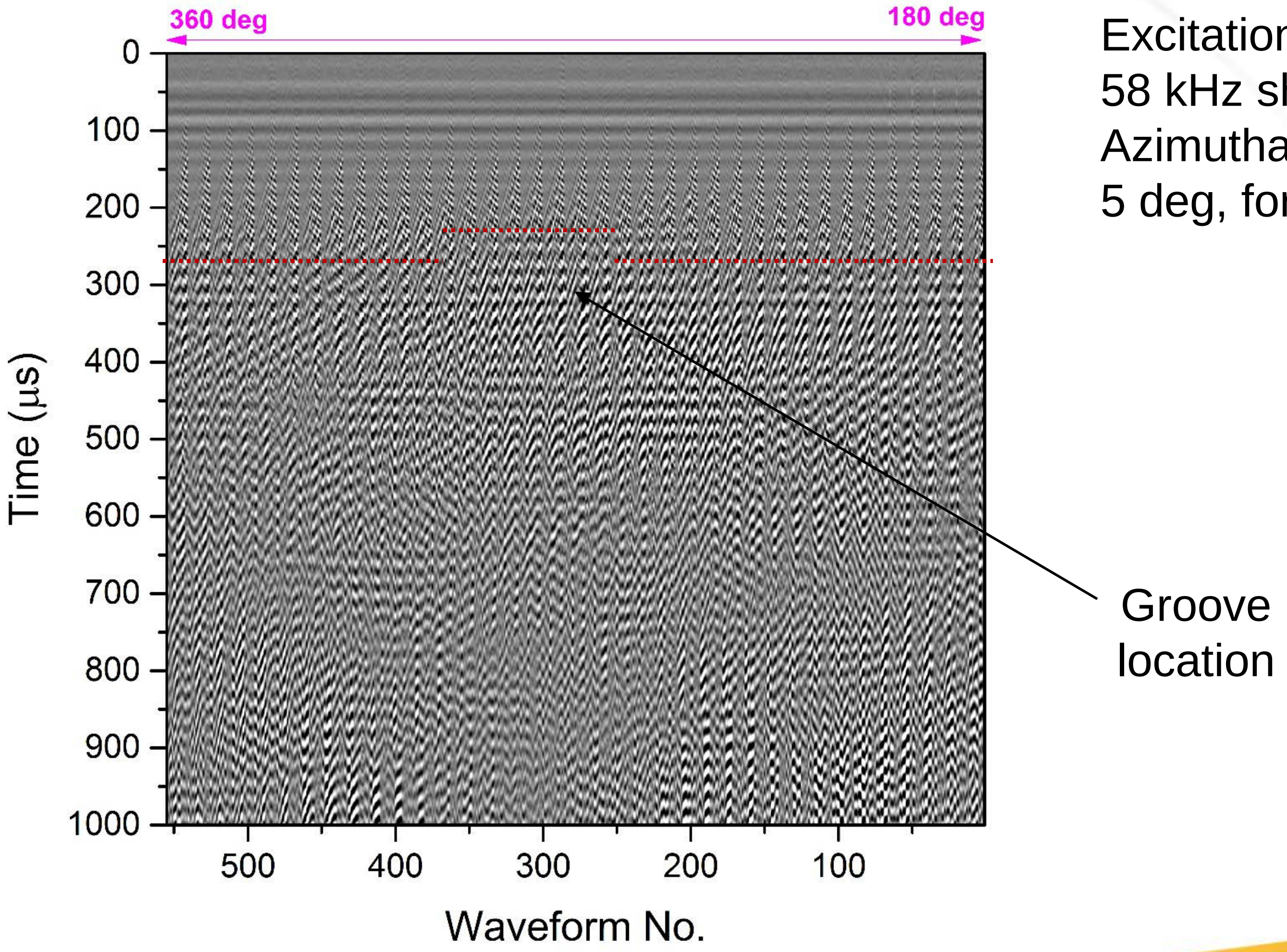


Excitation:
42.4 kHz shaped pulse
Azimuthal data collected every 5 deg, for a 180 deg span.

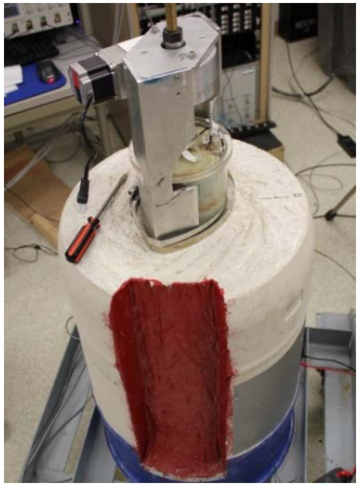


Scientific/Technical Approach
Imaging with Bessel-like source

Open borehole configuration (Plexiglas-lined cement barrel)
Reflection seismology – Common azimuth representation

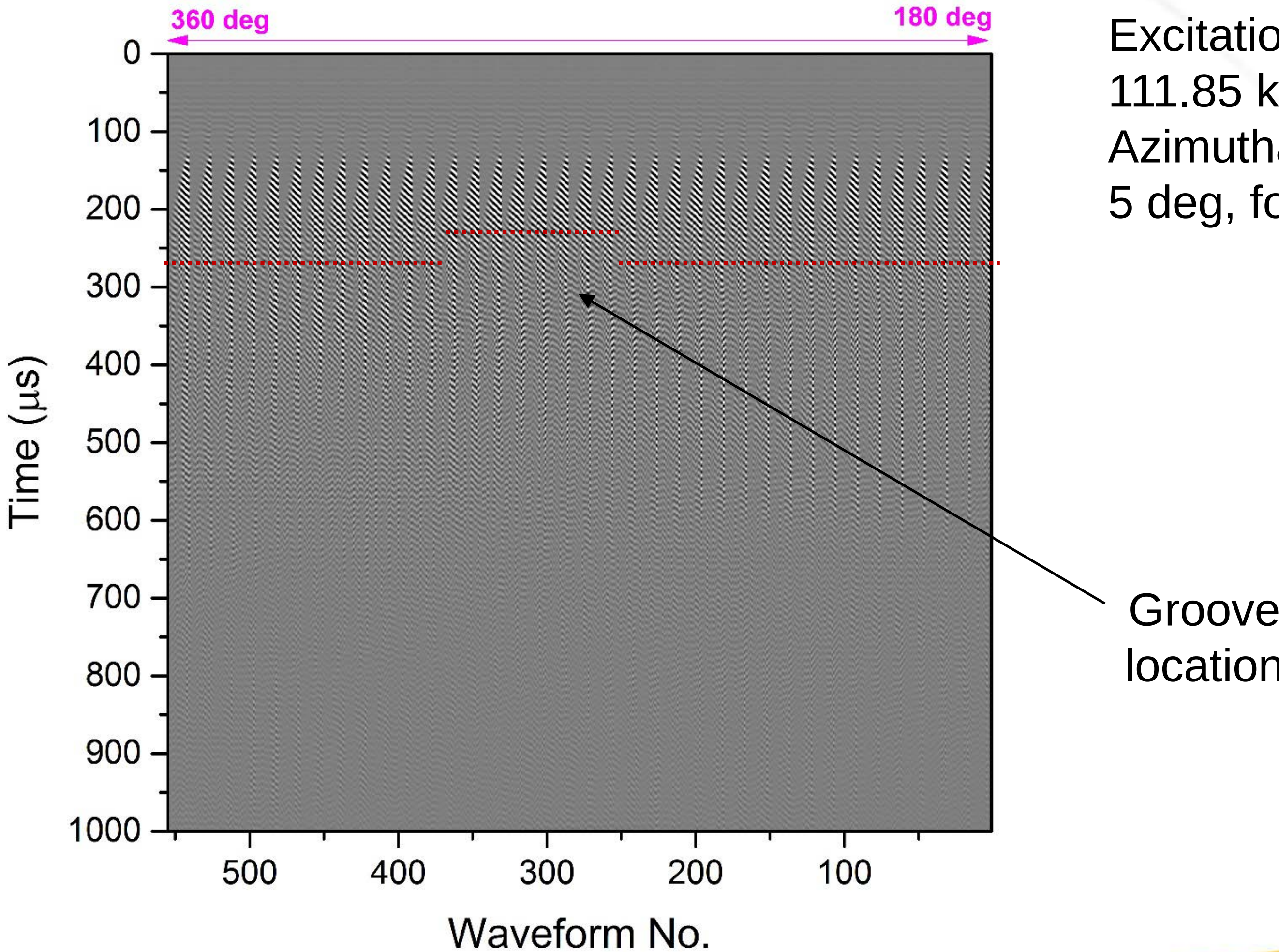


Excitation:
58 kHz shaped pulse
Azimuthal data collected every 5 deg, for a 180 deg span.

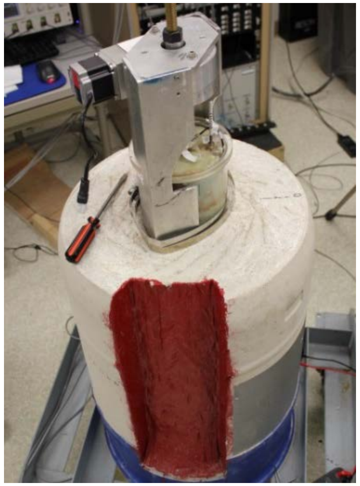


Scientific/Technical Approach
Imaging with Bessel-like source

Open borehole configuration (Plexiglas-lined cement barrel)
Reflection seismology – Common azimuth representation



Excitation:
111.85 kHz shaped pulse
Azimuthal data collected every 5 deg, for a 180 deg span.



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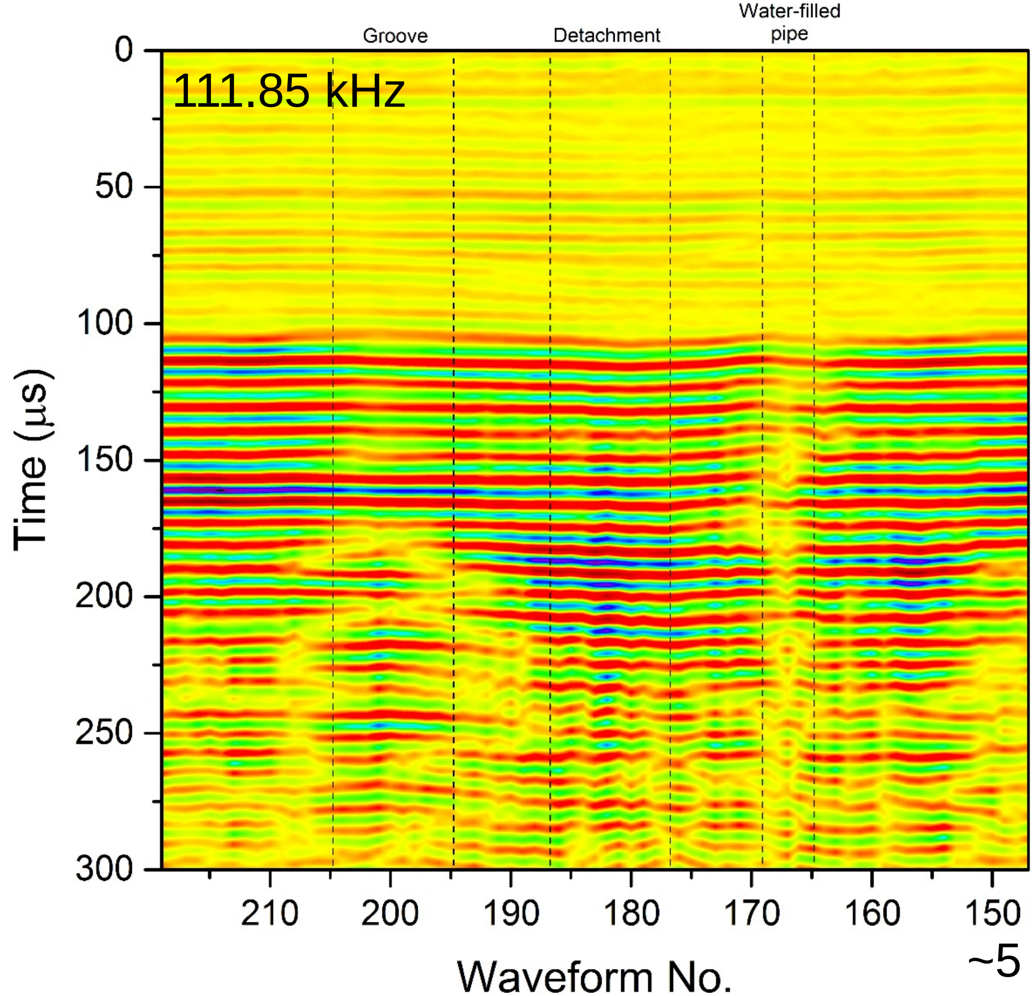
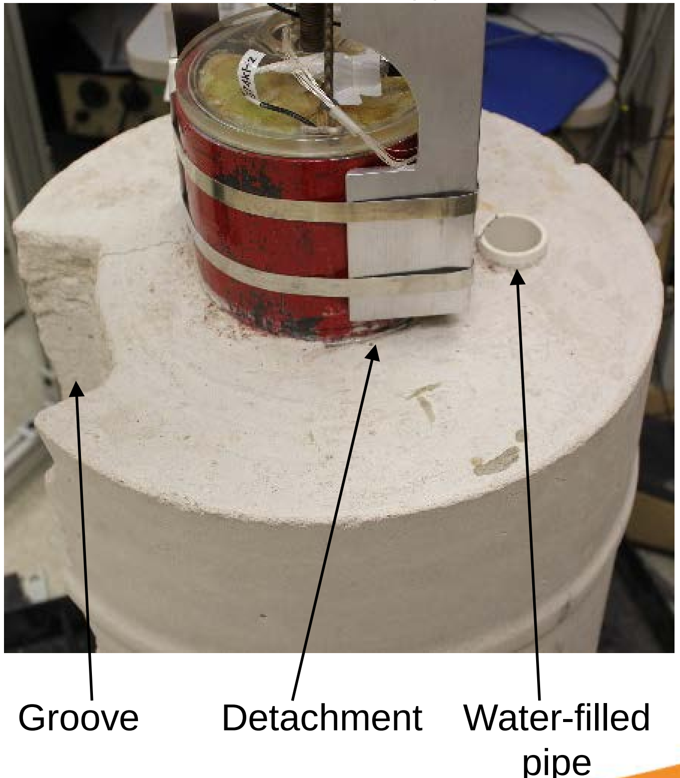
Scientific/Technical Approach
Defects detection – Bessel-like Source

Cased borehole configuration (Steel-lined cement barrel)
Reflection seismology – Common receiver representation



Cement OD: 460 mm
Cement ID:170 mm
Steel pipe ID: 148 mm
Steel pipe thickness: 10 mm
Groove depth: 50 mm
Plastic pipe location: 25 mm

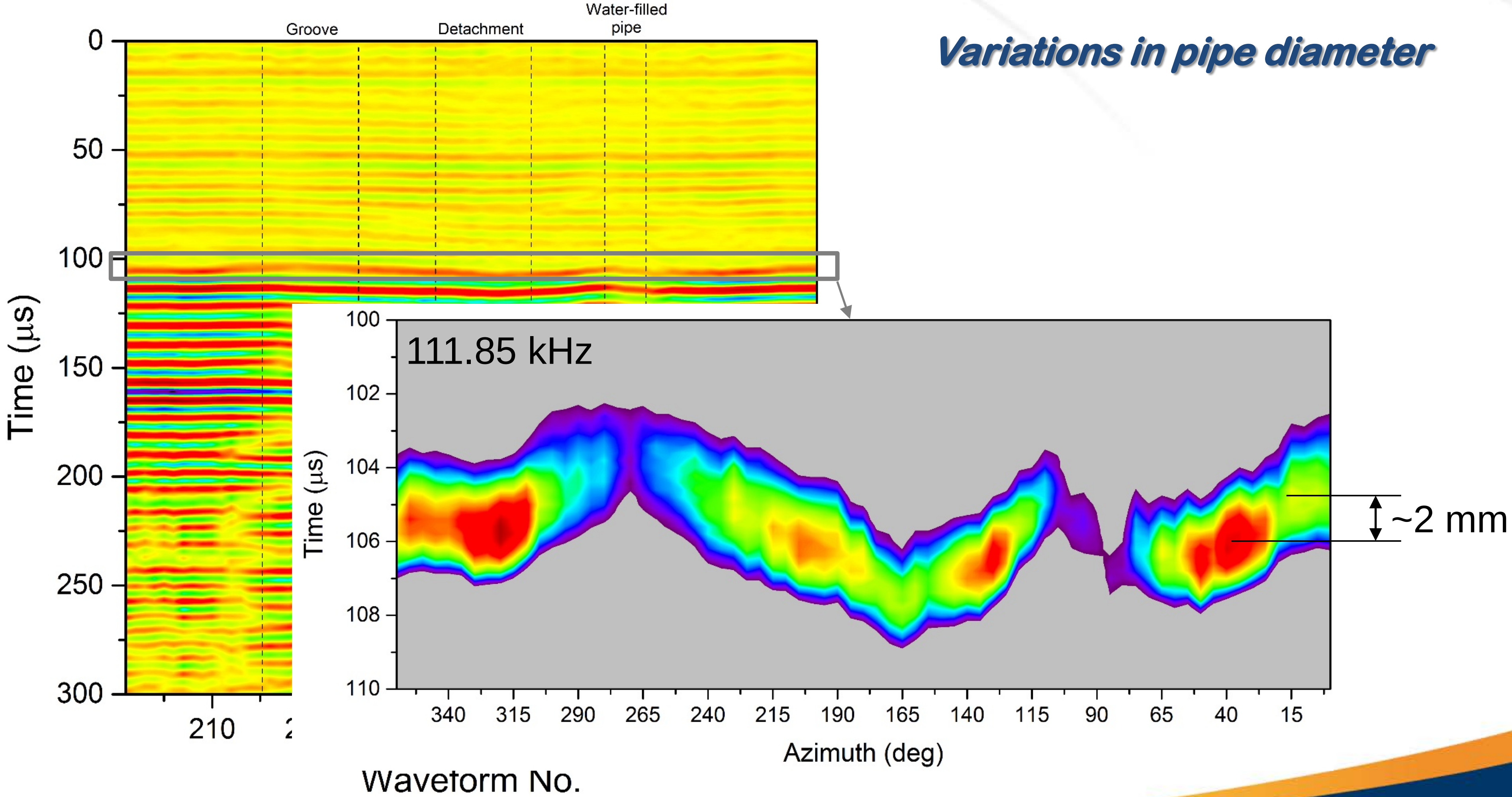


~5 deg azimuthal resolution

Scientific/Technical Approach
Defects detection – Bessel-like Source

Steel casing barrel – Bessel-like Source

Variations in pipe diameter



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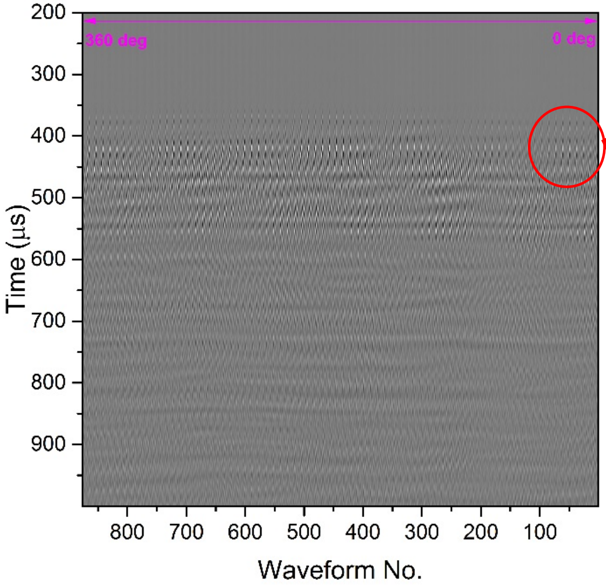
Scientific/Technical Approach
Resolution determination

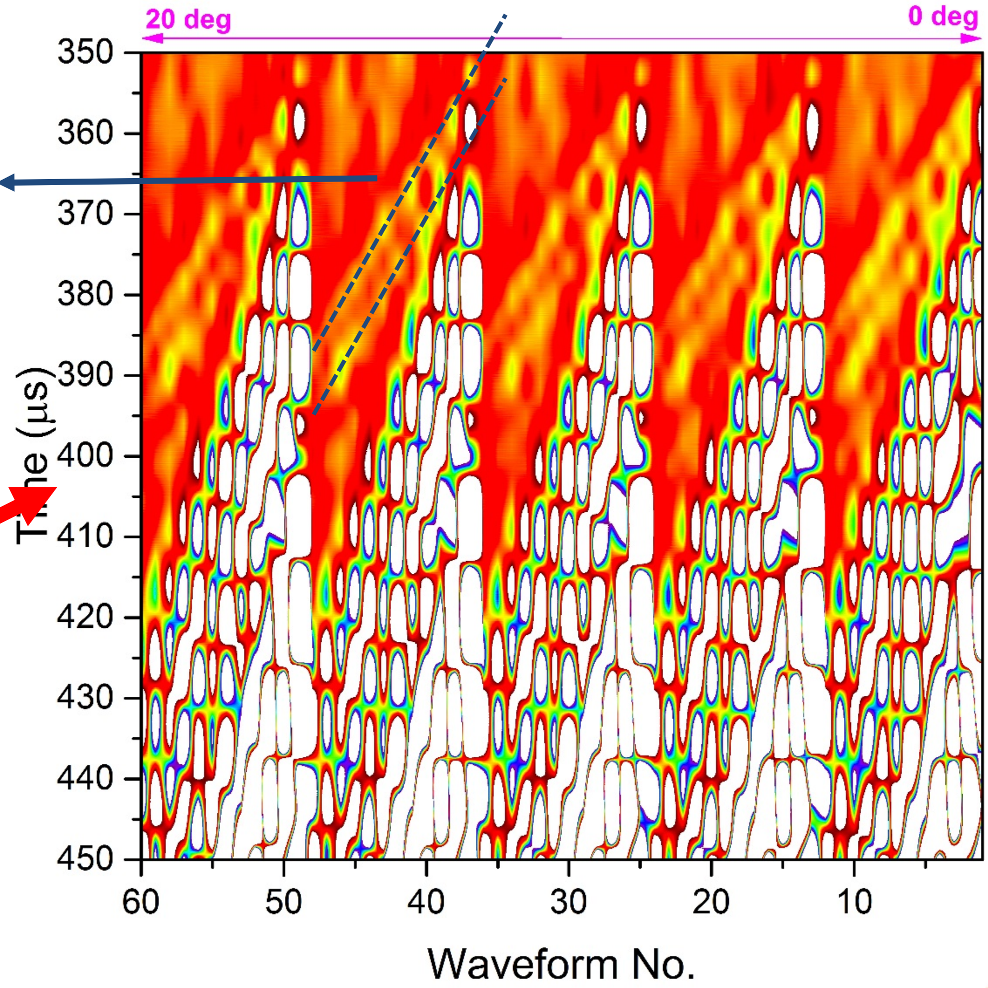
Steel casing barrel – Parametric Source

Calculations:

- Sound speed: ~5.8 km/s
- Thickness: ~10 mm

→ ***Steel***





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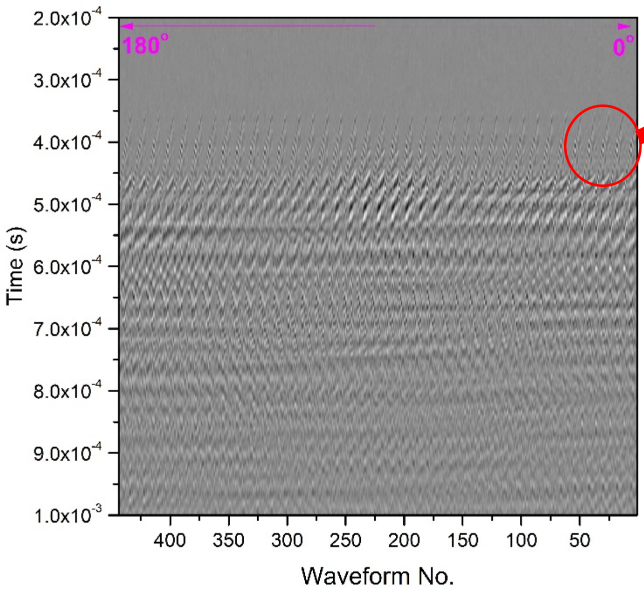
Scientific/Technical Approach
Resolution determination

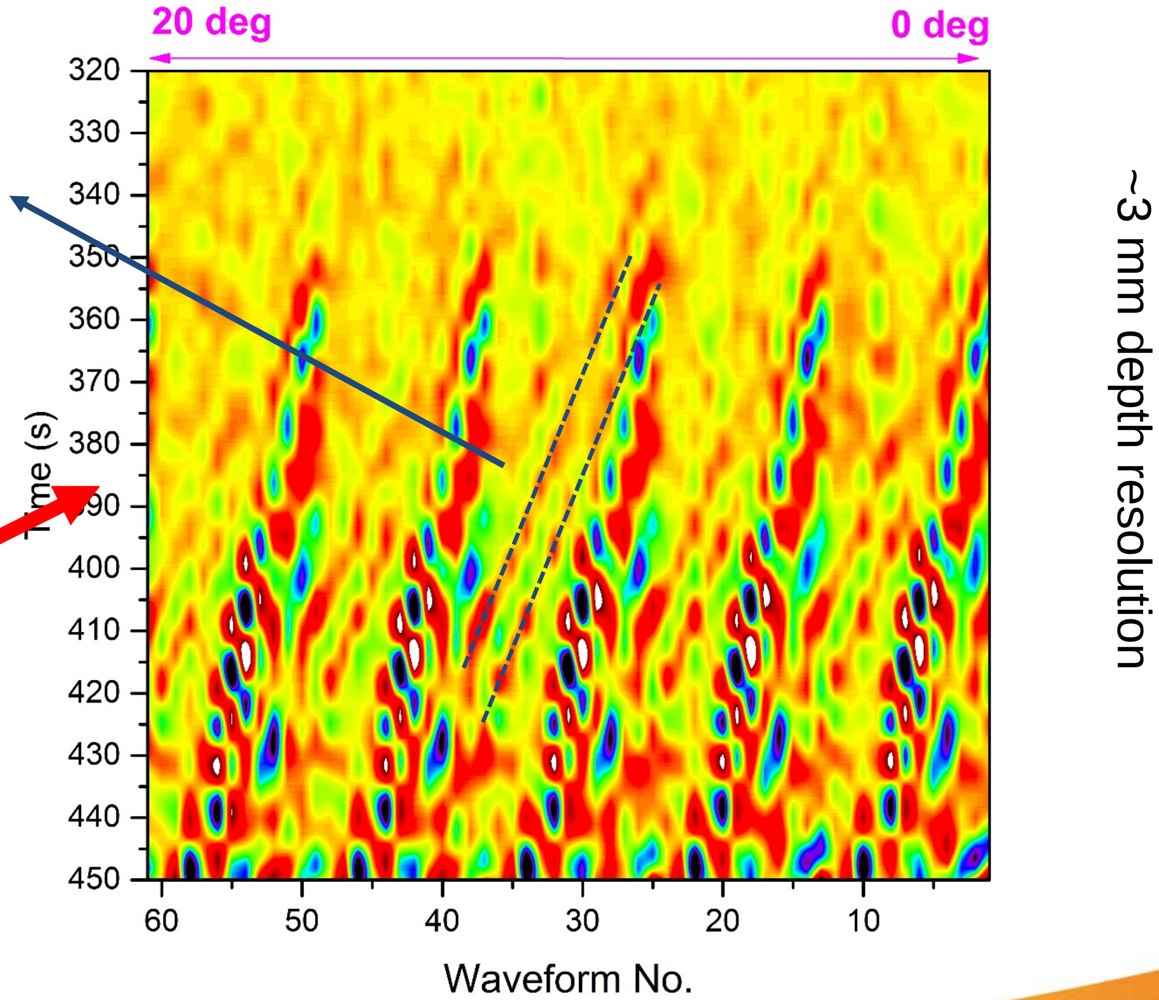
Plexiglas casing barrel – Parametric Source

Calculations:

- Sound speed: ~2.8 km/s
- Thickness: ~3 mm

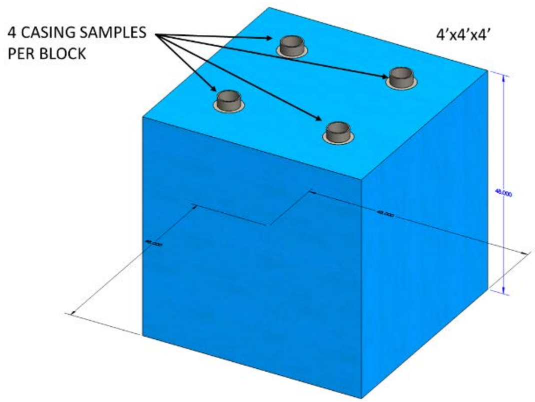
→ ***Plexiglas***





Scientific/Technical Approach
Granite Block Samples – Sandia National Laboratory

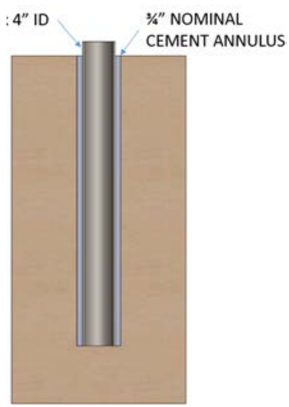
Rock sample in drilling facility



Targeted Casing Defects:

- **Wall thinning**
  - **Pre-machine thin section in casing prior to cementing**
- **Casing eccentricity**
  - **Offset casing with jig during cementing**
- **Channeling**
  - **Removable insert**
- **Delamination**
  - **Thin-layer Silicone insert**

4 holes: 6" dia x ~40.5" deep



Quartered Granite block

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Summary

- Built and experimentally validated three different acoustic sources that provide a collimated beam of low frequency.
- Beam collimation is maintained after passing trough an inhomogeneous scattering medium (concrete barrel).
- Gained insight in understanding foamed cements, by determining elastic properties and performing CT scans.
- Demonstrated imaging capabilities of the system, in both open- and cased-borehole, for different induced defects (groove, detachment, fluid-filled pocket, casing).
- Determined a depth resolution as low as 3 mm, with an azimuthal resolution better than 5 degrees.
- Long-term plan: refine and enhance the capabilities of the 3D imaging system for more realistic environments, and extended investigation range beyond the wellbore casing.