Report No. 10446

Seismic in the Drilling Workflow: MinEx CRC Project 5 – Phase 2

Results of research carried out as MRIWA Project M10446

at Curtin University and MinEx CRC

by

Konstantin Tertyshnikov, Emad Al-Hemyari, Pavel Shashkin, Olivia Collet, Roman Pevzner, Roman Isaenkov and Andrej Bona

DOI 10.71342/625067501794

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Acknowledgements

MINISTER FOR MINES AND PETROLEUM
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REFERENCE
The recommended reference for this publication is:
Tertyshnikov, K., Al-Hemyari, E., Shashkin, P., Collet, O., Pevzner, R., Isaenkov, R., and Bona, A., 2025, MinEx CRC Project 5, Phase 2: Seismic in the Drilling Workflow. *MinEx CRC Report 2025/54.* Report DOI 10.71342/625067501794

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SPONSORING ORGANISATIONS
Anglo American Exploration (Australia) Pty Ltd, BHP Pty Ltd, The Minerals Research Institute of Western Australia, Rio Tinto Technological Resources Pty Ltd, MinEx CRC

ABOUT THIS PUBLICATION
This publication presents the results of work carried out under Project 2 of the Mineral Exploratioin Cooperative Research Centre (MinEx CRC) in relation to Commonwealth Milestone RP2.3.3: Report on instrumented field case study 1 completed. Recommended instrumentation and workflow required to establish instrumented field at other locations.

Report DOI 10.71342/625067501794

KEYWORDS AND TAGS
Mineral exploration, exploration technology, drilling, geophysics, seismic

Published 2025 by the Minerals Research Institute of Western Australia
This report is published in digital format (PDF) and is available online at
https://www.mriwa.wa.gov.au/research-projects/project-portfolio/

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1. Introduction

1.1 Mineral Exploration Cooperative Research Centre

The Mineral Exploration Cooperative Research Centre (MinEx CRC) is the world's largest collaborative mineral exploration research venture. The CRC brings together thought leaders from industry, government and research organisations to discover and develop innovative technologies and methods to support the future success of Australia's mineral resources industry.

Over its 10-year lifetime from 2019 to 2029, the CRC's two-fold aims are:

1. To turn successful research outcomes into mining innovation, including integrating technological and business innovation to significantly improve Australia's mining competitiveness and manufacturing capabilities, and;
2. To facilitate commercialisation of intellectual property developed through the work of the CRC in such a manner as to ensure maximum benefit accrues to Australia, including the Australian mining industry, Australian manufacturing, the Australian environment and the Australian economy generally.

The activities of the CRC are organised under 3 primary research programs

1. Drilling Technologies – Developing engineering solutions to improve the productivity and safety, and reduce the cost and environmental impact of exploration drilling.
2. Data from Drilling – Developing and improving technologies for the capture and interpretation of geochemical, petrophysical and geophysical data during drilling to support timely decision-making within the exploration workflow.
3. National Drilling Initiative – Delivering drilling programs – including through the use of novel technologies developed by the MinEx CRC – to map regional geology and architecture to define mineral systems potential in areas of Australia where known prospective geology is concealed beneath cover rocks.

1.2 MRIWA Support of the MinEx CRC

The Minerals Research Institute of Western Australia (MRIWA) supports the work of the MinEx CRC in line with the Institute's priority of addressing the challenges of making significant new mineral discoveries in Western Australia.

MRIWA supports specific research projects under this participation framework identified as offering the potential to systematically advance knowledge and capability to improve mineral exploration productivity through detection, exploration technology and prediction performance.

In doing so, MRIWA aims to stimulate research outcomes that will inform the pre-competitive geological, geochemical and geophysical knowledge base of Western Australia and create exploration capability to:

- Position Western Australia as a global leader in exploration technology, and;
- Facilitate private sector investment in existing and newly identified Western Australian mineral provinces to develop the State's rich natural resources.

2. Research Context

Resolving the nature and geometry of subsurface geological layers can make a valuable contribution to mineral exploration by helping define and target domains of potential mineralisation (Urosevic *et al.,* 2007; 2016). Modern mineral exploration is dominated by the use of invasive drilling to access and sample below the surface. By improving technologies for the non-invasive imaging of buried geology, we could reduce the amount of drilling needed to discover and characterise buried mineral systems.

Seismic imaging is essentially unchallenged over a very large depth range in its capacity to provide clear images of subsurface structures, and in particular is uniquely effective in resolving complex structures (Stolz *et al*., 2004; Milkereit *et al.,* 2000; Pretorius *et al*., 2011, Urosevic *et al.,* 2017). However, factors including inconsistent application of seismic reflection methodologies, a lack of adequate software for integrating seismic data with other geophysical, geological and mining information, and a lack of experienced seismic analysts working in the mining sector have long prevented seismic surveying from becoming a mainstream exploration method.

This project will support the development of more efficient and cost-effective methods for using seismic sensors to enhance understanding of rocks and structural features concealed beneath the surface. By increasing the amount of data gathered from each drillhole and helping to visualise the surrounding geology in 3-dimensions, this technology is intended to reduce the number of drillholes required to test potentially mineralised targets, making it cheaper and easier to discover and develop ore bodies hidden deep below the surface.

To address these issues, MinEx CRC Project 5 incorporates three linked streams of research:

1. Improvement of the performance and reduction of the environmental footprint of established borehole seismic sensing methods;
2. Development of methods for reducing the cost and environmental footprint of surface seismic sensing, and;
3. Development of methods for rapid seismic data acquisition and subsurface characterisation.

Over the life of the MinEx CRC, this research is intended to deliver the following outcomes:

- Reduction in the cost of borehole seismic surveying by 50%
- Development of new and improved seismic sensing and interpretation technologies delivering a 50% reduction in the drilling needed for brownfields exploration
- Implementation of a fully instrumented demonstration field at a participating organisation, incorporating deployment of seismic sensor technologies in boreholes, underground workings and on the surface to deliver data supporting continuous updating of a subsurface geological model for mine planning and safe operation.

3. Potential Value to Western Australia

Mineral exploration and discovery represent the foundations of Western Australia's successful mining sector. Maintaining the productivity of this key industry into the future will require the discovery and characterisation of ore bodies deeper below the surface and hidden from traditional methods of discovery, pushing industry to reduce both the cost and the environmental footprint of exploration technology.

By lowering the cost of seismic sensing to within the limits of routine mineral exploration budgets and improving the accuracy and quality of information returned, the improved seismic sensing technology which this research aims to develop could reduce the amount of drilling required to identify and define buried mineralisation. In addition to making it cheaper and easier to explore across the widespread covered areas of WA, this improved drilling efficiency would reduce the environmental impacts of mineral exploration in remote and sometimes ecologically fragile areas of the State.

4. Project Structure

Improved seismic sensing and interpretation packages delivering the anticipated benefits to mineral exploration are intended to be developed through three staged phases of research over the life of the MinEx CRC. MRIWA Project M10446 represents Phase 2 of this development program (Fig. 1).

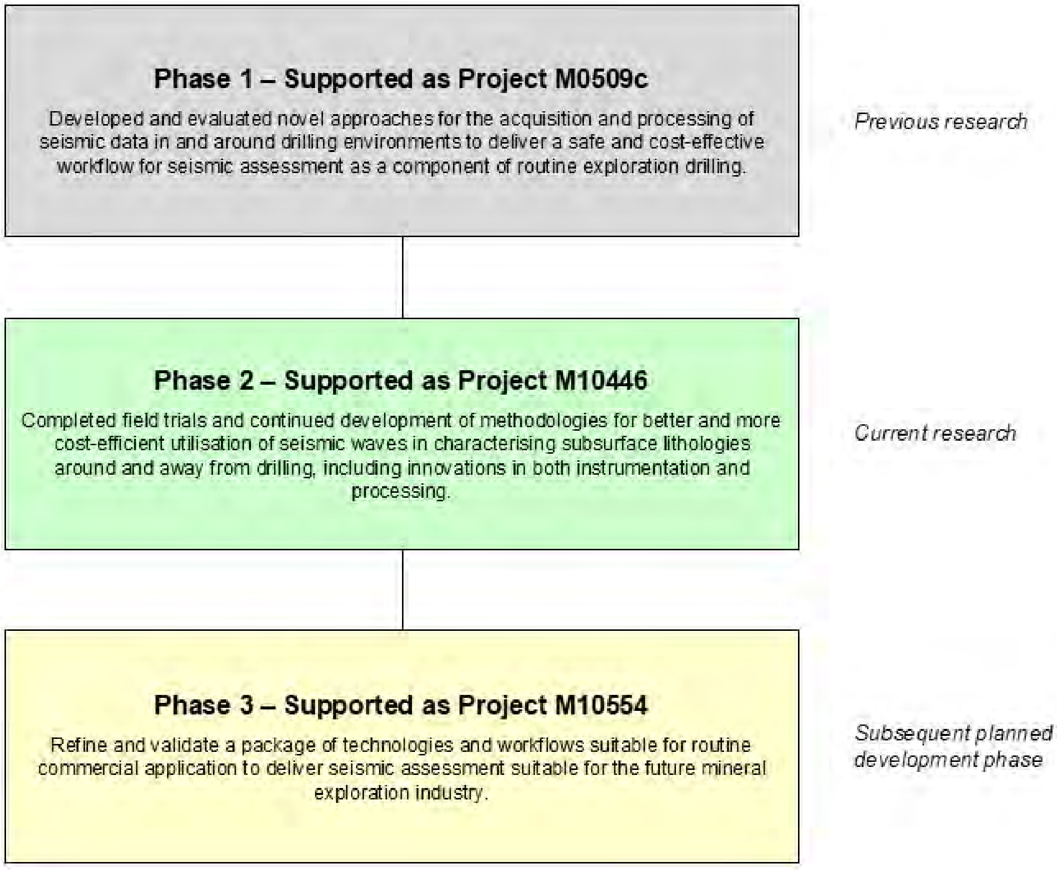

Figure 1: *Phased development plan for MinEx CRC Project 5. The work supported by MRIWA as M10446 comprises Phase 2 of this program.*

5. Overview of Project Outcomes

As summarised in **Appendix 1**, ten deployments undertaken at a range of field locations and active mine sites are used to explore different combinations of seismic sources, acquisition geometries, fibre optic cable types, interrogators and processing methods. Together these field studies provide an overview of the challenges and advantages of fibre optic distributed acoustic sensing (DAS) and associated technologies compared to conventional seismic techniques in mineral exploration and mine settings.

DAS provides high resolution, rapid acquisition of active data and, where necessary, continuous data acquisition along entire boreholes. These properties support the mapping and characterisation of ore bodies and geology surrounding instrumented holes, thereby contributing to both stream 2 (reducing the cost and environmental footprint of seismic sensing) and 3 (rapid seismic data acquisition and subsurface characterisation) of project research.

In initial trials of multi-hole instrumentation, the system demonstrated the viability of cross-hole geological characterisation (mapping structures, ore bodies and other geologically distinct features between drill holes), and monitoring dynamic change in rock properties (e.g., through injection of fluid or gas from the drill hole, or changes due to fracture and ground disturbance caused by mining operations).

Use of fibre optic cable eliminates the need for multiple discrete sensors, allowing the recording of high-resolution data at unprecedented spatial sampling intervals with broad frequency band sensitivity, while at the same time minimising operational costs and time required for array installation and data acquisition. Fibre optic sensors offer further advantages over traditional sensors including durability, minimal space requirements, and the ability to leverage existing telecommunications infrastructure for cost-effective deployment. These attributes make fibre optics a preferred choice for long-term monitoring deployments in harsh environments.

Installation of optical fibre sensing arrays can be easily adapted for a variety of geometries and deployment methods, including cementing behind borehole casing, tubing-conveyed deployment, and wireline suspension, offering flexibility based on site-specific requirements.

The project research team released an open-source library of pre-trained neural networks for reducing the instrument noise (e.g., electronic and thermal) inherent to each DAS recording system. These de-noising algorithms are developed in Python and can be implemented in commercial QC software for real-time application during data acquisition, providing significant improvements in noise reduction and seismic event detection.

Instrument noise patterns vary dramatically between different interrogator unit designs so this library will need to be continuously updated with models for different instrument architecture and recording parameters.

Continuous data collection with fibre arrays enables real-time analysis and feedback, providing an effective basis for the technology to monitor geotechnical hazards and mine operations, as well as allowing subsurface characterisation using passive seismic energy to support adaptive exploration strategies and decision-making during drilling operations. The greater speed of acquisition and smaller seismic sources required for DAS arrays also reduces the environmental footprint of deployment.

Under the relevant contractual terms governing this research, intellectual property (IP) created through the project is owned legally by MinEx CRC, and owned beneficially by the Project Parties – including MRIWA on behalf of the WA State Government – in accordance with their respective Project Contributions.

MinEx CRC is currently working with seismic service provision companies (HiSeis and Southern Geoscience) to assess the commercialisation potential of the technologies and intellectual property developed in this work as a complement to their existing businesses. In parallel MinEx CRC is also considering the potential of a spin-out company from Curtin University.

A provisional patent application has been lodged, covering the novel three-component seismic source developed through this project.

Any enquiries as to the technical detail of the project outcomes and current disposition of relevant IP should be directed to Professor David Giles, Chief Scientific Officer of the MinEx CRC.

6. Future Research

In line with the staged research plan outlined in Section 4 above (Fig. 1), the outcomes of this project are being further developed by the MinEx CRC research team in a third-and-final phase of work.

Supported by MRIWA as Project M10553, this third phase intended to deliver market-ready fibre optic DAS seismic technologies that will reduce the cost and increase the efficacy of seismic methods in mineral exploration.

7. Project Sponsors

Funding for this project was provided by the following sponsor organisations:

- Anglo American Exploration (Australia) Pty Ltd
- BHP Pty Ltd
- Rio Tinto Technological Resources Pty Ltd
- Sercel
- The Minerals Research Institute of Western Australia (MRIWA)
- MinEx CRC

8. References

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Urosevic, M., Ziramov, S., Kinkela, J., and Dwyer, J., 2016, Seismic exploration of mineral resources – an Australian prospective: The first conference on geophysics for mineral exploration and mining, Proceedings; We Min PO5.

Urosevic, M., Bona, A., Ziramov, S., Pevzner, R., Kepic, A., Egorov, A., Kinkela, J., Pridmore, D., and Dwyer, J., 2017, Seismic for mineral resources – a mainstream method of the future: Exploration 07: Seventh Decennial International Conference on Mineral Exploration, Toronto, Canada.

Appendix 1

MinEx CRC Report 2022/35

Submitted as Commonwealth Milestone Report for Project 5: Seismic in the Drilling Workflow

June 2025

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Commonwealth Milestone Report

Project 5: Seismic in the Drilling Workflow

Commonwealth Milestone RP2.3.3

Report on instrumented field case study 1 completed. Recommended instrumentation and workflow required to establish instrumented field at other locations.

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Compiled by:
David Giles
CSO MinEx CRC, University of South Australia

Date: June 2025

MinEx CRC Report 2025/54

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Australian Government
Department of Industry, Innovation and Science

Business Cooperative Research Centres Program

* Consent for release provided by MinEx CEO 21/05/2026

EXECUTIVE SUMMARY

This document is a compilation of three end-of-year Project Review Panel presentations and one technical report produced by researchers within MinEx CRC Project 05 Phase 02 (Petrophysics for Mineral Discovery During Drilling). Together these presentations demonstrate progress towards and completion of Commonwealth Milestone RP2.2.3: Report on instrumented field case study 1 completed. Recommended instrumentation and workflow required to establish instrumented field at other locations.

The materials are presented in chronologic order to demonstrate progression of the underlying science and technology. Although the Commonwealth Milestone requires completion of only one instrumented field case study, we report on ten case studies – nine in the November 2024 technical report and one in the Q4 2022 Project Review Panel presentation (a collaboration with Rio Tinto that does not feature in the summary technical report). Multiple case studies were chosen due to the requirement test and apply different combinations of seismic sources, acquisition geometries, fibre optic cables, interrogators and processing methods unique to each case study scenario.

Generalised advice on the selection of appropriate instrumentation and workflows (as required by the Commonwealth Milestone) in provided in Sections 3 to 7 of the November 2024 technical report.

1. MinEx CRC Project 05 Phase 02: Fourth quarterly Project Review Panel meeting Q4 2022 (December 2022)

Presents survey design, acquisition methodology and results from a fibre optic DAS instrumented field site in the Pilbara region of Western Australia, conducted in collaboration with MinEx CRC Partner Rio Tinto (slides 4 to 15). This case study tested the potential to use fibre optic DAS cable as a seismic "land streamer" - with the cable towed behind a light vehicle and followed by a lightweight, mobile seismic source – to facilitate rapid and cost-effective data acquisition. This methodology is particularly useful for relatively shallow (tens of meters) surface wave analysis in which seismic velocity can be used as a proxy for rock mechanical properties.

2. MinEx CRC Project 05 Phase 02: Eighth quarterly Project Review Panel meeting Q4 2023 (December 2023)

Summarises progress on new technologies and methods being developed to reduce acquisition times (thus cost), improve data quality and deliver geologically meaningful seismic interpretations from fibre optic DAS instrumented sites, including:

- Progress on the build of a field prototype three-component seismic source (slides 4 and 5), following encouraging results from a laboratory prototype deployed at the Curtin University test borehole.
- Summary of recent work assessing machine learning approaches to denoising fibre optic DAS data (slides 6 to 10) including two recently submitted papers. 'Denoising' addresses a key challenge of fibre optic DAS compared to conventional geophones, namely lower signal-to-noise ratios. The machine learning denoising algorithms deliver data of comparable signal-to-noise to conventional seismic techniques.
- Assessment of a new-to-market "OptoDAS" fibre optic DAS interrogator (slides 11 to 12). There are now multiple DAS interrogators in the market, each with strengths and weaknesses. The MinEx CRC Project 5 team are assessing each interrogator technology to provide advice on the most appropriate tool for various deployment scenarios.
- Use of machine learning algorithms to improve subsurface characterization and geological interpretation from fibre optic DAS data (slides 15 to 25). This work uses data from our Otway basin instrumented site case study. The machine learning techniques can be used for improved location of microseismic events in passive seismic datasets and for more accurate location of reflectors in seismic-while-drilling data.

3. MinEx CRC Project 05 Phase 02: Twelfth quarterly Project Review Panel meeting Q4 2024 (December 2024)

Summarises progress on new technologies and methods being developed to reduce acquisition times (thus cost), improve data quality and deliver geologically meaningful seismic interpretations from fibre optic DAS instrumented sites, including:

- Results of the first deployment of the MinEx CRC field prototype three-component seismic source (slides 4 to 9) with seismic recording using fibre optic DAS seismic sensors in the ~1000m deep Curtin borehole. Data can be processed in the acquisition co-ordinate field (with the three orthogonal components rotated at 45º from the vertical and horizontal) or transformed to a conventional geographic co-ordinate field (north, south and vertical). The data quality is encouraging (although the work identifies potential for improvement) and demonstrate anisotropic response, which should help interpret geological structures and seismic properties in three dimensions.

- Results of cross-hole seismic tomography utilizing fibre optic DAS coupled with a new-to-market "Treble+" interrogator and a high-frequency 'sparker' source deployed in adjacent drill holes (slides 10 to 13). This is an instrumented site case study demonstrating the potential for cross-hole geological characterization (e.g. for mapping structures or ore bodies between drill holes) and to monitor change (e.g. injection of fluid or gas from the drill hole or changes in rock properties due to mining operations). In this case, there was a measurable seismic response (change in velocity) due to the injection of CO_2 from the 'source' drill hole.

- Update on recent work assessing machine learning approaches to denoising fibre optic DAS data highlighting the potential to enhance data quality and/or enable use of low power (thus cheaper) sources, which typically have lower signal-to-noise (slides 14 to 18). Unique denoising algorithms are required for each fibre optic DAS interrogator system. The MinEx CRC Project 5 team have created, and made public, pre-trained denoising algorithms specific to the "Silixa iDAS" interrogator with plans to deliver pre-trained models fo the Treble+, OptoDAS and iDAS-MG interrogators.

4. Recommendations for Instrumented Field Sites with Fibre Optic Sensors Open-Source Library of Pre-Trained Neural Networks for DAS Data Denoising and Application to Data Acquisition. MinEx CRC Technical Report 2024/61, 65pp (November 2024)

The report presents nine case studies of field sites instrumented with fibre optic distributed acoustic sensing (DAS) for collection of seismic data. The case studies were conducted during Phase 1 (2019-2021) and Phase 2 (2022-2024) of MinEx CRC. Each case study presents unique challenges and opportunities – requiring bespoke survey design, energy sources, data collection and processing. Together they provide an overview of the challenges and advantages of fibre optic DAS (and associated technologies) compared to conventional seismic techniques.

Fibre optics offer high resolution, rapid acquisition of active data and, if necessary, continuous data acquisition along entire exploration boreholes, allowing the mapping and characterisation of surrounding ore bodies and geology. Fibre optic systems reduce the need for multiple discrete sensors, minimising operational costs in data acquisition. Continuous data collection with fibre arrays enables real-time analysis, hazard monitoring and mine operations monitoring, as well as using passive energy for subsurface characterisation for adaptive exploration strategies and decision-making during drilling operations. More rapid acquisition with smaller seismic sources and fibre optic arrays helps reduce environmental footprints.

The report outlines several factors for the instrumentation of a field site that need to be considered for optimal configuration. Namely, selecting the fibre optic deployment options and optimising installation methods to maximise the benefits of the technology; choosing the cable design and fibre type for sufficient data quality; and selecting an interrogator unit for the appropriate acquisition of the seismic wavefield, in particular acquisition settings. Proposed denoising machine learning workflows are developed to streamline data quality improvement processes during the acquisition. Supervised deep learning approaches are identified for detection and location of passive events and for subsurface characterisation. The report emphasises the enhancement in efficiency and effectiveness in mineral exploration with adopting the fibre optic sensing for instrumenting the field sites as well as in overall improvement in sustainability and safety.

OBJECTIVE(S)	RESULT(S)
Demonstrate completion of Commonwealth Milestone RP2.3.3	A compilation of 3 Project Review Panel Presentations and 1 technical report produced by the MinEx CRC Project 5 research team fulfills the requirements of the milestone.

NEXT STEP(S)	TIMING
Deliver market-ready fibre optic DAS seismic technologies that will reduce the cost and increase the efficacy of seismic methods in mineral exploration.	2025-2027 inclusive

MINEX CRC MILESTONES

Commonwealth Milestone RP2.2.3: Report on instrumented field case study 1 completed. Recommended instrumentation and workflow required to establish instrumented field at other locations.

UTILISATION/COMMERCIALISATION OPPORTUNITIES

We are working with seismic service provider companies (HiSeis and Southern Geoscience) to assess commercialization opportunities of MinEx CRC technologies and methods as a complement to their existing businesses. In parallel MinEx CRC will consider the potential of a spin-out company from Curtin University.

IP

We are working on a Provisional Patent application covering the novel three-component seismic source that has been developed in MinEx CRC Project 5.

CONFIDENTIALITY

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APPROVED BY

Prof David Giles
Chief Scientific Officer MinEx CRC

Table of Contents

Acknowledgements

The work has been supported by the Mineral Exploration Cooperative Research Centre whose activities are funded by the Australian Government's Cooperative Research Centre Program. This is MinEx CRC Document 2025/54.

Project 5 : Seismic in the Drilling Workflow: project update

Andrej Bona, Olivia Collet, Konstantin Tertyshnikov, Roman Pevzner, Pavel Shashkin
Project 5
MinEx CRC

Agenda

- Project update
- Milestones for 2023
- AOB

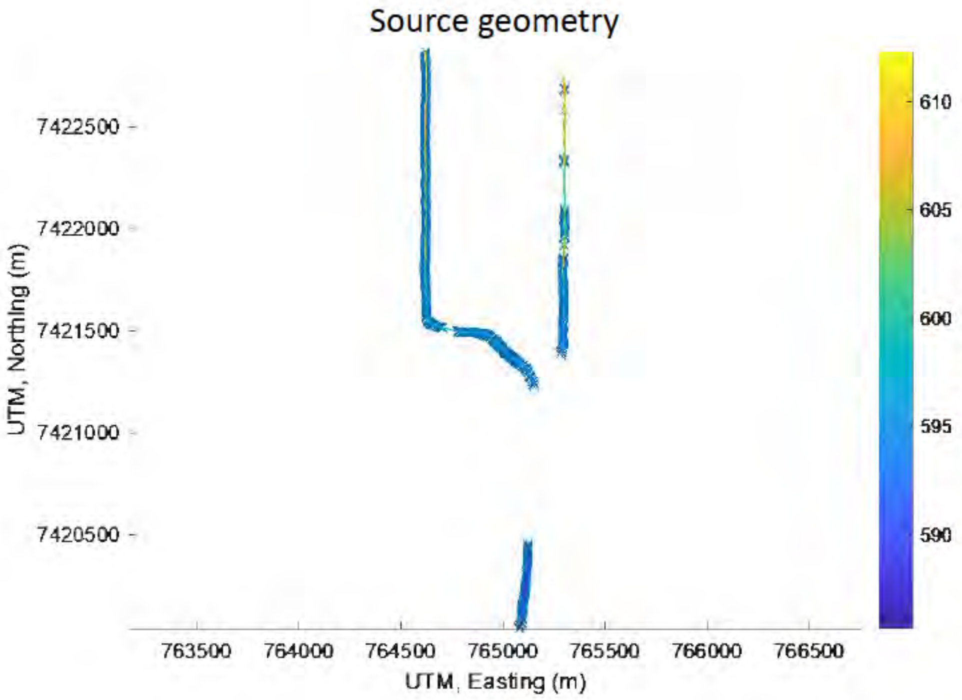
MinEx CRC

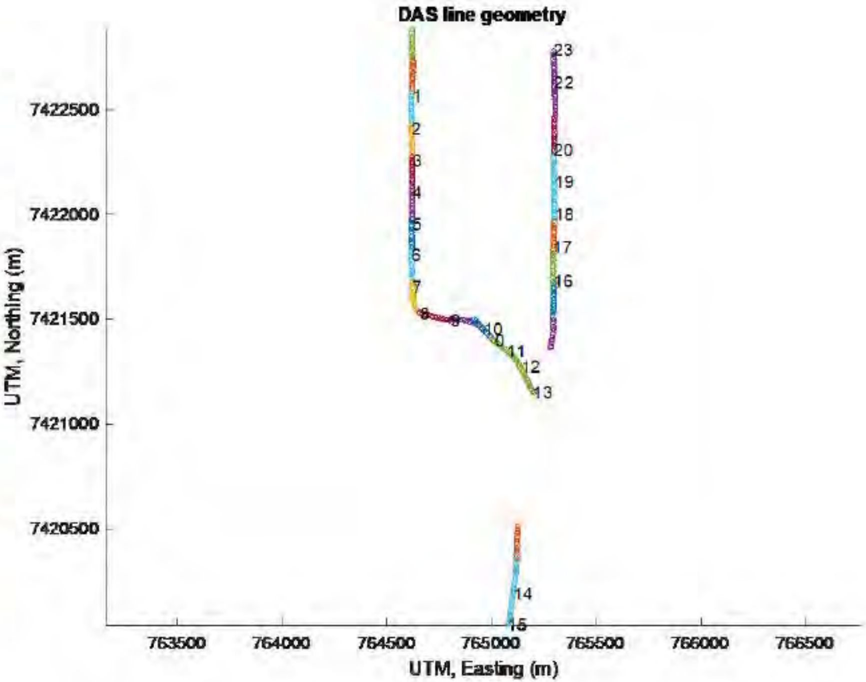
Project update

- Data from AA Moranbah horizontal drilling arrived (7TB+ equivalent to ~ 2000 HD movies)
- Land streamer experiment at Rio Tinto site
- Staffing update

Rio Tinto OldVic: surface streamer test

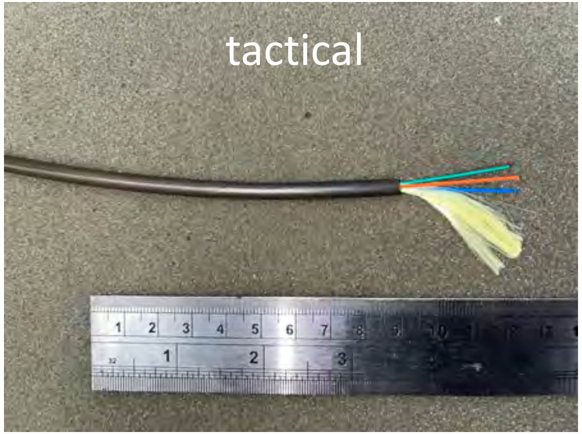
Acquisition geometry

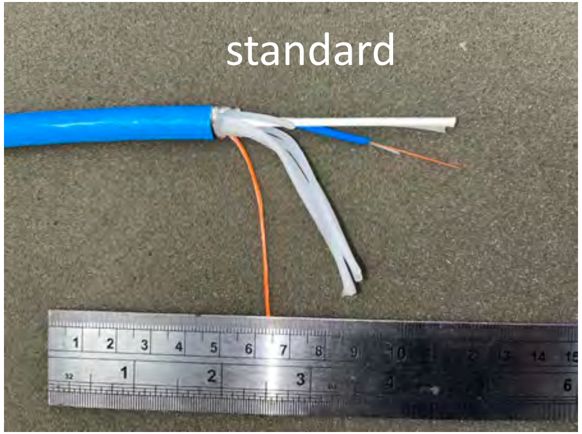




Tests of two cables and number of shots

- Test of 10 shots at a single location: 4 shots / location – best compromise between signal to noise and the acquisition time
- Comparison of”standard” and “tactical” cables: tactical cable better data and easier to deploy





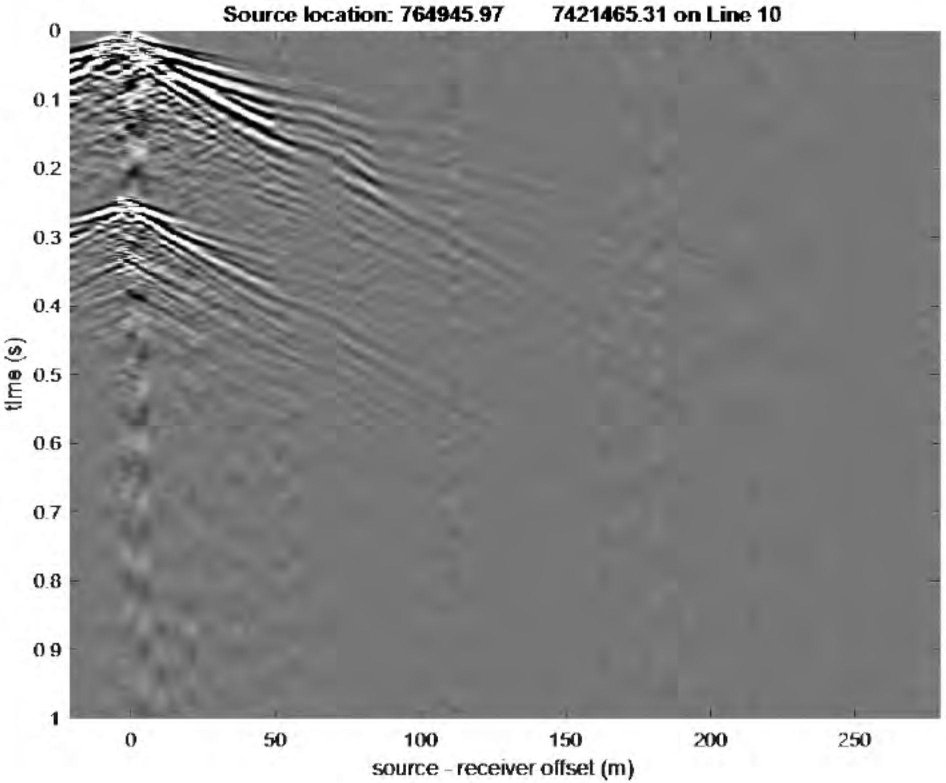
Acquisition

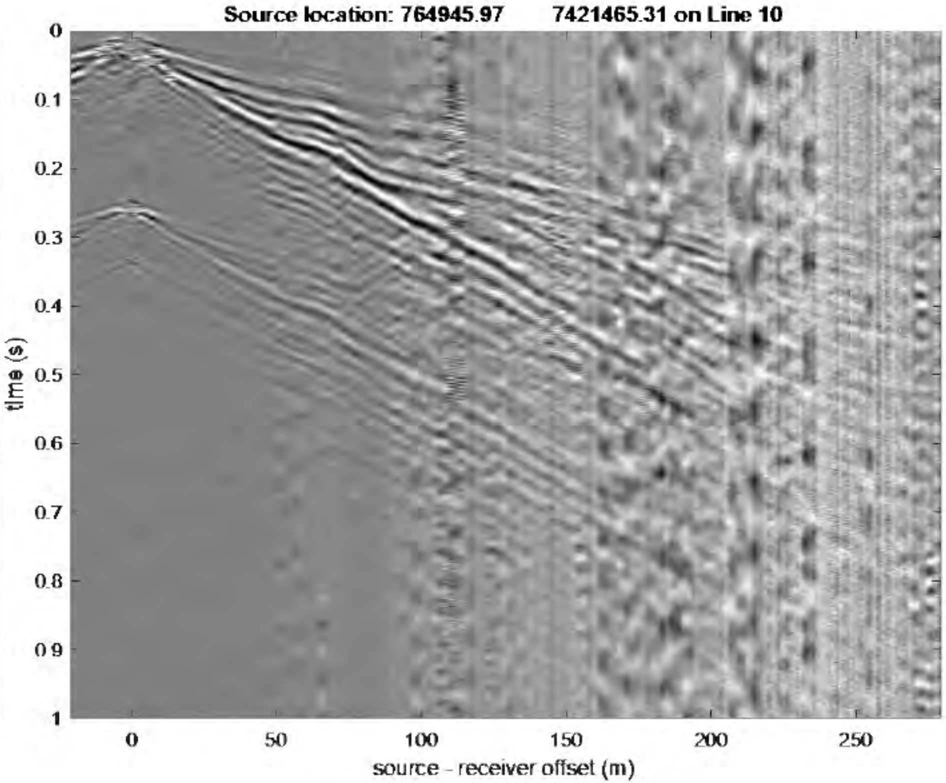
300m long DAS cable (Terra15: 0.82m ‘receiver’ spacing, 2.45m pulse)
150m overlap between lines
5m source spacing
4x Skid steer with weight-drop (Bobcat concrete breaker, 4880Nm impact force ~ 500kg from 1m)

Geometry workflow

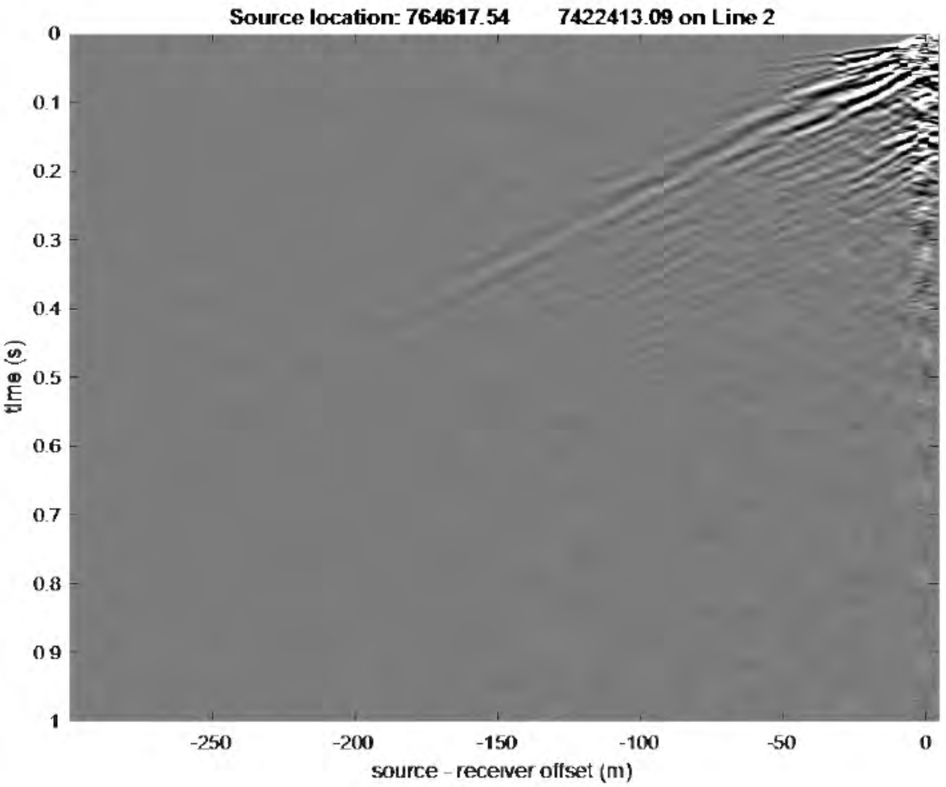
- Each line and shot record:
  - Eliminate bad records
  - Fix time shifts (due to early firmware bug in the interrogator)
  - Assign channel corresponding to the source location
- Assign GPS locations to shots recorded by “seismic source signature recorder” by finding nearest ‘rover’ location
- Interpolate the locations between channels with shot location information
- If shot channels did not have GPS from “signature recorder” then use the interpolated values

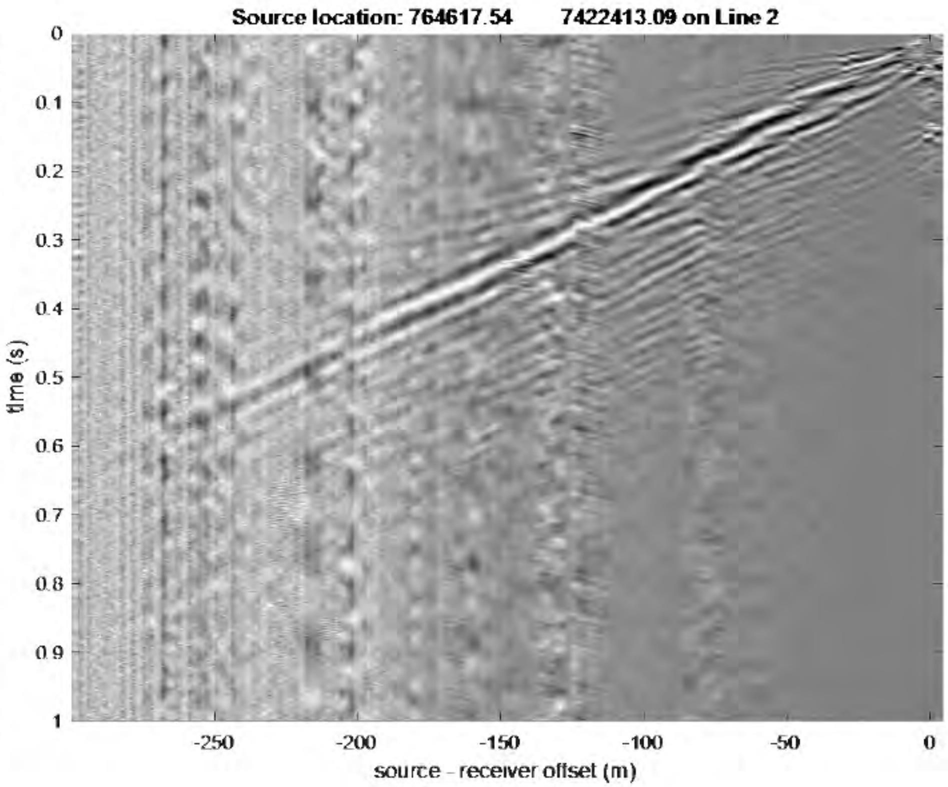
Examples of acquired data



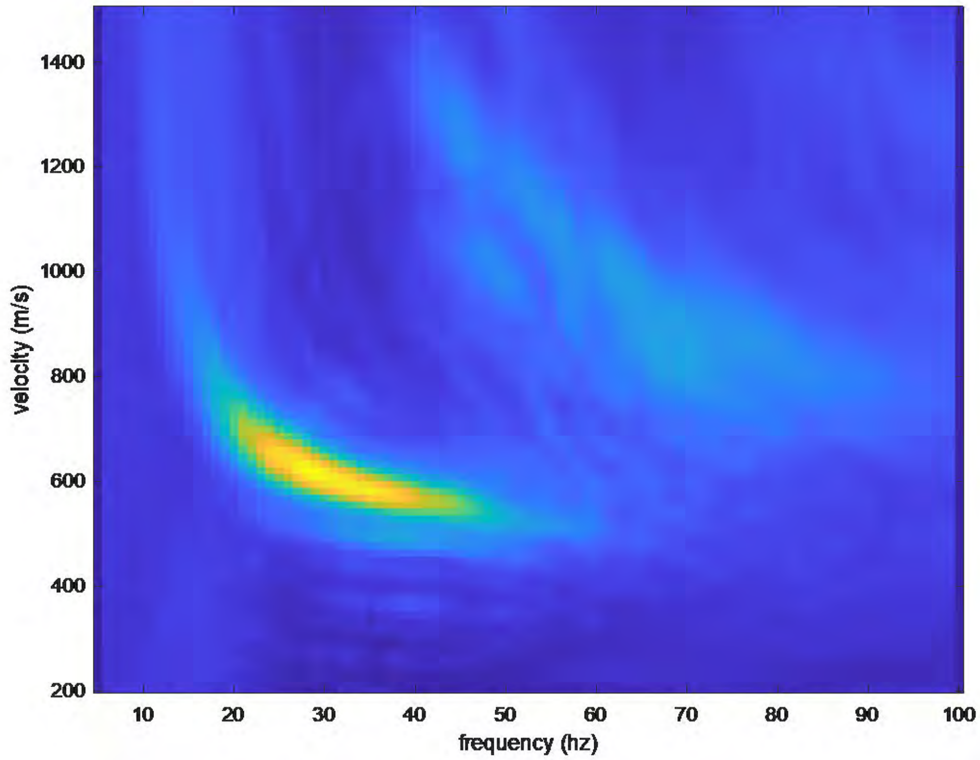


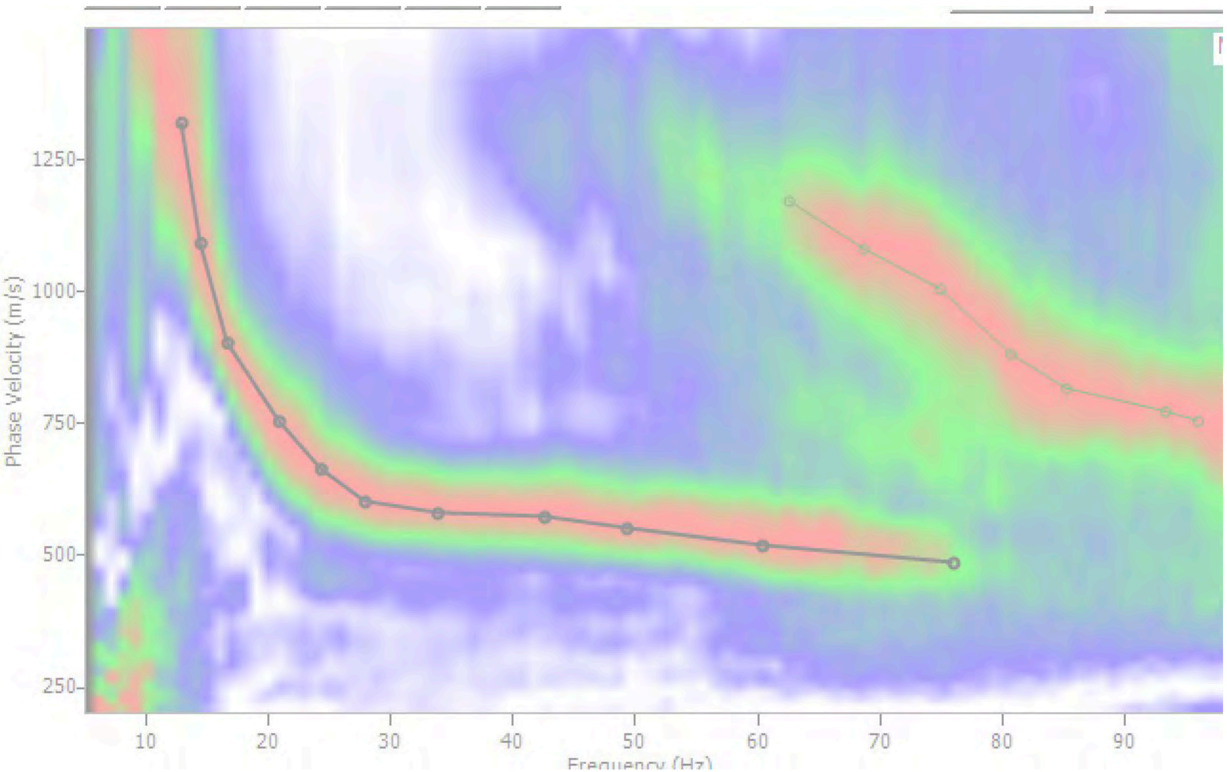
Examples of acquired data



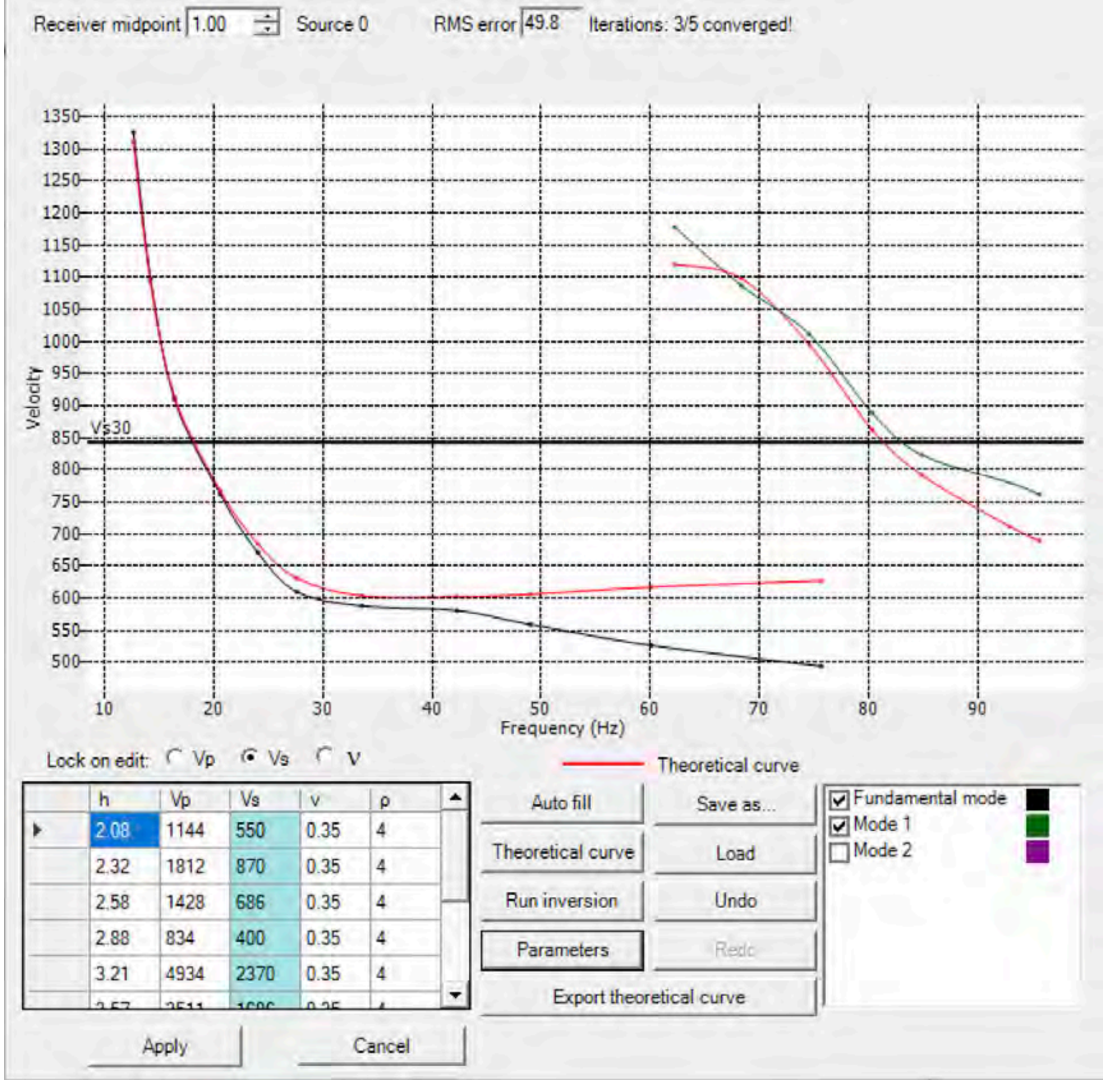


Surface wave dispersion (velocity vs frequency)

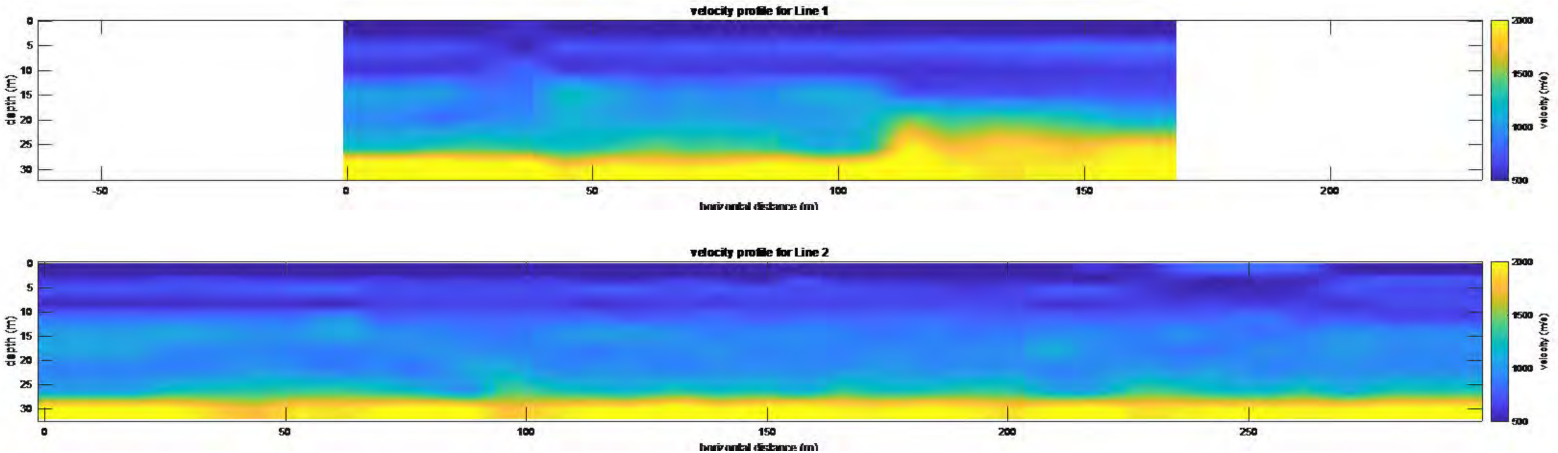




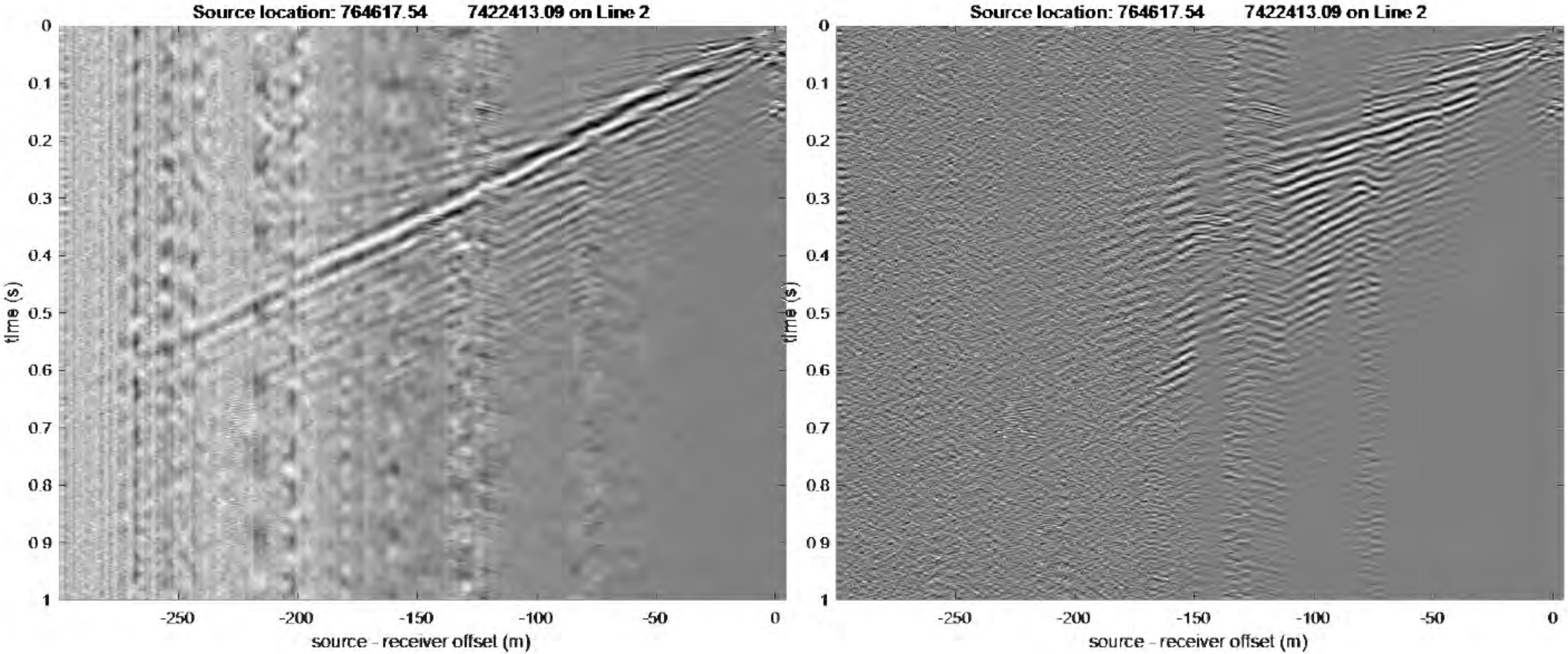
Phase Velocity (m/s)
1250
1000
750
500
250
10
20
30
40
50
60
70
80
90
Frequency (Hz)


Receiver midpoint 1.00
Source 0
RMS error 49.8
Iterations: 3/5 converged!
Velocity
1350
1300
1250
1200
1150
1100
1050
1000
950
900
850
800
750
700
650
600
550
500
Vs30
10
20
30
40
50
60
70
80
90
Frequency (Hz)
Lock on edit: Vp Vs V
Theoretical curve
h Vp Vs v ρ
2.08 1144 550 0.35 4
2.32 1812 870 0.35 4
2.58 1428 686 0.35 4
2.88 834 400 0.35 4
3.21 4934 2370 0.35 4
Auto fill
Save as...
Theoretical curve
Load
Run inversion
Undo
Parameters
Redo
Export theoretical curve
Fundamental mode
Mode 1
Mode 2
Apply
Cancel

Surface wave analysis



Reflection pre-processing: filtering



Staffing

- Welcome Olivia Collet:
  - Our in-house expert in ML for seismic
- Goodbye Andrej Bona:
  - Hopes to stay involved in the project ☺

MinEx CRC

Proposed milestones for 2023

Q1
1. Analysis and processing of streamer data
2. Staffing profile agreed Curtin

Q2
3. Analysis of SWD data from Anglo

Q3
4. Sparker test on BHP or Curtin site

Q4
5. Based on the SWD analysis, design workflows for ML approach to the data processing and interpretation

AOB

- Commercialisation?

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Project 5
Seismic in the Drilling Workflow
Project update

Konstantin Tertyshnikov, Olivia Collet, Pavel Shashkin,
Emad Al-Hemyari, Roman Isaenkov, Xihao Gu, Roman Pevzner, Nikita Beloborodov
Project 5
MinEx CRC

Agenda

- HSE
- Project 5 Team and PhD students updates
- Project update
  - 3C Seismic Source with DAS – update
  - ML Denoising of SWD data – update
  - Supervised Machine Learning for Subsurface Characterisation
- 2024 Milestones
- Commecialisation Update
- AOB

Project 5 Team and PhD students updates

Project Students

- Alina Suchkova - PhD student (abandoned waiting for the visa)
- Mikhail Vorobev - PhD student (starting soon, student visa granted)
- Eamd has been awarded 2024 MRIWA Odwyn Jones PhD Scholarship.

Image redacted for reasons of commercial sensitivity

Image redacted for reasons of commercial sensitivity

ML for DAS Data Denoising

- Suppress noise inherent to the DAS recording system
- Increase signal-to-noise of DAS passive and active data
  Traditional Approach
- NoiseToNoise (N2N) Approach

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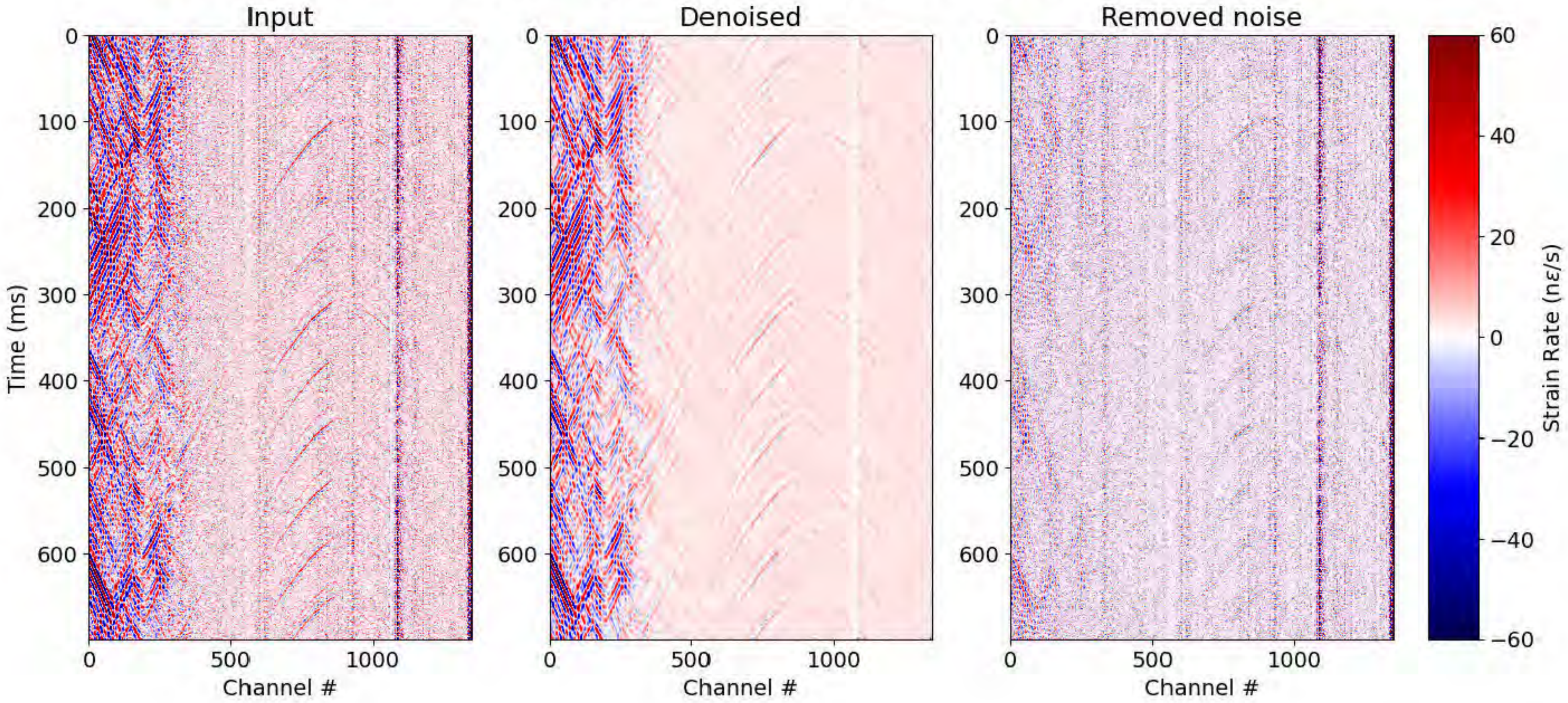
ML for DAS Data Denoising

Two papers submitted to GEOPHYSICS

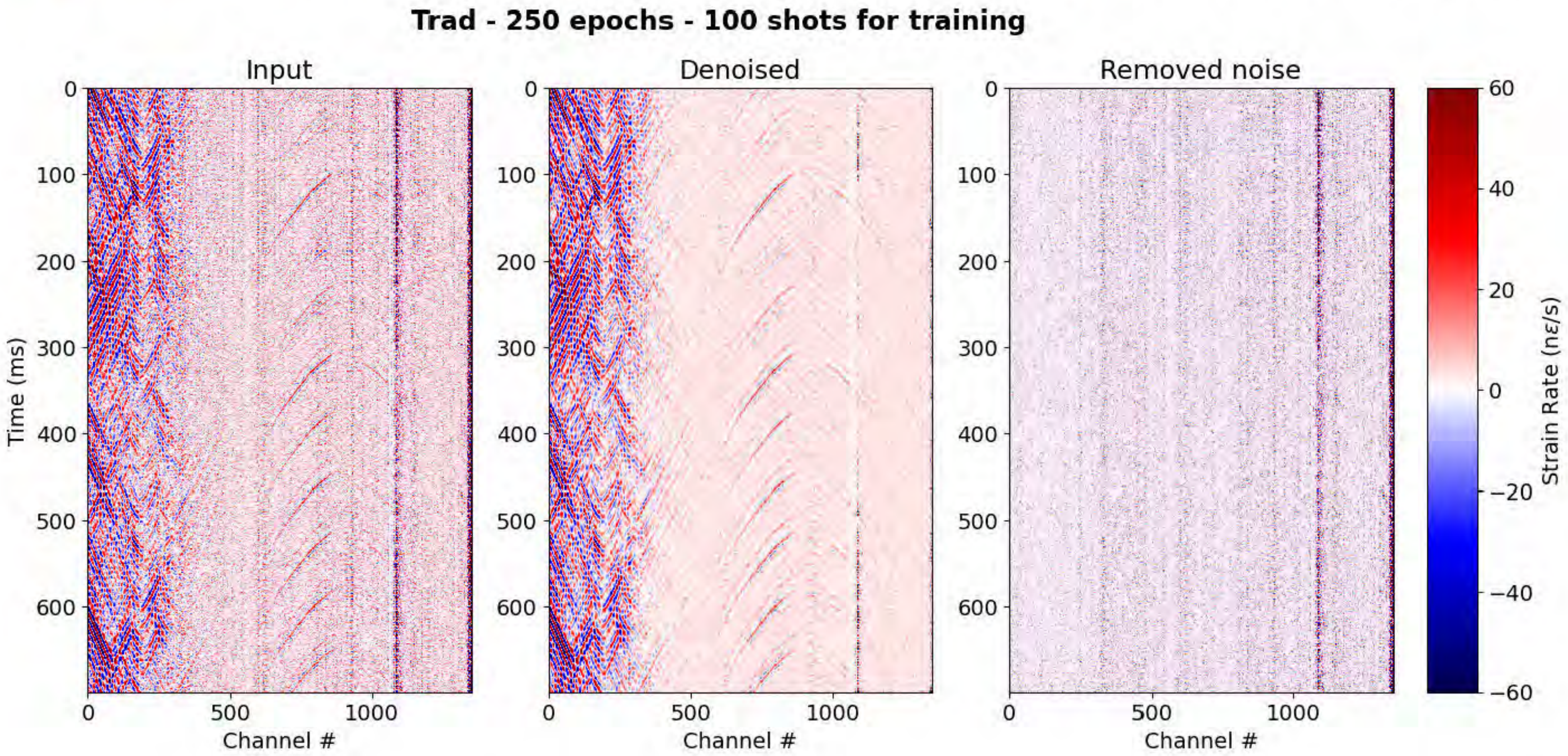
- GEO-2023-0680 — "DEEP LEARNING FOR DAS DENOISING. PART 1: SUPERVISED TRAINING USING SYNTHETIC SIGNALS AND ACTUAL HARDWARE NOISE“
- GEO-2023-0681, "DEEP LEARNING FOR DAS DENOISING. PART 2: USING THE NOISE2NOISE APPROACH TO REMOVE HARDWARE NOISE“

SWD Data – Noise2Noise Result

N2N - 30 epochs - in/target: upgoing/downgoing - Patch size: (128,96) - Fliplr

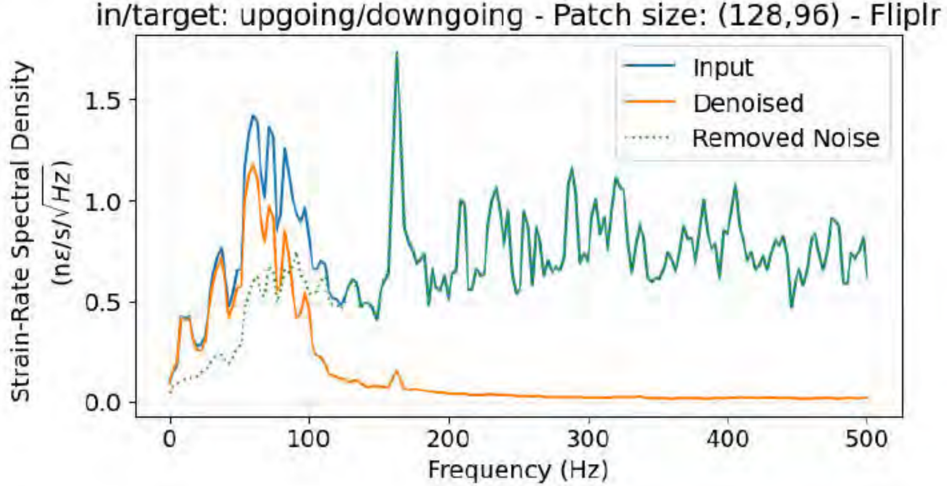


SWD Data – Traditional Supervised Result

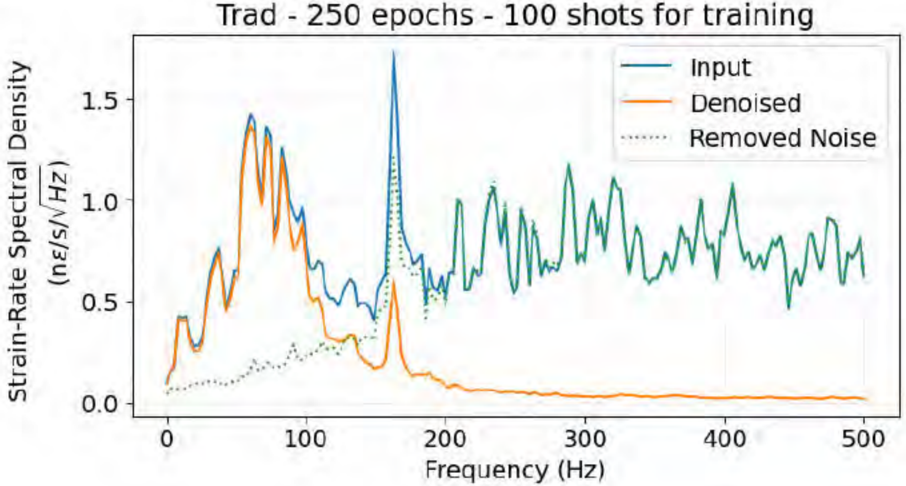


Spectral Densities

Noise2Noise



Traditional Supervised



OptoDAS interrogator test

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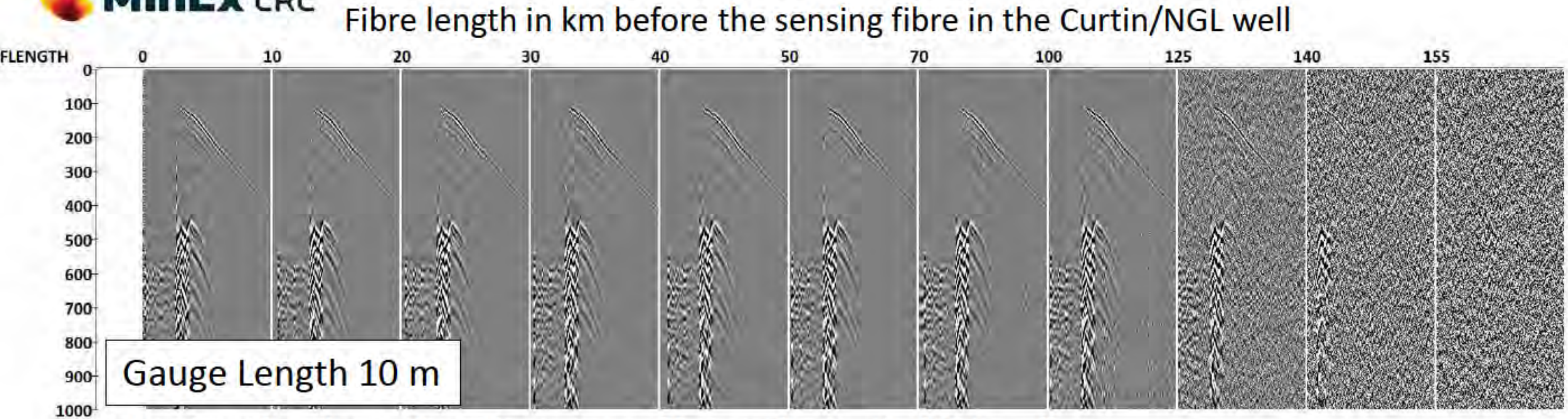
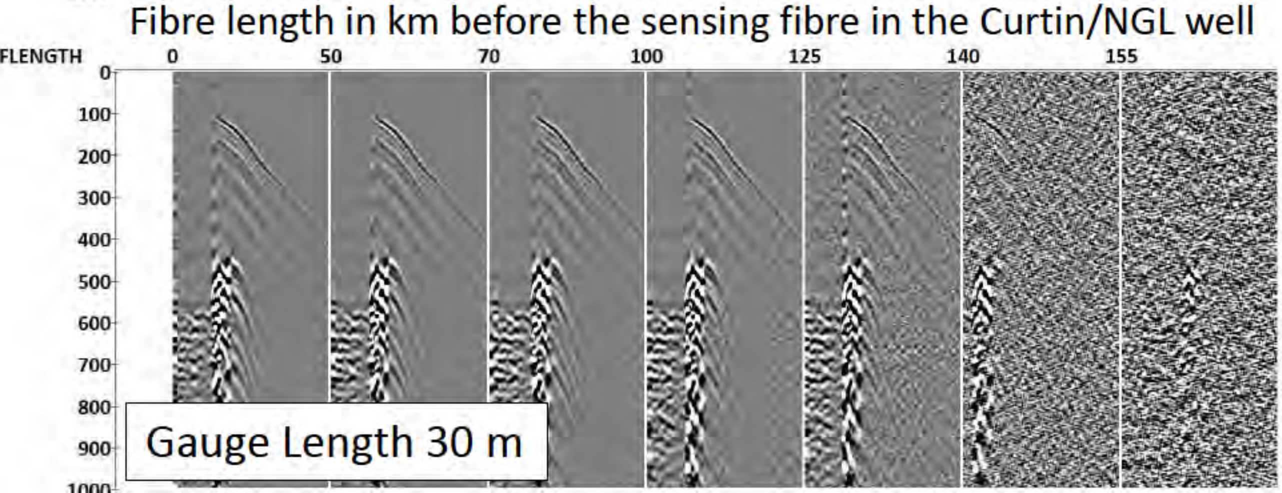


Fibre length in km before the sensing fibre in the Curtin/NGL well
FLENGTH
0
10
20
30
40
50
70
100
125
140
155
0
100
200
300
400
500
600
700
800
900
1000
Gauge Length 10 m



Fibre length in km before the sensing fibre in the Curtin/NGL well
FLENGTH
0
50
70
100
125
140
155
0
100
200
300
400
500
600
700
800
900
1000
Gauge Length 30 m

Supervised Machine Learning for Subsurface Characterisation - update

Background

Last PRP Meeting:

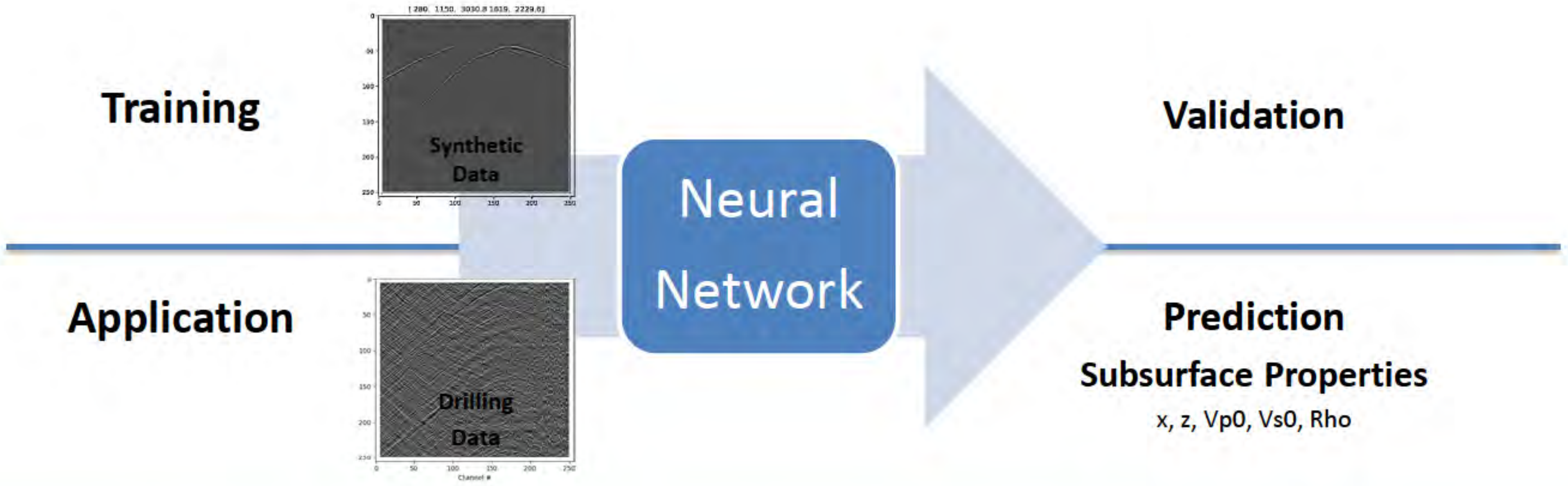
- Introduced a ML workflow for subsurface characterisation
- Challenges identified
- The aim is to simultaneously predict passive sources locations (x, z) and invert for subsurface properties (V_{p0}, V_{s0}, ρ)
- Synthetic training data preparation workflows were developed
- Initial prediction tests were performed using synthetic and SWD data

This PRP Meeting:

- Reporting on the progress
- Micro-seismic dataset from Otway made available
- More prediction tests were performed on micro-seismic data
- In-depth investigations of predictions performance were conducted

Challenges

- Lack of labelled training data
- The gap between synthetic and field data



Challenges

Modelling

Supervised Machine Learning

Model Building
- 1D
- Vp, Vs, ρ

Model Perturbation
- Number of layers
- Property ranges
- Acquisition Geometries
- Anisotropic Parameters

Seismic Sources
- Vertical Source
- Horizontal Source
- Source types
- Dominant Frequency

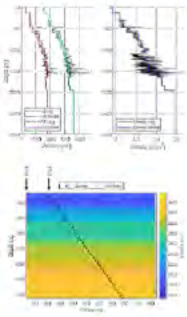
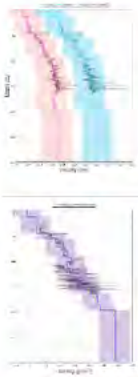
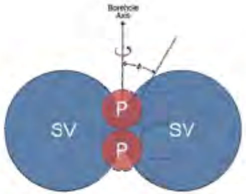
Seismic Modelling
- Particle Velocity

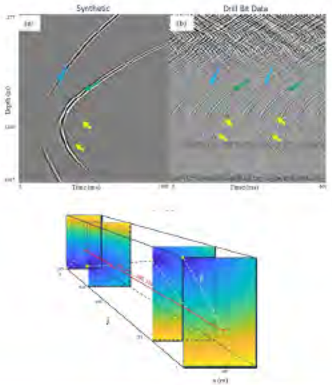
DAS Modelling
- Converting to Strain

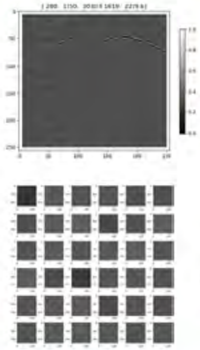
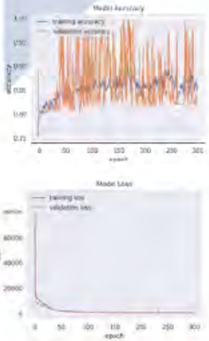
Generating Training Data
- DAS data patches
- Real field noise
- Data labels x, z, Vp, Vs, ρ

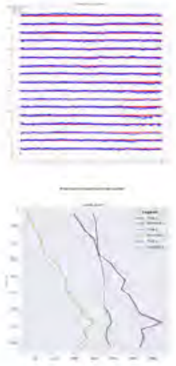
Neural Network Training
- Training
- Testing
- Validation

Predictions
- Application to SWD field data
- Analysing Performance



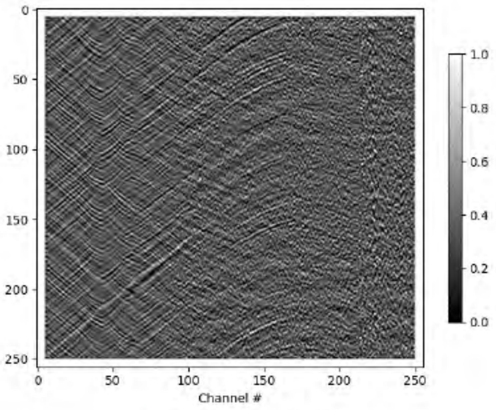





Predictions (SWD)

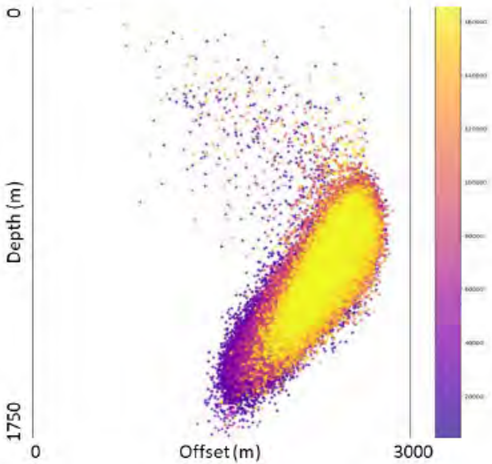
Drilling Data

Depth ~ 1150m

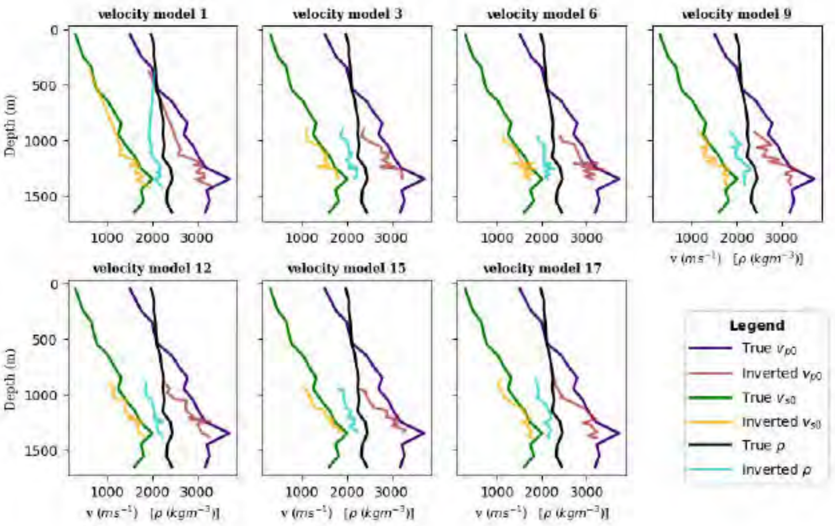


168,577 images
(256x256 pixels)

Event Locations

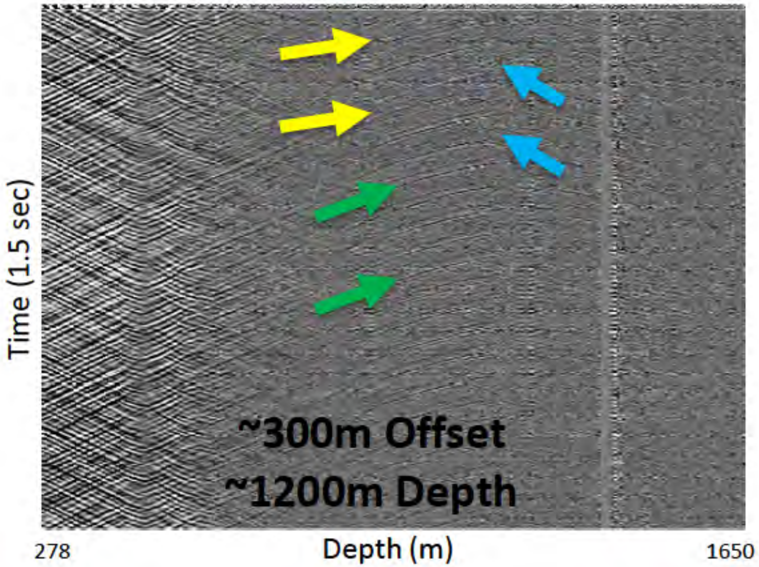


Reconstructed Logs

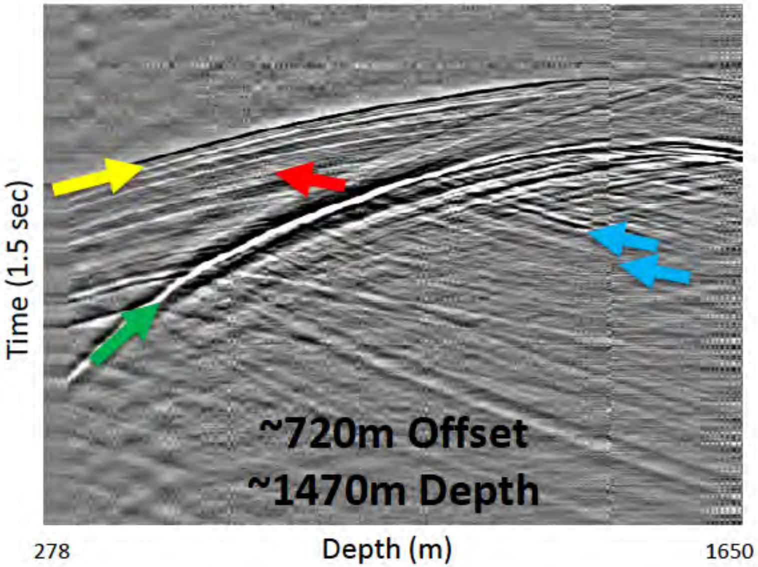


Datasets

Seismic While Drilling



Micro-Seismic



P-wave | S-waves | P-wave reflections | S-wave reflections

co2crc
Building a low emissions future

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Predictions (Induced Seismicity)

Australian Government
Department of Industry, Science, Energy and Resources

Business
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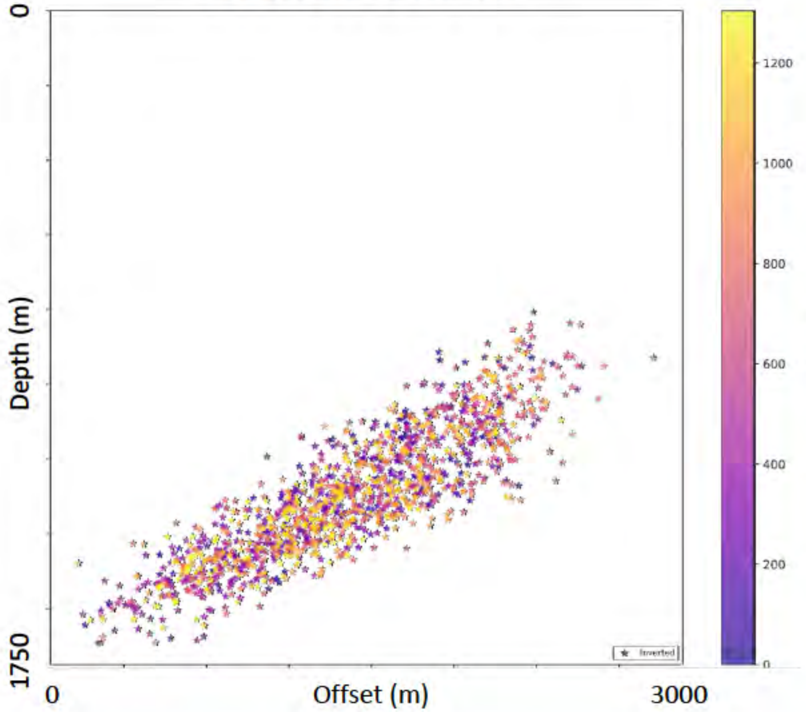
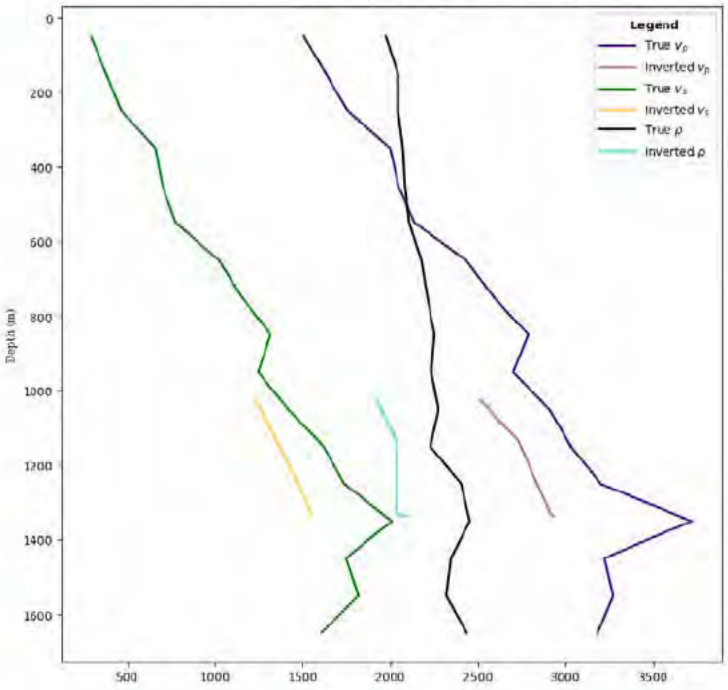
Event Locations

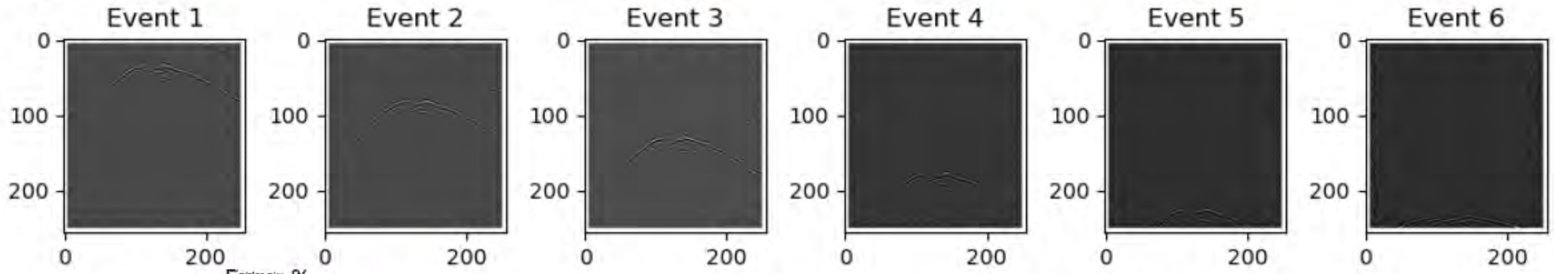


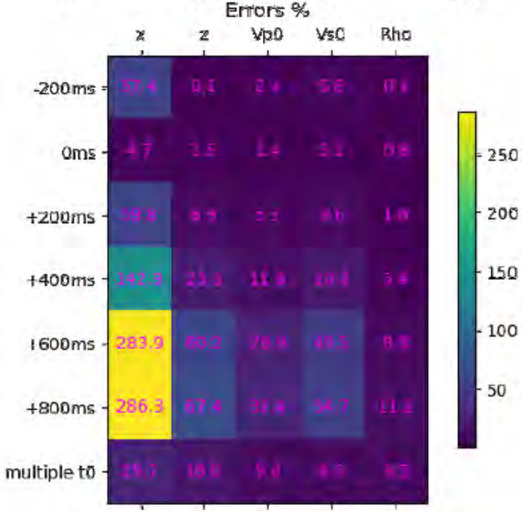
Reconstructed Logs

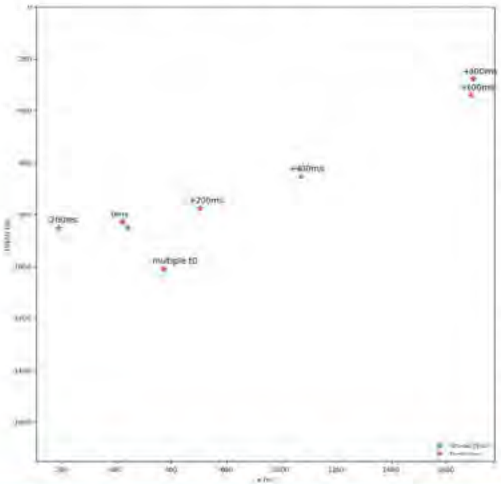


In-Depth Investigations Using Synthetics

t0 shift: -200ms 0ms 200ms 400ms 600ms 800ms







Observations & Considerations:

- ✓ Look at all synthetic events at one depth to decide on patch size
  - ✓ Compare with Otway micro-seismic events
  - Consider anisotropy
- ✓ Extend patch time axes to include both P & S waves
- Limit x or events offsets to +/-1600m
- Incorporate t0 shifts
  - In the 3rd dimension
  - Or as a separate images with the same labels within a large window
- All features except x have lower errors as they are dependent on depth
- Use representative noise
- Review network input shape (256,256,1)
  - Consider resizing and potential aliasing

Induced Seismicity Otway

TABLE 2

Catalog of the Microseismic Events Induced by the Brine and CO_2 Injections during the Stage 3 Experiment

Seq.	Number	Date and Time (yyyy/mm/dd hh:mm) (UTC)	UTM East (m)	UTM North (m)	Depth (m)	M_w	f_c (Hz)	Strike/Dip/Rake (°)	Offset (m)
1	2	2020/10/29 02:29	658631.5	5733858	1490	−1	90	70/30/270	1308.79
2	4	2021/01/30 16:55	657999.1	5733742	1470	−1.1	180	40/70/270	719.19
3	5	2021/01/30 18:46	657992.4	5733723	1470	−0.5	180	40/70/270	720.32
4	6	2021/02/06 10:41	657979.2	5733722	1450	−0.7	180	40/70/270	708.63
5	7	2021/02/07 13:19	657991.7	5733721	1450	−1.3	130	40/70/270	720.48
6	8	2021/02/07 14:20	658016.3	5733785	1430	−1.5	110	40/70/270	720.65
7	9	2021/02/07 14:21	658010.5	5733768	1450	−1	150	40/70/270	720.66
8	10	2021/02/07 15:48	657999.4	5733740	1470	−1.5	150	40/70/270	720.22
9	11	2021/02/25 20:23	658804.5	5733873	1510	Nan	Nan	Nan	1479.31
10	12	2021/02/25 22:10	657879.3	5733980	1470	Nan	Nan	Nan	548.59
11	13	2021/02/25 23:10	657899	5733950	1470	Nan	Nan	Nan	570.61
12	14	2021/02/26 09:39	657997	5733742	1470	−0.6	180	215/20/270	717.24
13	16	2021/03/16 01:54	658013.6	5733770	1450	Nan	Nan	Nan	722.91
14	18	2021/04/14 08:58	658454.8	5733845	1470	Nan	Nan	Nan	1135.28
15	20	2021/06/13 05:11	658633.5	5734494	1490	−0.3	140	35/10/265	1389.23
16	21	2021/06/25 05:48	658562.1	5734460	1450	0.1	140	35/10/265	1310.47
17	24	2021/11/06 23:35	658347.3	5733978	1450	−1	120	Nan	1016.29

Nan, the signal-to-noise ratio is insufficient for accurate estimation of the parameters.

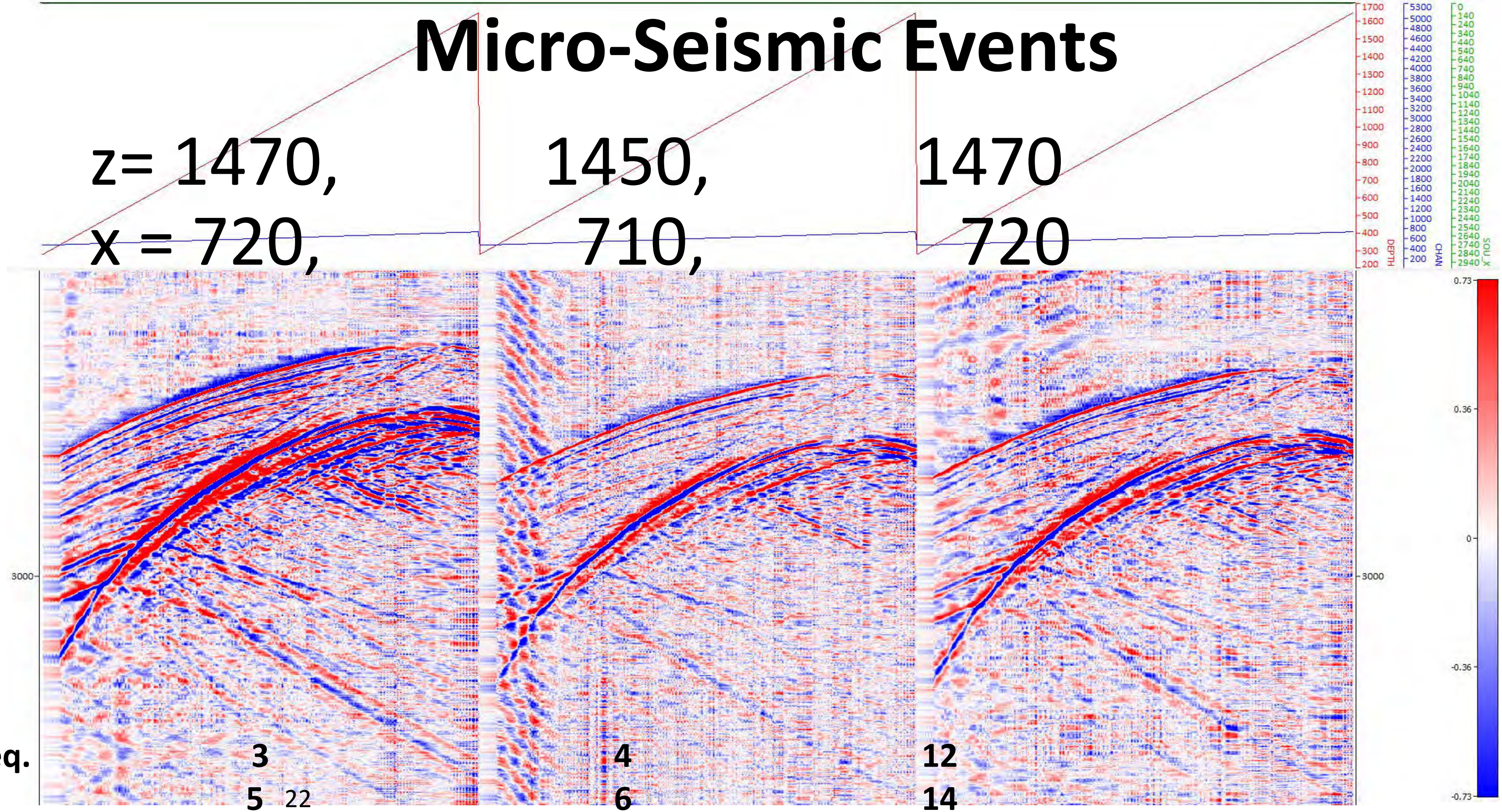
Glubokovskikh et. al., 2023

Micro-Seismic Events

z= 1470, x = 720,

1450, 710,

1470 720

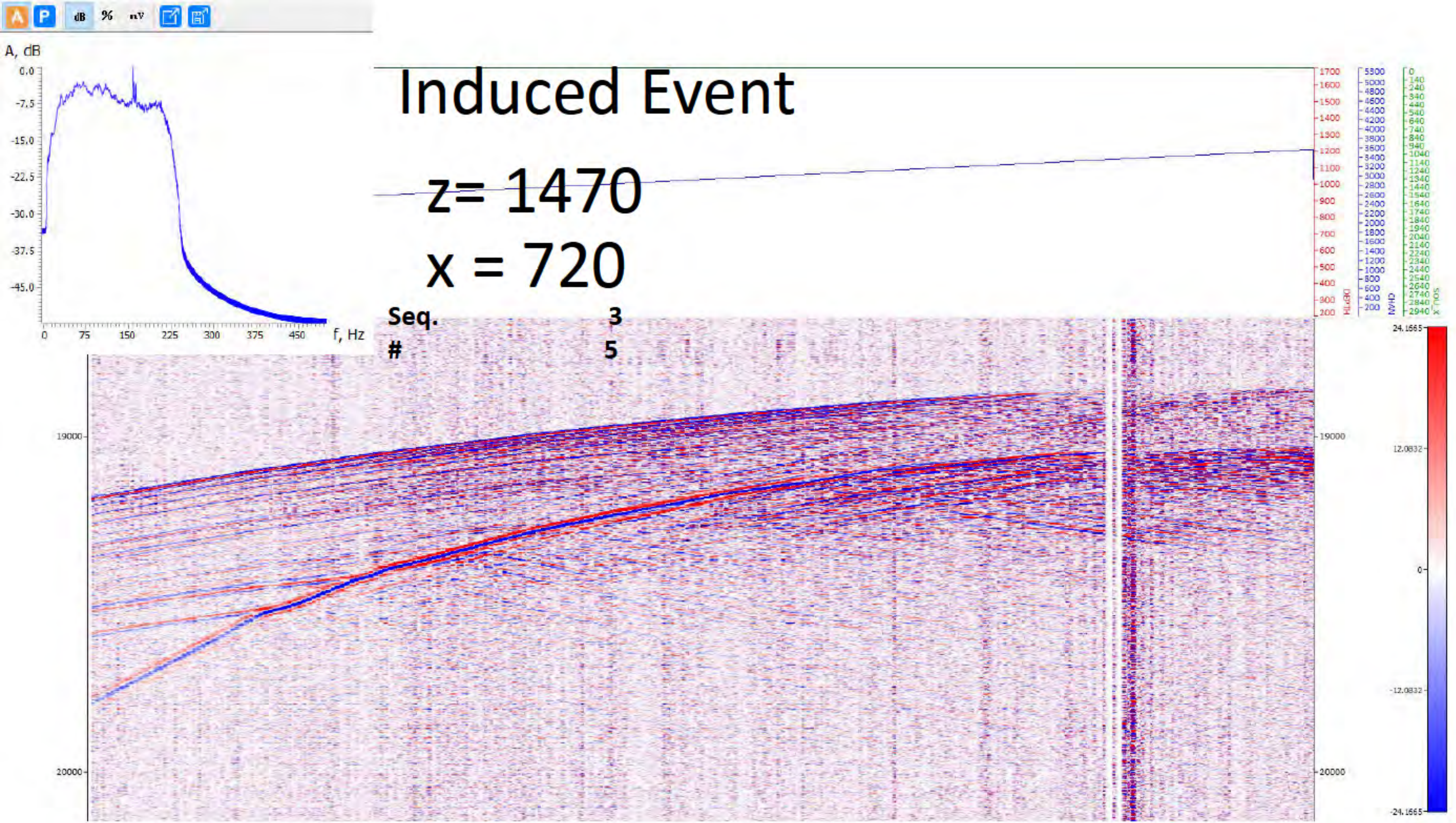


Seq. #	3 5 22	4 6	12 14

Induced Event

z= 1470

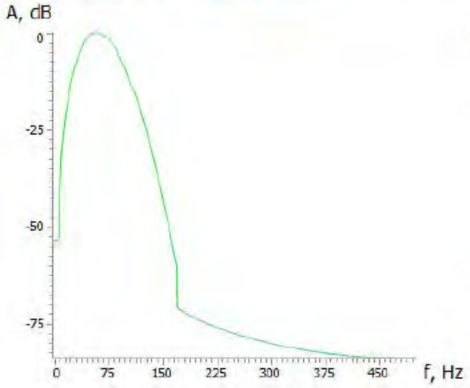
x = 720

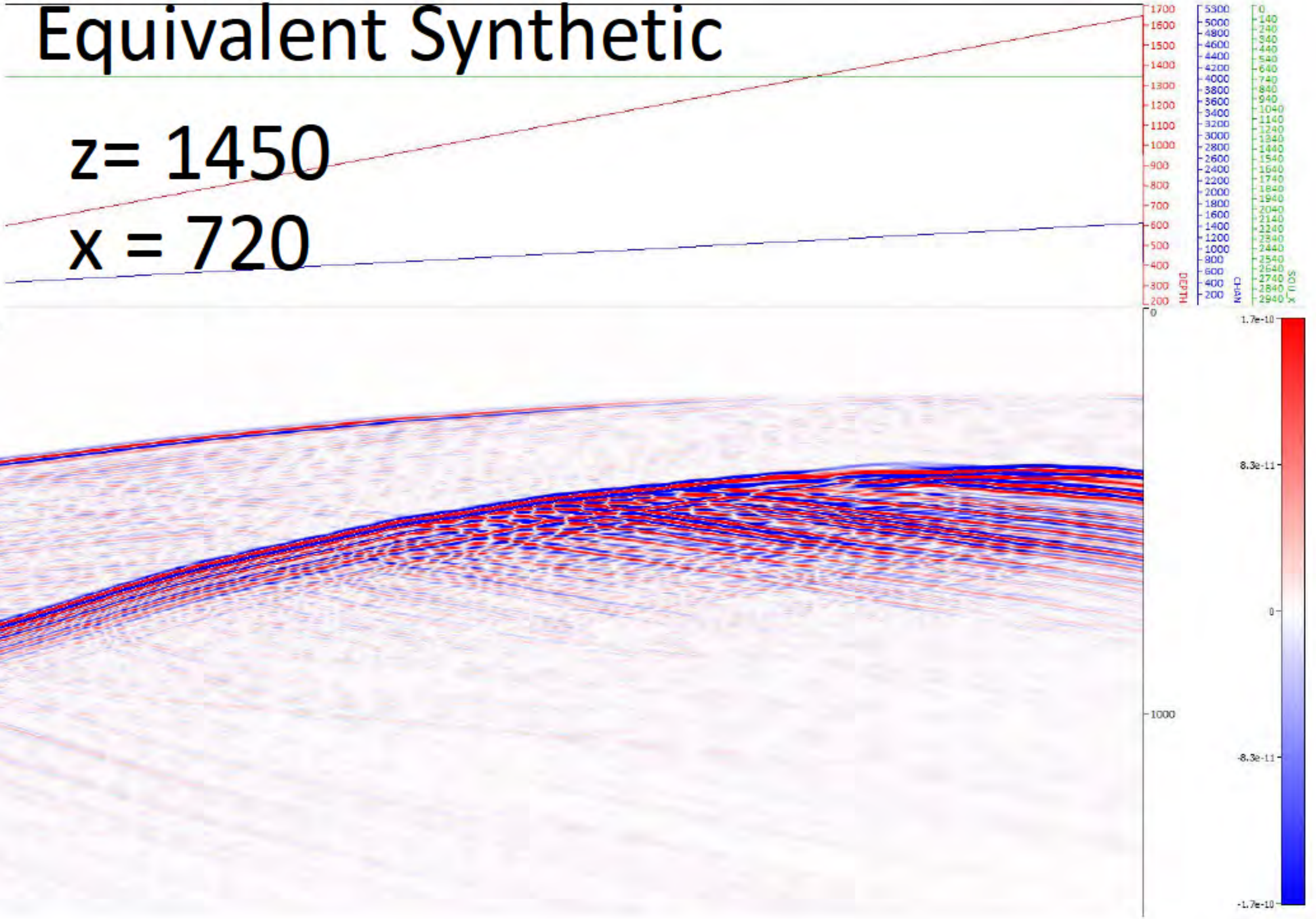


Equivalent Synthetic

z= 1450

x = 720





Future Work

- Extending the training dataset
  - Acquisition geometry generalisation
  - Perturbation of properties and models
  - Matching wavelets
  - Include anisotropy
- Explore different CNN architectures

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2024 Milestones

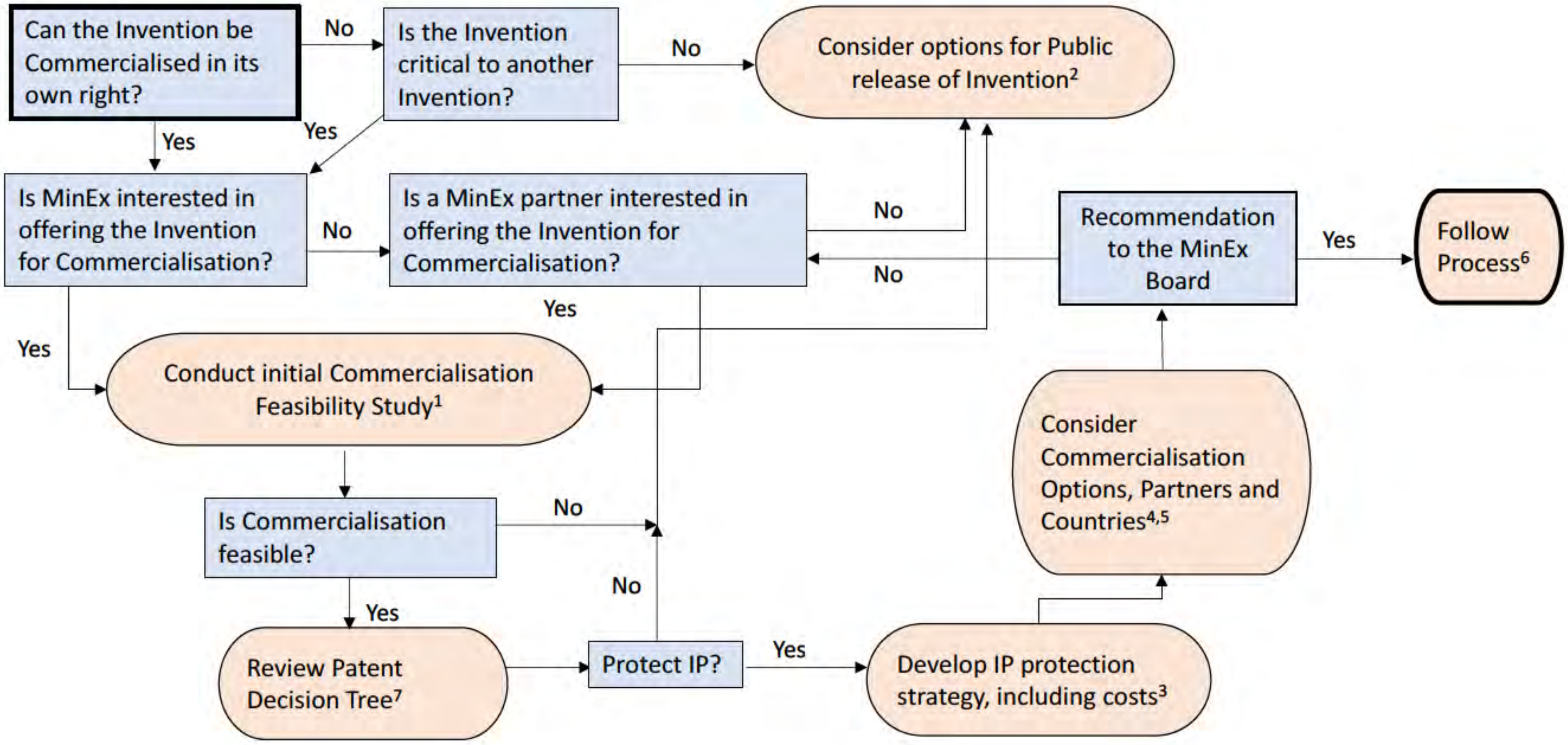
- Q1 Achieve consensus of participants on Phase 3 scope for Project 5 (workshop early February?)
- Q1 Report on the field evaluation of the comparative performance of different DAS interrogators and low-power sources

- Q2 Report on the development of advanced denoising algorithms for different DAS interrogators and training of relevant neural networks
- Q2 Complete evaluation of ML algorithms on field data, including legacy data from sponsors' sites

- Q3 Report on the trial application of denoising algorithms during field data acquisition
- Q3 Release open-source library of pre-trained neural networks
- Q3 Report on recommendations for an instrumented field site and associated workflows.

- Q4 PJ05-Ph02-M11 Commercialisation and IP Roadmap outputs utilised to facilitate Phase III planning.
- Q4 PJ05-Ph02-M12 Report and workshop for participants on machine learning approaches to invert seismic data based on the approaches identified earlier in the project and tested on field datasets.

IP and Commercialisation Process Decision Tree



Commercialisation Update

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Software and Algorithms

- ML for DAS denoising algorithms
- ML event detection/location of seismicity
- Surface Waves Tomography + ANT

Hardware

- Autonomous Fibre Optic Sensing Edge Computing Platform
- Light 3C Seismic Source
- DAS Land Seismic Streamer (MASW, multicomponent DAS)

Autonomous Fibre Optic Sensing Edge Computing Platform – Prototype

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TECHNOLOGY READINESS LEVEL (TRL)

DEPLOYMENT	9	ACTUAL SYSTEM PROVEN IN OPERATIONAL ENVIRONMENT
DEPLOYMENT	8	SYSTEM COMPLETE AND QUALIFIED
DEPLOYMENT	7	SYSTEM PROTOTYPE DEMONSTRATION IN OPERATIONAL ENVIRONMENT
DEVELOPMENT	6	TECHNOLOGY DEMONSTRATED IN RELEVANT ENVIRONMENT
DEVELOPMENT	5	TECHNOLOGY VALIDATED IN RELEVANT ENVIRONMENT
DEVELOPMENT	4	TECHNOLOGY VALIDATED IN LAB
RESEARCH	3	EXPERIMENTAL PROOF OF CONCEPT
RESEARCH	2	TECHNOLOGY CONCEPT FORMULATED
RESEARCH	1	BASIC PRINCIPLES OBSERVED

TRL 6 – Public Release or Initial Commercialisation Feasibility Study

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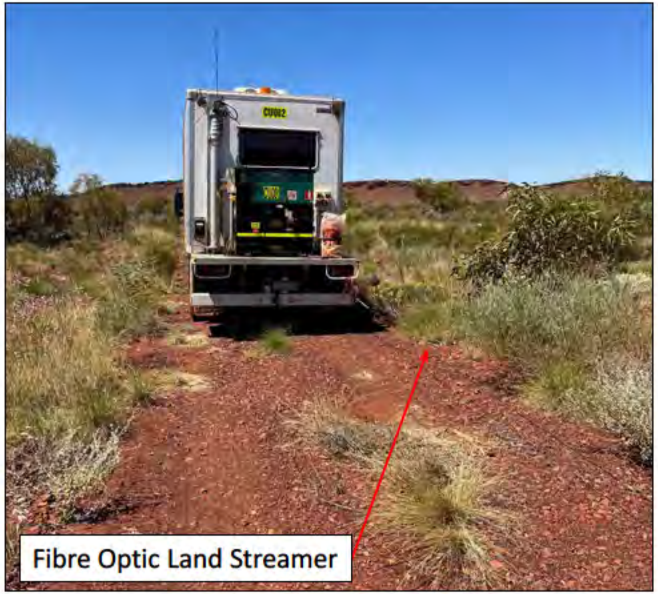
Fibre Optic Land Streamer - Prototype



TRL 6 – Public Release or Initial Commercialisation Feasibility Study

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Light 3C Seismic Source - Prototype

[redacted]

[redacted]

TRL 5 – Public Release or Initial Commercialisation Feasibility Study

ML DAS Denoising Algorithms

- Open-source access – Library of pre-trained neural networks

+

- Embedding in commercial software – external vendor (initial conversation)

ML Event Detection/Location Algorithms

- Open-source access codes

  +

- Embedding in commercial software – external vendor

Interferometric MASW + Tomography (+ Ambient Noise)

- Open-source access codes

  +

- Embedding in commercial software – external vendor

TECHNOLOGY READINESS LEVEL (TRL)

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Project 5
Seismic in the Drilling Workflow
Project update

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Project 5
MinEx CRC

Agenda

- HSE (KT)
- Project 5 Team and PhD students updates (KT)
- Project update (KT)
  - Milestone M12 Workshop on Machine Learning approaches (KT)
  - Data Processing and Inversion for Seismic While Drilling and Mining Using DAS (EH)
  - Update on 3C acquisition with DAS (3C source) (KT)
  - Milestone M11 Commercialisation and IP Roadmap outputs utilised to facilitate Phase III planning
- AOB

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Project 5 Team and PhD students updates

Project Students – all on track

- Mikhail Vorobev - PhD student

  Working on the detection and location of passive events with a combination of geophones and DAS

- Nikita Beloborodov - PhD student

  A paper draft is ready

  Laric Hawkins Award “for the most innovative use of a geophysical technique from a paper presented at the conference” ASEG Discovery Symposium

- Emad Al-Hemyari - PhD student

  The second paper is submitted

  Student Panellist at MinEx annual conference

Milestone M12
Workshop on Machine Learning Approaches

at MinEx Annual Conference 2024

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Workshop on Machine Learning Approaches

Theory-Guided Data Science (TGDS) Approach for Subsurface Characterization	Olivia Collet Curtin University
Multi-mineral segmentation of micro-tomographic images using a convolutional neural network	Jiabin Liang CSIRO
Removing Instrumental Noise in Distributed Acoustic Sensing Data: A Comparison Between Two Deep Learning Approaches	Olivia Collet Curtin University
Understanding the Complexity of Supervised Deep Learning for Detecting and Locating Passive Seismic Events Recorded with DAS: A Case Study	Emad Al-Hemyari Curtin University
Machine-Learning Based Event Detection and Arrival-Picking in Continuous DAS Recordings	Nepomuk Boitz Freie Universität Berlin

Workshop on Machine Learning Approaches

- Attendance (open to all MinEx members)
    - ~ Participants in total
        - In Person ~ 9 participants
        - Online ~ 8 participants

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Data Processing and Inversion for Seismic While Drilling and Mining Using Distributed Acoustic Sensing

Background

Last PRP Meeting:

- Regenerating Training Data
  - Extending microseismic AOI to shorter offsets
  - Include more time shifts (200ms)
  - Including noise recordings from multiple wells
  - Narrowing signal scalar range
- Prediction on wells CRC3, CRC4 & CRC6
  - Testing for geometry generalisation

This PRP Meeting:

- Published article
- Overview of latest results
- Problem Complexity

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Australian Government
Department of Industry, Science, Energy and Resources

Business Cooperative Research Centres Program

Published Article

sensors

MDPI

Article

Supervised Deep Learning for Detecting and Locating Passive Seismic Events Recorded with DAS: A Case Study

Emad Al-Hemyari, Olivia Collet, Konstantin Tertyshnikov and Roman Pevzner *

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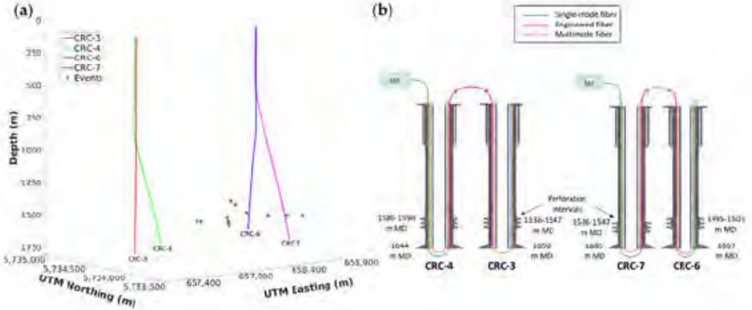
emad.al-hemyari@postgrad.curtin.edu.au (E.A.-H.); olivia.collet@curtin.edu.au (O.C.);
konstantin.tertyshnikov@curtin.edu.au (K.T.)
* Correspondence: r.pevzner@curtin.edu.au

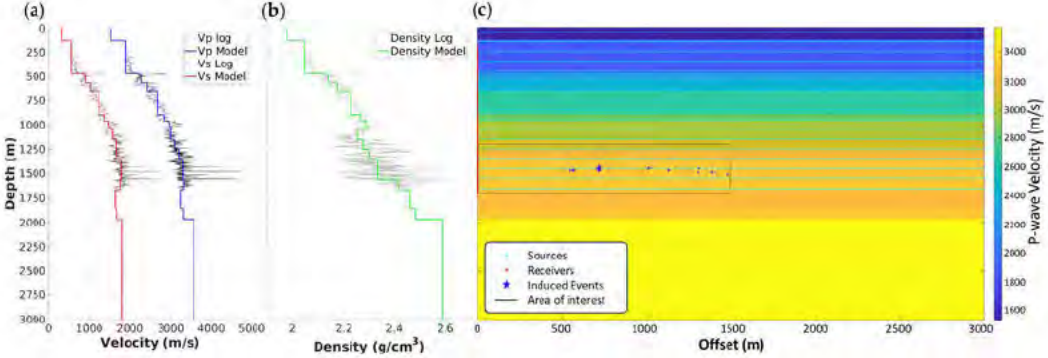
Abstract: Exploring shallow mineral resources requires acquiring denser seismic data, for which Distributed Acoustic Sensing is an effective enabler and relevant to mining operations monitoring. Passive seismic can be of interest in characterizing the subsurface; however, dealing with large amounts of data pushes against the limits of existing computational systems and algorithms, especially for continuous monitoring. Hence, more than ever, novel data analysis methods are needed. In this article, we investigate using synthetic seismic data, paired with real noise recordings, as part of a supervised deep-learning neural network methodology to detect and locate induced seismic sources and explore their potential use to reconstruct subsurface properties. Challenges of this methodology were identified and addressed in the context of induced seismicity applications. Data acquisition and modelling were discussed, preparation workflows were implemented, and the method was demonstrated on synthetic data and tested on relevant seismic monitoring field dataset from the Otway CO_2 injection site. Conducted tests confirmed the effects of time shifts, signal-to-noise ratios, and geometry mismatches on the performance of trained models. Those promising results showed the method's applicability and paved the way for potential application to more field data, such as seismic while drilling.

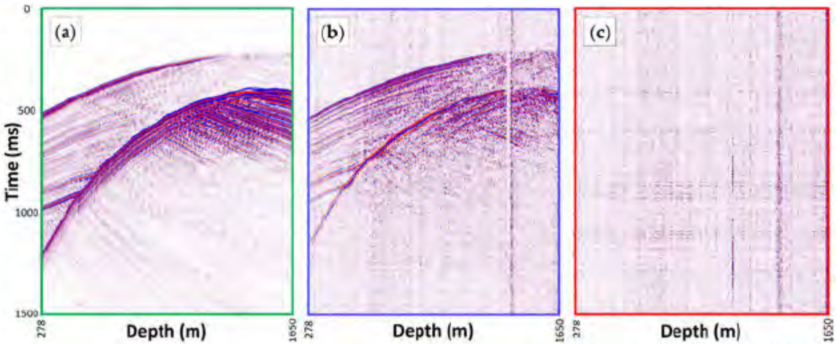
Open Access | Feature Paper | Article

Data acquisition and modelling

- Induced seismicity dataset
- Model building and Modelling
- Field vs. Modelled Data





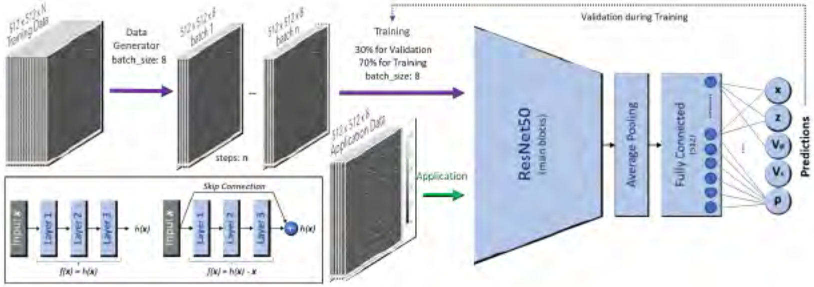


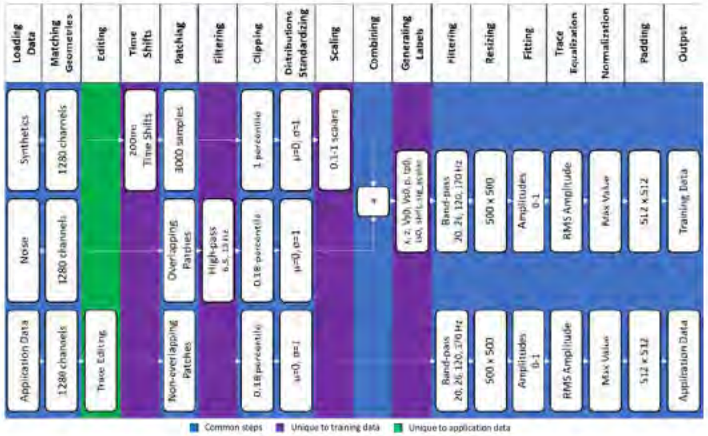
Supervised Deep Learning

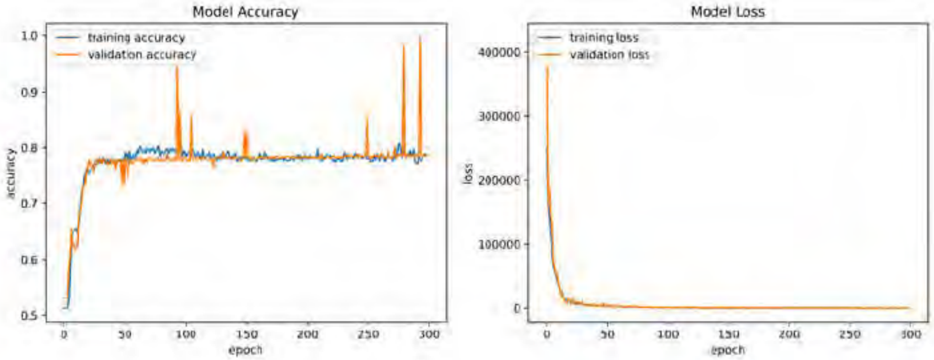
– ResNet50

– Data Preparation Workflows

– Training







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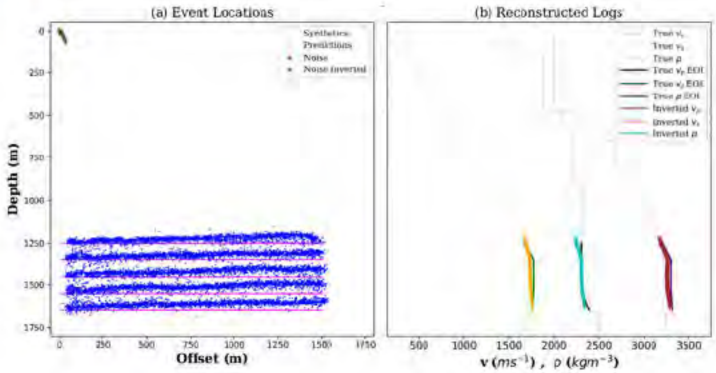
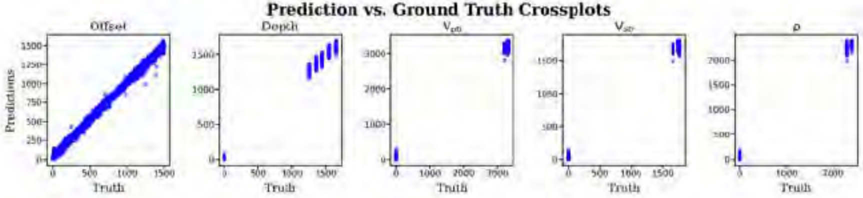
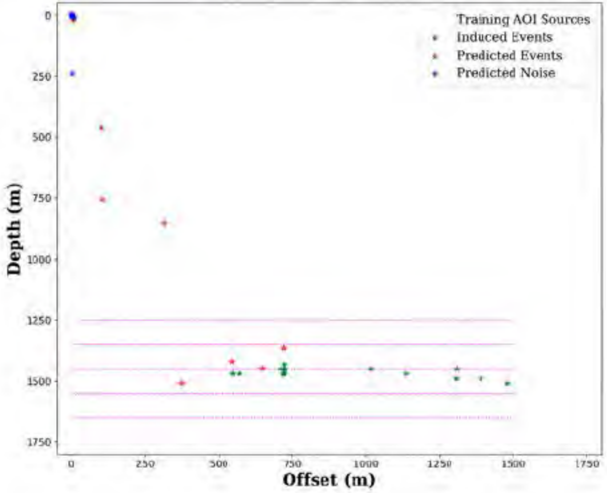
Results

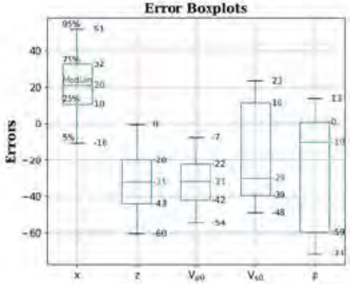
– Testing on Synthetic Data

– Application on Field Data









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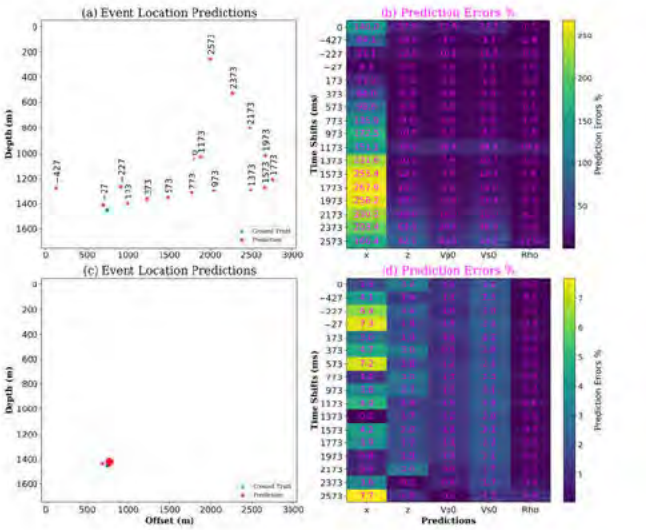
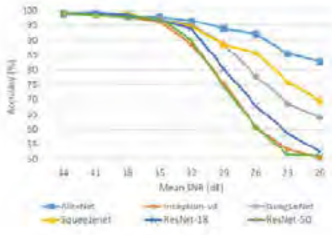
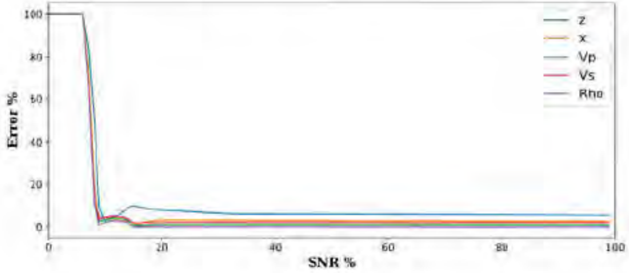
Discussion

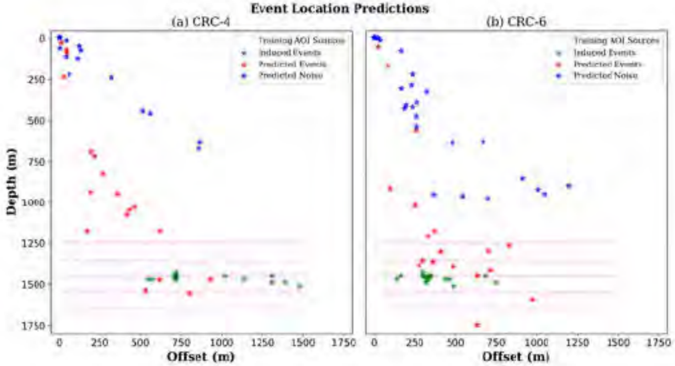
- The Problem Complexity
- Effects of Time-Shifts
- Effects of Signal-to-Noise Ratio
- Application on Other Wells Field Data





Dale, et al., 2021





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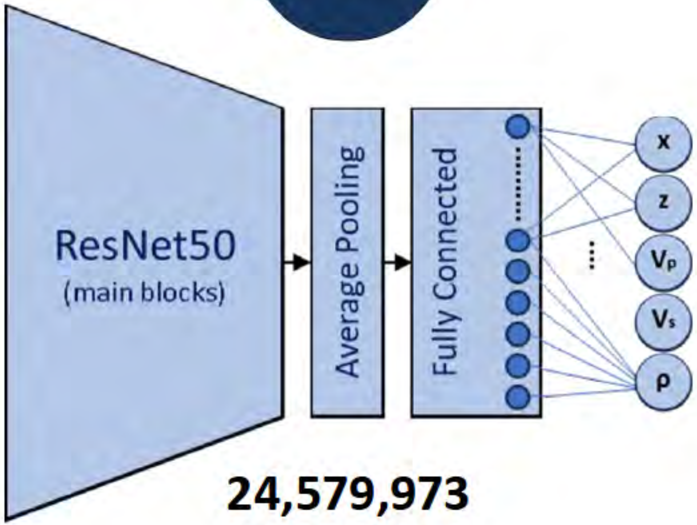
Problem Complexity

3

Training Dataset Complexity

1



24,579,973 Trainable Parameters

2

Number and Scales of Predictions

Future Work

- **Continue to optimise the CNN training**
  - Using AlexNet architecture
  - Transfer learning
  - Data generators
- **Utilisation of HPC resources to scale up**
  - Extend synthetic modelling
    - Data sufficiency
    - Model SWD data
  - Extend SNR perturbations
  - Incorporate all learnings
- **Retrain & Predict**
  - Predictions using overlapping data patches

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Submitted Article

geosciences

MDPI

Article

Multichannel Analysis of Surface Waves: A Passive Seismic Dataset from a Mineral Exploration Site in the Pilbara Region of Western Australia

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Abstract: Passive seismic surveys have interested many geological and geotechnical applications in the past few decades, mainly in reconstructing models of near-surface properties. They are also interesting to mineral exploration of shallow deposits where targets lay on or within the bedrock and are covered by loose sediments above. A good understanding of the cover thickness and its lateral variations is essential to map the top of the bedrock. Qualitative analysis of passive seismic data acquired by geophones and DAS showed the potential and challenges of using different sensing technologies. We investigate the use of passive seismic surveys to retrieve surface waves. They were mainly used to retrieve Rayleigh waves and invert them to reconstruct shear-wave velocity profiles of the near-surface. Comparing dispersion images from both geophone and DAS data improved our understanding of contributing factors affecting their quality. Some of these factors are related to the surrounding environment, present noise sources, acquisition setup, and the methods used in reconstructing dispersion images and inverting them. We have successfully demonstrated the multichannel analysis of surface waves (MASW) using a relatively short period of continuous recording using a 2D array of geophones at a mineral exploration site in the Pilbara region of Western Australia.

3C borehole seismic data with DAS
Update on 3C source

Image redacted for reasons of commercial sensitivity

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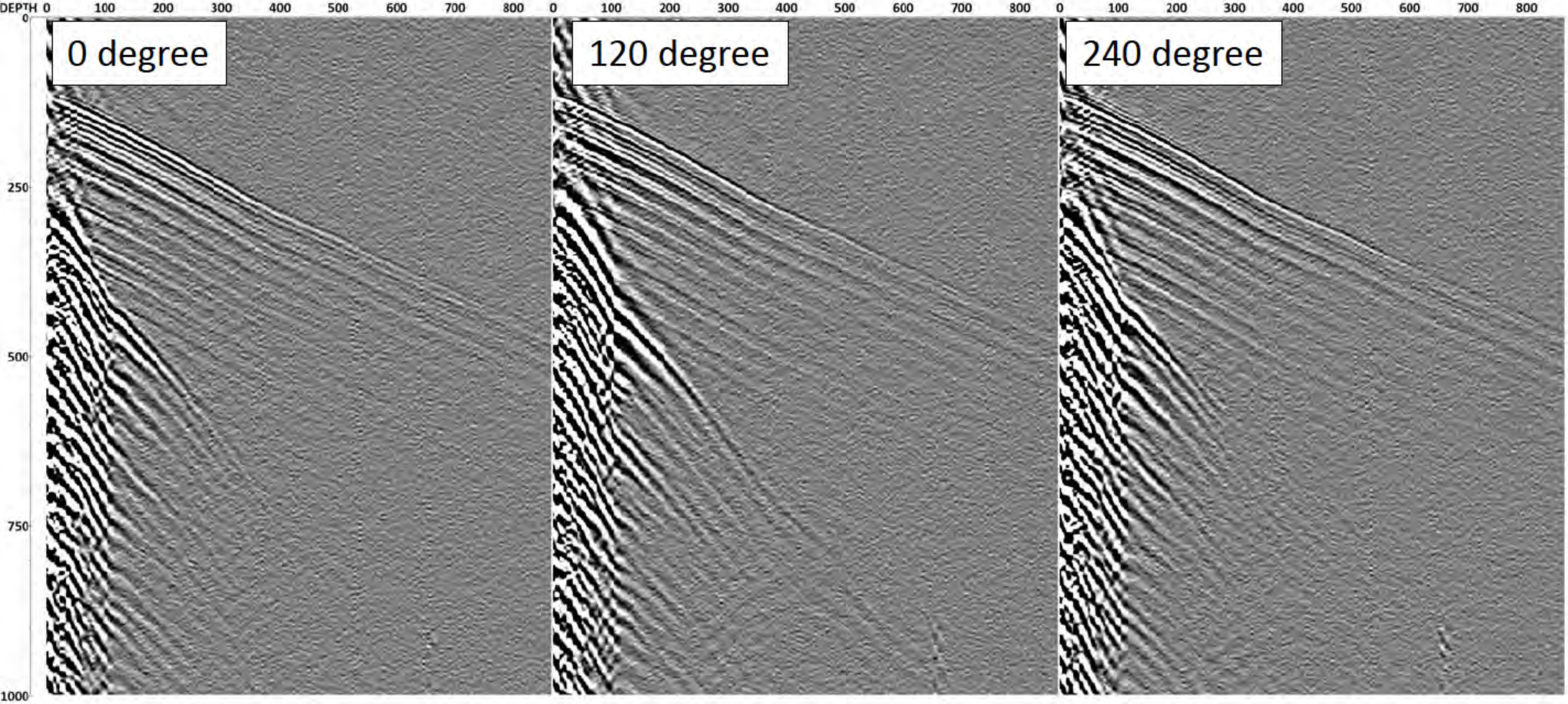
3C Source

Sweep 12-50 Hz

Data in the acquisition coordinate system



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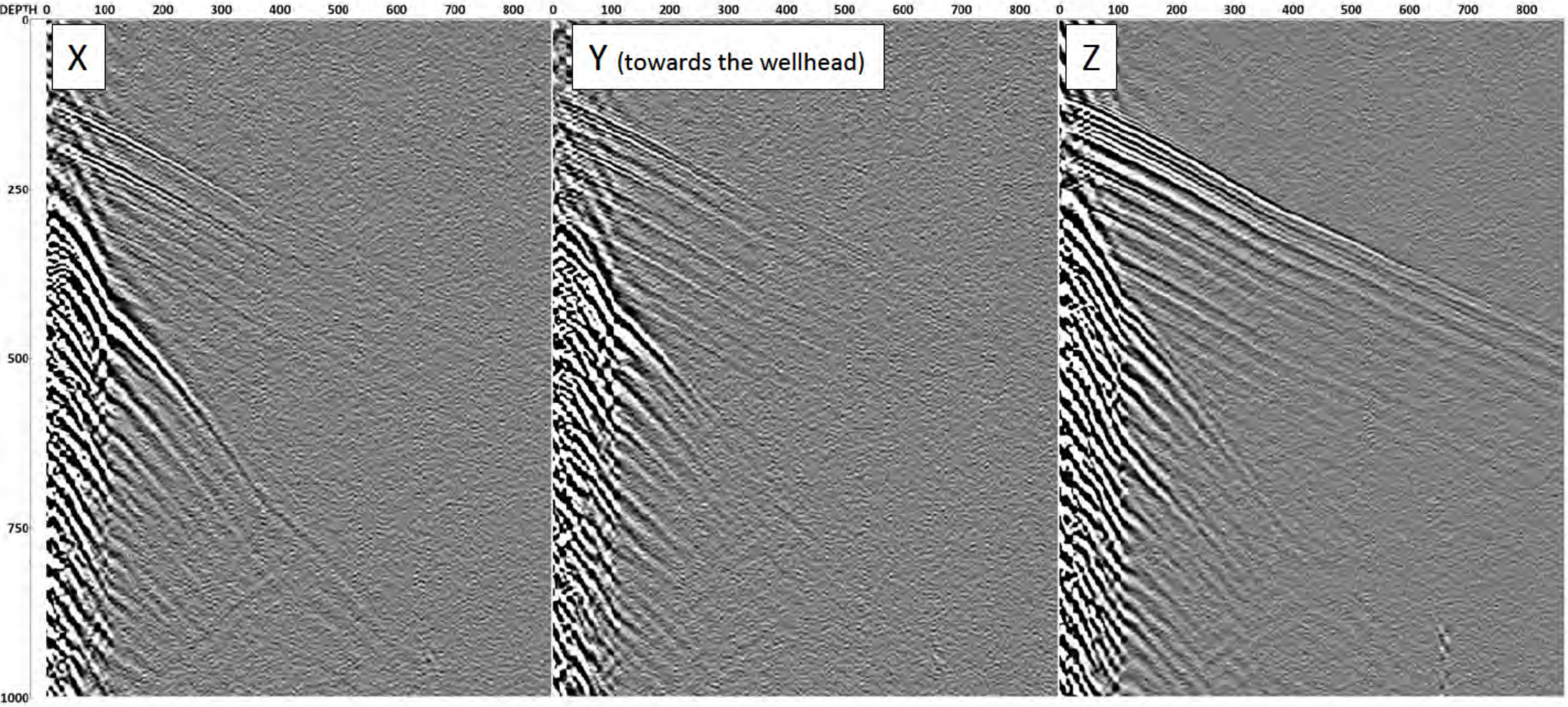
Sweep 12-50 Hz

3C Source

Data in the orthogonal coordinate system



3C Source

Patent

Next Steps:

- Increase vector fidelity
- Test with baseplate accelerometers/geophones
- Multi-channel deconvolution during acquisition

Milestone M11 Commercialisation and IP Roadmap outputs utilised to facilitate Phase III planning

Outputs implemented into Phase III

- DAS vs standard seismic
  - Field trials (2026 - 2027)
- 3C Seismic source for DAS
  - Field trials (2025)
  - Patenting?
- Algorithms & Software
  - GitHub library

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Recommendations for Instrumented Field Sites with Fibre Optic Sensors

Open-Source Library of Pre-Trained Neural Networks for DAS Data Denoising and Application to Data Acquisition

Project 5: Seismic in the Drilling Workflow

Authors:
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Date: 03 November 2024
MinEx CRC Report 2024/61

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EXECUTIVE SUMMARY	
Developments of fibre optic distributed sensing technology within Project 5 have demonstrated benefits of its application in mineral exploration. The value of instrumenting field sites with fibre optic sensing technologies is to provide comprehensive and efficient data acquisition of active and passive seismic with ability to fuse it with temperature and static strain measurements as well as accommodate real-time data acquisition and monitoring. Deploying a large number of sensors at field sites improves data collection as it allows the recording of high-resolution data at unprecedented spatial sampling with broad frequency band sensitivity. Fibre optic sensors offer unique advantages over traditional sensors, including durability, minimal space requirements, and the ability to leverage existing telecommunications infrastructure for cost-effective deployment. These attributes make fibre optics a preferred choice for long-term monitoring deployments in harsh environments. The installation of optical fibre sensing arrays can be easily adapted for a variety of environments, including downhole boreholes and surface installations. Fibre optic cables can be deployed using methods such as cementing behind the casing, tubing-conveyed deployment, and wireline suspension, offering flexibility based on site-specific requirements. A single fibre optic cable can simultaneously collect data for DAS, DTS, and DSS systems, providing comprehensive, multi-parameter insights from a single deployment. This reduces costs and improves data integration. Selecting the optimal fibre optic sensing solution for each site requires considerations that include the type of fibre optic cable, the choice of the interrogator, and the deployment strategy, all of which can influence data quality and cost-effectiveness. Advancements in machine learning workflows, such as deep learning for noise reduction and seismic event detection, are vital methods for enhancing data quality and interpretation. These outlined advantages of distributed fibre optic sensing are supported by multiple case studies from various field trials conducted within Project 5. We released an open-source library of pre-trained two neural networks for de-noising instrument noise (electronic, thermal), which is inherent to each DAS recording system. The interrogator unit design dramatically affects the instrument noise patterns, so the library will be continuously updated with models for various instrument architecture and recording parameters. The de-noising algorithms are developed in Python and can be implemented in commercial QC software for real-time application during the acquisitions. The acquisition test of the denoising approaches was carried out at the Curtin research facility with a small seismic source. The results are summarised in a recommendations report and the release notes of the open-source library of pre-trained neural networks for de-noising DAS data and application in field data acquisition.	
OBJECTIVE(S)	**RESULT(S)**
Provide recommendations for an instrumented field site with fibre optic sensors. Release open-source library of pre-trained neural networks for de-noising of DAS data and application in field data acquisition.	Recommendations on the instrumented field site with fibre optic sensors are combined in a comprehensive report. Two advanced machine-learning pre-trained neural networks are published on GitHub. Trial of application of the developed ML denoising algorithms for field acquisition with a low power source is conducted at the Curtin research well facility.
NEXT STEP(S)	**TIMING**
Further continuous updates of the machine learning de-noising open-source library. Create and add models for other instrument architectures.	1-3 years

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Conducting additional trial at the instrumented field sites. Apply lessons learned from experiments in further studies.	

MINEX CRC MILESTONES
PJ05-Ph02-M23 CY24Q3 Report on the trial application of denoising algorithms during field data acquisition PJ05-Ph02-M24 CY24Q3 Release open-source library of pre-trained neural networks PJ05-Ph02-M25 CY24Q3 Report on recommendations for an instrumented field site and associated workflows.
UTILISATION/COMMERCIALISATION OPPORTUNITIES
Implementation of the ML algorithms to commercial seismic processing software. Open-source library of pre-trained neural networks for different DAS interrogators is released.
IP
None
CONFIDENTIALITY
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Recommendations for Instrumented Field Sites with Fiber Optics and Associated Data Workflows

K. Tertyshnikov*, R. Pevzner*

*MinEx CRC, Curtin University

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1. Introduction

The mineral exploration sector is increasingly driven by the need to discover new, economically viable deposits in more challenging and remote environments. As global demand for critical minerals and metals grows, the necessity for advanced exploration and monitoring technologies has become more explicit. Traditional exploration approaches sometimes lack the detail required to provide accurate subsurface insights, particularly in complex geological settings. To address these challenges, there is a need to integrate novel technologies that enhance data quality, operational efficiency, cost-effectiveness for decision-making processes.

Fibre optic sensing technology presents a transformative solution for the mineral exploration industry by enabling more cost-effective seismic acquisitions and seismic monitoring. Deploying fibre optics in instrumented field sites enables continuous, high-resolution data not only of acoustic signals but also of temperature and static strain. This capability is essential for characterising geological formations, detecting mineralisation zones, and understanding dynamic subsurface processes. A single fibre optic cable can allow simultaneous recording of Distributed Acoustic Sensing (DAS), Distributed Temperature Sensing (DTS), and Distributed Strain Sensing (DSS) data, which collectively provide a toolkit for exploration data acquisition and real-time site monitoring.

This report provides an overview of the advantages of deploying fibre optic technologies at field sites in mineral exploration based on multiple case studies across the project's life. Fibre optics offer high-resolution, rapid acquisition of active data and, if necessary, continuous data acquisition along entire exploration boreholes, allowing the mapping and characterisation of surrounding ore bodies and geology. Fibre optic systems reduce the need for multiple discrete sensors, minimising operational costs in data acquisition. Continuous data collection with fibre arrays enables real-time analysis, hazard monitoring and mine operations monitoring, as well as using passive energy for subsurface characterisation for adaptive exploration strategies and decision-making during drilling operations. More rapid acquisition with smaller seismic sources and fibre optic arrays helps reduce environmental footprints.

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The report outlines several factors for the instrumentation of a field site that need to be considered for optimal configuration. Namely, selecting the fibre optic deployment options and optimising installation methods to maximise the benefits of the technology; choosing the cable design and fibre type for sufficient data quality; and selecting an interrogator unit for the appropriate acquisition of the seismic wavefield in particular acquisition settings. Proposed denoising machine learning workflows are developed to streamline data quality improvement processes during the acquisition. Supervised deep learning approaches are identified for detection and location of passive events and for subsurface characterisation.

The report emphasises the enhancement in efficiency and effectiveness in mineral exploration with adopting the fibre optic sensing for instrumenting the field sites as well as in overall improvement in sustainability and safety.

2. Instrumented sites cased studies

2.1 Lake Cary (2D and 3D survey with buried fibre optic cable for Matsa Resources)

The Lake Carey experiment, detailed in the study by Ziramov et al. (2022), involved the application of Distributed Acoustic Sensing (DAS) technology for a 3D seismic reflection survey in a challenging hyper-saline environment. The objective was to demonstrate the effectiveness of fibre optic-based seismic surveying in mineral exploration, particularly in areas where traditional seismic methods face limitations due to environmental conditions.

The experiment was conducted on the soft, saturated, and hyper-saline clay surface of Lake Carey, Western Australia. This environment poses significant challenges for conventional seismic equipment due to equipment loss risks and corrosion. Lightweight, bare fibre optic cables were deployed across lines using a portable ploughing method. This method allowed for rapid deployment and minimised disturbance to the fragile lake surface. The DAS system was coupled with a portable seismic source (a percussion rod) that used 12-gauge blank cartridges, providing a cost-effective and flexible solution for

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seismic energy generation. Two interrogators were used to monitor deformation rates along the fibre optic cables, capturing seismic signals over a 1.5 km² survey area.

The DAS data, with its high spatial data density, enabled the formation of digital arrays prior to processing and allowed for effective multi-channel filtering, resulting in improved seismic imaging. The survey produced high-quality reflection seismic results down to a depth of 2 km, comparable to those obtained with more expensive traditional seismic methods. The experiment highlighted the benefits of using DAS in harsh environments like salt lakes, showing that fibre optic technology can offer substantial cost savings and enhanced data density compared to conventional geophone-based systems. The study identified challenges with cable-ground coupling due to surface roughness and temperature variations. Despite these challenges, DAS technology demonstrated its potential for low-cost, high-quality seismic acquisition in mineral exploration.

The Lake Carey survey is the first 3D seismic acquisition with fibre optics for mineral exploration. Overall, the Lake Carey experiment underscores the potential of DAS technology as a viable and efficient alternative for seismic exploration in environmentally challenging settings, offering significant advantages in cost, deployment ease, and data quality.

2.2. Fibre Optic VSP Seismic deployment – Chimera Prospect

The Chimera Prospect experiment aimed to test the FibreLine Intervention (FLI) downhole fibre optic tool for borehole seismic surveys in mineral exploration (Tetyshnikov et al. 2022). This experiment marked the first deployment of such a tool in a highly deviated (~60°) uncased mineral borehole. The FLI tool (Figure 1), designed for rapid deployment, unspools fibre optic cable down the bore, enabling distributed acoustic and temperature measurements.

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Figure 1 a) FLI probe in a case; b) FibreLine Intervention tool – a landing holder/plate on top of the bore and connected to an interrogator at the surface, probe deployed into the borehole.

The FLI tool was successfully deployed in a borehole, demonstrating its ease of deployment and effectiveness in acquiring high-quality seismic data. Various seismic sources were tested, including a vibroseis truck, a 700 kg weight drop, and a 45 kg accelerated weight drop. The results showed that even low-energy sources could provide adequate data quality for seismic velocity estimation. The Zero-Offset Vertical Seismic Profile (VSP) and Walk-Away VSP data collected helped construct a P-wave velocity model, identifying at least six fracture or fault zones intersected by the borehole (Figure 2).

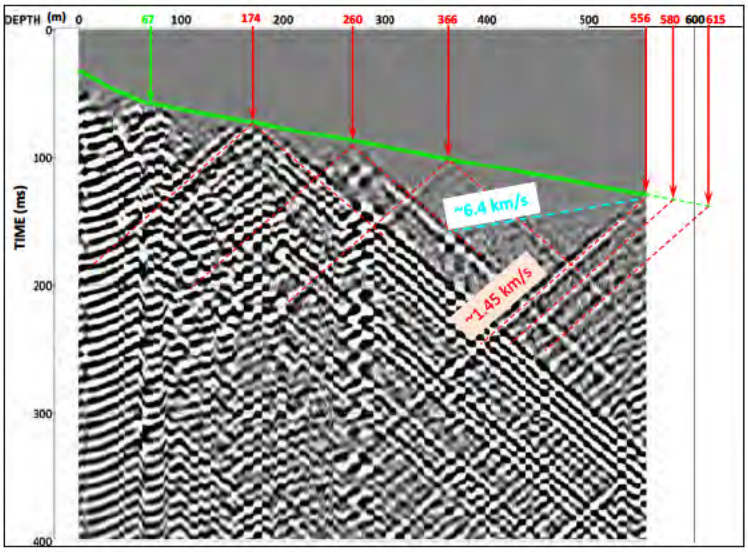

Figure 2 Zero-offset VSP shot gather after suppression of primary downgoing wavefield. Green line – first breaks (direct P-wave arrivals) (approximate depth of the regolith is shown by a green arrow and number); Red dashed lines – tube waves (approximate intersection of the fracture zones are shown by red arrows and numbers); Blue dashed line – reflection from a fracture zone.

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The study concluded that the FLI tool allows for efficient and cost-effective borehole seismic surveys, reducing the need for traditional geophone relocations and enabling rapid acquisition with minimal crew and equipment.

2.3. 3D DAS VSP in well with permanently installed cable for Coal Exploration (Anglo American)

The study explores the use of Distributed Acoustic Sensing (DAS) technology for 3D Vertical Seismic Profiling (VSP) in coal seam exploration at a coal mine in Queensland, Australia (Tertyshnikov et al. 2024). DAS technology utilises fibre-optic cables to record seismic data, providing a cost-effective alternative to traditional borehole seismic acquisition methods.

Fibre-optic cables were cemented in three vertical boreholes to image coal seams at approximately 400 m depth. The DAS acquisition was conducted concurrently with a surface 3D seismic survey, using a vibroseis truck as the seismic source. High-quality 3D VSP seismic data was obtained, clearly identifying coal seams around the boreholes (Figure 3). The study tackled imaging difficulties caused by near-surface basalt layers, which typically degrade seismic signals. Synthetic modelling was used to optimise data processing and enhance the interpretation of results. The use of DAS provided dense spatial sampling along the boreholes, reducing the cost and time associated with data acquisition compared to conventional geophones. The study demonstrated that DAS could be effectively integrated into standard coal exploration workflows.

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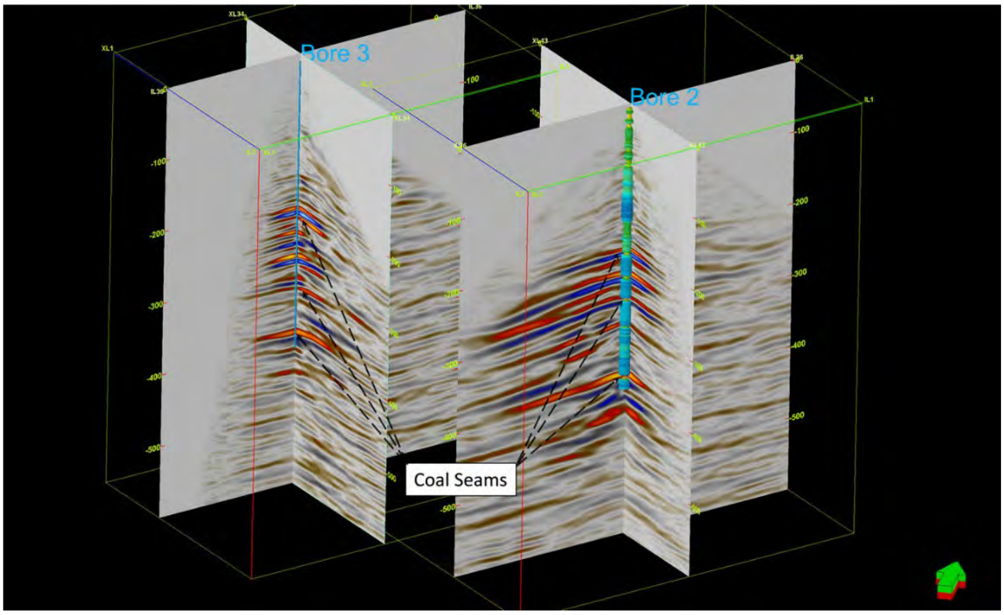

Figure 3 3D DAS VSP migrated volumes for two boreholes. The density log is overlayed on the seismic volume.

Permanently installed fibre-optic cables offer additional benefits, such as ongoing monitoring of underground stability and detection of methane accumulations, enhancing safety and operational efficiency in mining operations. Overall, the study highlights DAS technology's potential for coal seam exploration and monitoring, offering both economic and operational advantages over traditional seismic methods.

2.4. The BHP Bonobo Passive Seismic Survey

The BHP Bonobo Passive Seismic Survey, conducted in 2023, utilised distributed acoustic sensing (DAS) technology and geophones to explore subsurface characteristics at a BHP exploration site. The main objective was to assess the feasibility of passive seismic methods for subsurface characterisation during drilling operations (Tertyshnikov et al. 2023).

The survey combined surface and downhole passive seismic data acquisition. A 570 m surface DAS cable was buried along a track, while a 145 m DAS cable was deployed in the first drilled borehole. Additionally, 128 wireless 3-component geophones were deployed on the surface, and data were

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recorded concurrently with drilling activities. The survey utilised various processing techniques, including Multi-Channel Analysis of Surface Waves (MASW) (Figure 4) and Horizontal-to-Vertical Spectral Ratio (HVSR) methods. These methods helped in constructing shear wave velocity profiles up to a depth of 100 m, which correlated well with borehole log data. The presence of noise from drilling operations, particularly from diesel engines, posed challenges for data quality. Filtering techniques and selective signal-to-noise ratio stacking were employed to enhance data quality.

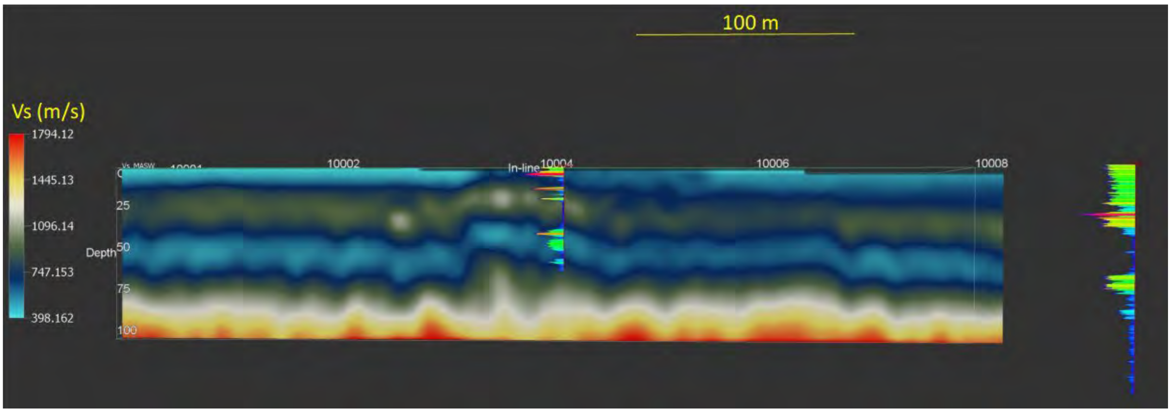

Figure 4 Near-surface Vs velocity model obtained from MASW with overlaid results of gamma-logging.

The DAS data provided high-resolution insights into subsurface structures, demonstrating the viability of using fibre optic technology for passive seismic surveys. The study successfully characterised subsurface conditions. The Bonobo survey showcased the effectiveness of combining DAS technology with traditional geophones for passive seismic surveys. The results demonstrated the potential of DAS for high-resolution, subsurface imaging and provided a basis for future improvements in passive seismic data acquisition and analysis methodologies in the mining industry.

2.5. Ultra-high resolution cross hole seismic with permanent DAS installation

The study presents a cross-well seismic field trial using Distributed Acoustic Sensing (DAS) technology with a high-frequency sparker source conducted at the CO2CRC's Otway International Test Centre in Victoria, Australia. The trial aimed to demonstrate the effectiveness of DAS in high-resolution subsurface imaging for tasks such as mineral exploration and CO2 leakage monitoring.

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The trial involved two shallow wells: Brumbys-3 (100 m deep) for CO_2 injection and Brumbys-1 (122 m deep) for deploying a high-frequency (1.2 kJ) sparker source. Fibre optic cables were cemented in both wells, and DAS data were recorded using a Terra15 Treble+ interrogator. The experiment included injecting approximately 17 tons of CO_2 into Brumbys-3 over eight days. Several datasets were acquired, including baseline data before injection and multiple post-injection data points, capturing changes in seismic signals due to CO_2 injection. High-resolution seismic data showed a clear time delay and polarity inversion of direct wave signals in response to CO_2 injection, indicating a detectable change in acoustic impedance caused by CO_2 presence.

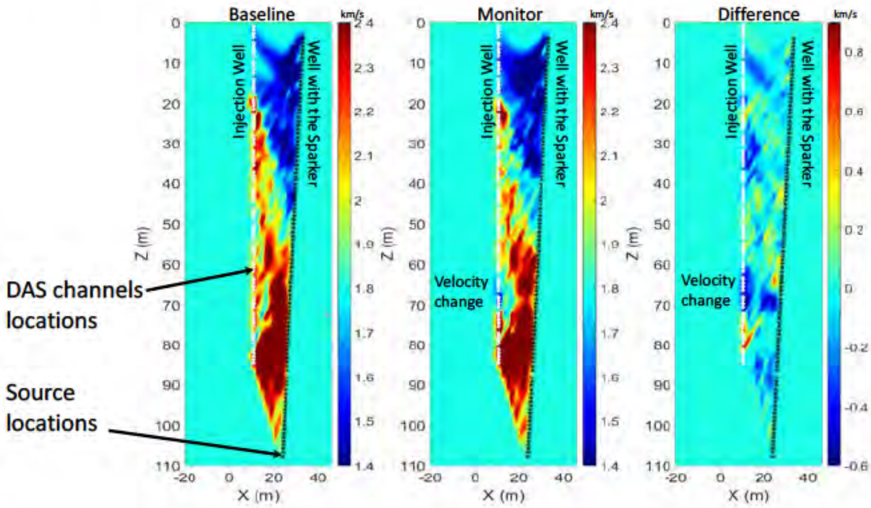

Figure 5 Cross-hole seismic with DAS Tomography Results.

The field trial successfully demonstrated the application of DAS technology with a high-frequency source for precise subsurface characterisation. This method allows for rapid and effective recording of seismic data, enabling high-resolution tomographic imaging (Figure 5) for detecting small objects like mineral deposits or monitoring small CO_2 leakage. The results underscore the potential of combining DAS with high-frequency seismic sources to enhance geophysical exploration and monitoring capabilities in challenging environments.

2.6 Downhole DAS in well permanently instrumented during plug-and-abandonment.

The study focuses on transforming an abandoned well, the Harvey 3 well in Western Australia, into a permanent geophysical monitoring array using distributed fibre-optic sensing technologies (Sidenko et

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al, 2022). The Harvey 3 well, which was part of the South West Hub CO_2 geosequestration project, was instrumented with a fibre-optic cable during its decommissioning to monitor the cementation process and enable continuous seismic and temperature monitoring.

The fibre-optic cable was installed inside the well during decommissioning operations, allowing Distributed Temperature Sensing (DTS) and Distributed Acoustic Sensing (DAS) to monitor the cementing process. DTS data provided insights into cement curing and temperature distribution along the wellbore, while DAS detected vibrations related to cement setting. DAS data captured vibrational disturbances during the cement setting process, and DTS data highlighted temperature anomalies that revealed heterogeneities in cement quality. These observations help assess the integrity of the cement job and identify potential issues, such as crossflow behind casings.

A year after the decommissioning, a weeklong passive seismic survey using the installed fibre-optic array detected a range of seismic events, including earthquakes, mine blasts, and ocean microseisms. The data from these events provided valuable information about subsurface properties and demonstrated the potential for long-term passive seismic monitoring. The experiment successfully demonstrated that abandoned wells could be repurposed into permanent geophysical monitoring stations using fibre-optic sensing technology. Such installations can provide continuous, high-resolution data for a variety of applications, including monitoring well integrity, subsurface changes, and natural seismicity.

2.7 Microseismic monitoring in coal production using DAS and geophones: Moranbah North Project

The research builds on a dataset from a field experiment conducted at the Moranbah North coal mine in Queensland, Australia, where DAS technology was deployed alongside conventional geophone arrays to monitor microseismic events during longwall mining. The experiment involved the installation of three boreholes with fibre optic cables for DAS monitoring and a 3D surface geophone array set up

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in front of the advancing mining face. As the mining machine (shearer) moved forward, the surface geophone array was redeployed, resulting in four distinct spreads of continuous geophone records.

Preliminary results showed (Vorobev M. 2024) the ability of DAS to detect and locate microseismic events in both time and space. The initial data quality control revealed the presence of random noise bursts, noisy channels, and correlated noise caused by the mining shearer and operational activities. Despite these challenges, the DAS data, when combined with the geophone data, allowed for improved seismic event detection and localisation. The study utilised the STA-to-LTA ratio thresholding algorithm for event detection and used travel times computed with a 1D velocity law for initial event localisation. The DAS data also provided valuable information for refining velocity models, although its signal-to-noise ratio was generally lower than that of the geophone data.

The field example highlighted some challenges associated with DAS deployment, such as the need to optimise the DAS data processing workflow to handle high noise levels and enhance weaker event detection. The analysis also showed that the amplitude of microseismic events decays with distance, which means that fewer events are detected with DAS compared to the surface geophone arrays. Nevertheless, DAS offers the advantage of continuous monitoring over the entire borehole length, providing critical data that cannot be obtained from conventional point-based sensors alone.

The proposed approach for passive seismic monitoring using DAS technology is expected to significantly improve spatial coverage and real-time hazard prediction in mining environments. The enhanced detection algorithms and refined velocity models developed in this study will reduce the detection threshold for microseismic events, allowing for more precise estimates of stress distribution and energy release.

In conclusion, this research aims to establish a standard methodology for integrating DAS technology into passive seismic monitoring workflows, providing a more comprehensive and efficient solution for subsurface imaging and hazard prediction in complex geological environments. The findings from the

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Moranbah North field example demonstrate the potential of DAS to complement traditional geophone arrays and significantly enhance our understanding of subsurface dynamics.

2.8 Curtin field test site

The Curtin GeoLab Well Calibration and Training Facility is a specialised site designed for testing, calibrating, and training with geophysical and other scientific equipment. Located on Curtin University's Bentley campus, the facility features the research well—a unique ~900 m deep vertical borehole lined with fibreglass (150 mm inner diameter) to prevent interference with electronic or electromagnetic measurements. A fibre-optic cable runs along the entire length of the well, looping back at the bottom, providing approximately 2 km of fibre, which includes both single-mode and multi-mode fibres.

This facility offers exceptional capabilities for performing standardised measurements, re-testing, and calibrating equipment, as well as testing and configuring instruments before deployment. The availability of such a test well is highly beneficial for researchers, as access to actual field sites is often restricted, leaving little opportunity for field trials. Additionally, the high costs associated with using boreholes elsewhere are mitigated, making the GeoLab a cost-effective and accessible solution for testing and development.

The GeoLab is equipped with a wide range of state-of-the-art geophysical and scientific equipment, making it a highly versatile facility for research and training. The available equipment includes:

- Interrogators:
    - Distributed Acoustic Sensing (DAS): Silixa iDAS v2, iDAS-MG, Terra15 Treble+, Fotech Helios, Alcatel Subsea Networks OptoDAS.

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- Distributed Temperature Sensing (DTS): Bendweaver FireLaser.
- Distributed Strain Sensing (DSS): Silixa iDSS.

- Seismic Receivers:
  - Contemporary conventional seismic receivers, totalling 5,000 channels (comprised of Sercel 428 and Unite systems).
  - Downhole receivers, including Sercel SlimWave systems and hydrophone arrays.
- Seismic Sources:
  - Two Inova UniVibe 26,000 lbs vibroseis trucks.
  - Several weight drop systems ranging from 45 kg to 700 kg.
  - High-frequency sources, such as sparkers.
- Recording and Acquisition Systems:
  - Recording trucks equipped for both surface seismic and borehole acquisition, featuring a 3 km winch for deep well operations.
- Geophysical Equipment:
  - Ground Penetrating Radar (GPR) and Electromagnetic (EM) equipment.
  - Magnetometers for magnetic surveys.
- Support Facilities:

• Mechanical and electrical workshops for equipment maintenance, repair, and custom fabrication.

As such, this field research site has been utilised for a variety of tests and experiments.

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2.8.1. Comparison between geophone and downhole DAS

The study (Zulic et al. 2022) compares the performance of Distributed Acoustic Sensing (DAS) and conventional geophone sensors for borehole seismic acquisition. The research is motivated by the growing use of DAS technology in geophysical applications and the need to understand how DAS measurements compare to traditional geophone data.

The experiment aimed to compare the absolute strain rate measurements from DAS and geophones, which naturally measure different properties: DAS measures strain rate along a fibre optic cable, while geophones measure particle velocity. Data was acquired during a walk-away Vertical Seismic Profile (VSP) experiment, where both a single-mode fibre optic cable (DAS) and conventional three-component borehole geophones were used. The geophone data was converted to strain rate to allow direct comparison with DAS measurements (Figure 6). The study also simulated different gauge lengths to explore their impact on DAS signal quality. The results demonstrated that DAS and geophones show similar absolute strain rate values when converted appropriately. This suggests that, despite differences in how these sensors operate and the factors influencing their measurements (e.g., coupling quality, cable design), both DAS and geophones can provide comparable data quality for certain seismic applications.

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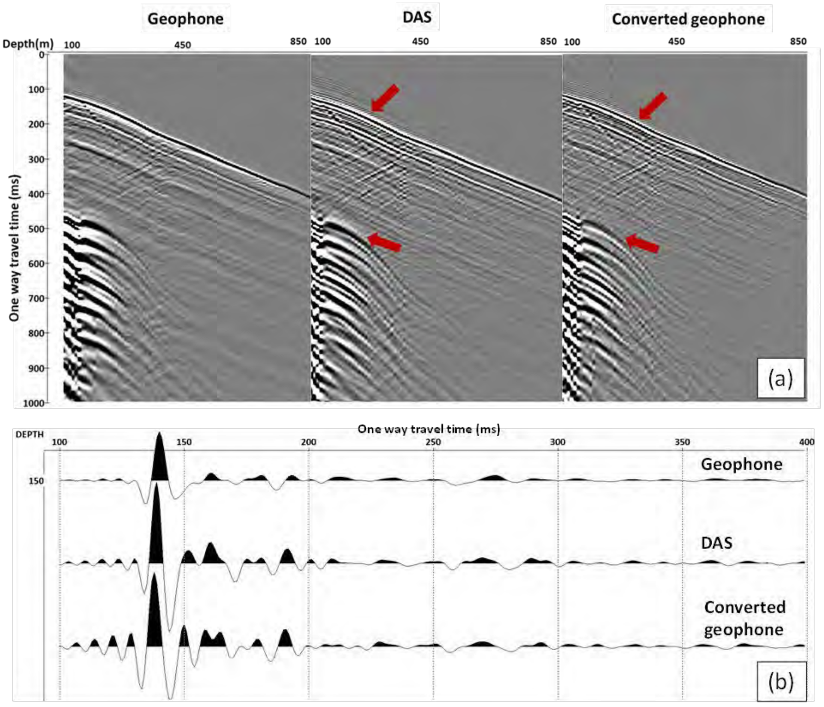

Figure 6 Near offset example: (a) from left to right: gathers of Geophone, DAS and converted geophone response; (b) from top to bottom: trace at a depth of 150 m of Geophone, DAS and converted geophone response. The red arrows indicate the difference in phase of P- and S direct waves between recorded DAS and converted geophone data.

The findings support the use of DAS as a viable alternative to traditional geophone-based methods for borehole seismic monitoring, especially where continuous and dense spatial sampling is required. The ability to simulate DAS response using dense geophone datasets further enhances the understanding and optimisation of DAS parameters for specific applications. Overall, the study highlights the potential for DAS technology to complement or even replace conventional geophone systems in specific scenarios, offering more flexible and scalable solutions for seismic monitoring and subsurface imaging.

2.8.2. Long-Range DAS-VSP Trials at Curtin GeoLab Facility

This study presents the results of long-range Distributed Acoustic Sensing (DAS) Vertical Seismic Profiling (VSP) trials conducted at the Curtin GeoLab facility. The research explores the feasibility of

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using DAS for active VSP data acquisition over extended fibre lengths, a critical challenge where long-distance signal transmission is required.

The primary goal was to evaluate the performance of DAS interrogators, specifically those designed for subsea applications, in acquiring high-quality seismic data over extended optical fibre lengths up to 140 kilometres. This is particularly relevant for offshore environments where signal transmission through long umbilical cables can be problematic. The experiment involved using a standard 26,000-pound INOVA UniVib seismic vibrator as the seismic source, performing linear sweeps from 6 to 150 Hz. Various lengths of additional bare G652D fibre were added to the optical path to simulate long cable scenarios, ranging from 0 to 140 kilometres. The study also tested different gauge lengths (ranging from 2 to 30 m) and vibroseis power settings to assess their impact on data quality. The results indicated that high-quality seismic data could be obtained using optical fibres up to 100 kilometres in length with standard gauge length settings (Figure 7). However, significant degradation in data quality was observed beyond this point. The trials demonstrated that long tie-back cables could be used without additional modifications to access downhole fibres, enhancing the feasibility of DAS applications in offshore and other long-range environments.

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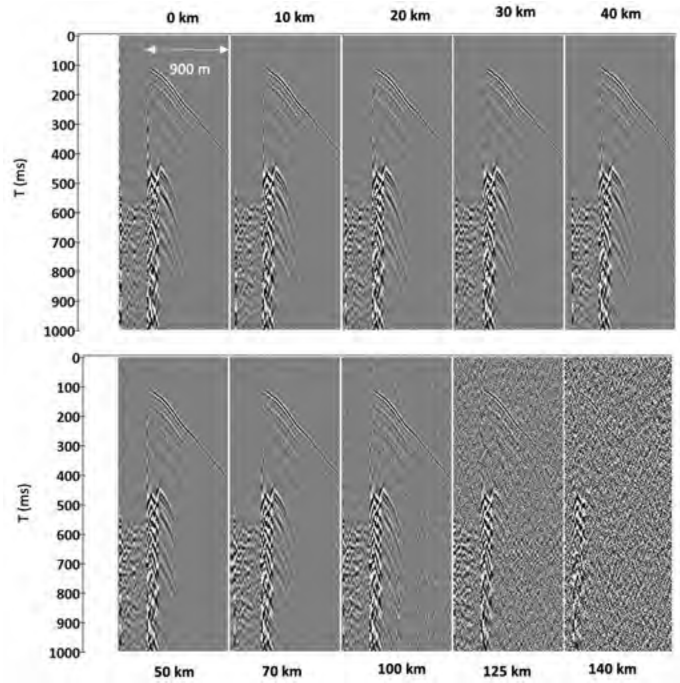

Figure 7 Examples of the shot gathers with 0-140 km of the extra fibre in front of the well recorded with 10 m gauge length.

The ability to connect multiple wells and other sensing cables to a single interrogator could substantially reduce operational costs and simplify the deployment of DAS technology. This capability opens up new opportunities for using DAS in extended monitoring applications where long-distance data transmission is essential. The study highlights the potential of DAS technology for long-range seismic monitoring, offering a cost-effective and scalable solution . The findings suggest that with the right configurations, DAS can be effectively deployed over extended distances, promoting its wider adoption in the industry.

2.8.3. High quality DAS VSP data with low power sources.

This study explores the use of Distributed Acoustic Sensing (DAS) technology for Vertical Seismic Profiling (VSP) with low-energy seismic sources, focusing on the potential to reduce costs and simplify logistics for borehole seismic surveys (Pevzner, R. and Tertyshnikov, K. 2022). DAS enables VSP data acquisition along the entire length of a well with a single seismic source excitation. However, earlier

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DAS interrogators generally had a lower signal-to-noise ratio compared to conventional geophones, prompting the use of high-energy sources like explosives or large vibroseis trucks for data acquisition.

The research investigates whether a low-energy source, such as a 45 kg accelerated weight drop, can produce high-quality VSP data using DAS technology. This approach could significantly reduce costs and make DAS-based VSP surveys more accessible and practical for various applications. The experiment involved using a 45 kg accelerated weight drop mounted on a vehicle at a distance of 165 m from the well to generate seismic signals. A series of 205 shots were recorded using a Silixa iDAS v2 interrogator connected to a fibre optic cable installed in a 900 m deep well. The study analysed the impact of stacking multiple shots on data quality, comparing cumulative seismograms obtained from 1, 50, 100, and 200 shots.

The results showed that stacking multiple excitations of the low-energy source significantly improved data quality. While a single shot provided limited data quality, stacking up to 200 shots achieved a signal-to-noise ratio comparable to that of higher energy sources. The study confirmed that the noise observed in DAS data is random, uncorrelated, and has a zero mean, making it suitable for noise reduction through stacking (Figure 8). The ability to acquire high-quality VSP data with low-energy sources using DAS presents a cost-effective alternative to traditional methods requiring high-energy sources. This capability could expand the use of DAS technology in VSP surveys, particularly in scenarios where minimising mobilisation costs and equipment requirements is crucial.

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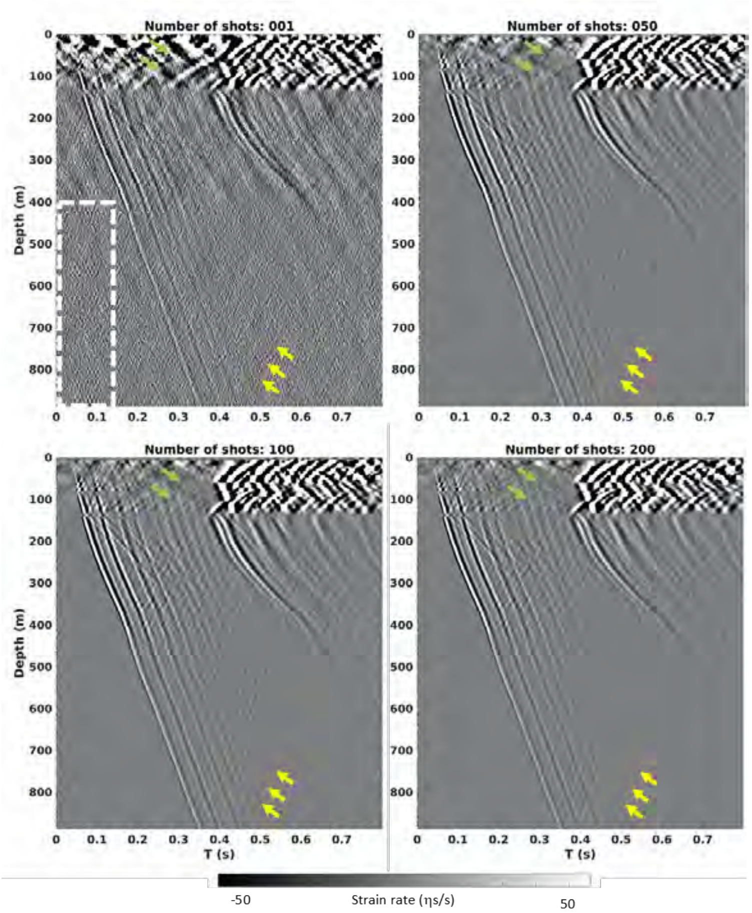

Figure 8 Cumulative average DAS VSP records acquired using 1, 50, 100 and 200 excitations of the seismic source. White rectangle shows the area used to estimate seismic noise level, green and yellow arrows show deep reflections pronounced on the data. 45 kg accelerated weight dropsource.

The study demonstrates that DAS technology can effectively acquire VSP data with low-energy seismic sources, offering a more economical and flexible solution for subsurface imaging and monitoring. This approach could enhance the feasibility of DAS deployments in various geophysical settings, making advanced seismic data acquisition more accessible and affordable.

2.8.4. Enhancing DAS Seismic Data with a Three-Component Electromagnetic Vibroseis Source

This study investigates the use of a three-component (3C) electromagnetic vibroseis source in combination with Distributed Acoustic Sensing (DAS) technology to acquire three-component seismic data. DAS is widely used for its ability to measure strain or strain rate along a fibre optic cable, offering

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significant advantages for borehole seismic and surface seismic acquisitions. Traditionally, DAS measures a single component of strain, but expanding its capability to record three-component seismic data could significantly broaden its applications in exploration geophysics (Tertyshnikov et al. 2023).

The primary goal was to test a multicomponent electromagnetic vibroseis source that generates seismic energy in three non-collinear directions. This allows polarisation analysis using a single-component receiver, such as a DAS fibre optic cable, to generate 3C seismic data. The experimental setup included a custom-built 3C electromagnetic vibroseis source using low-frequency actuators capable of generating vibrations in the 5-200 Hz frequency range. Data were acquired at three different azimuths, each rotated 120 degrees, with ten sweeps per azimuth to enhance the signal-to-noise ratio. The raw data were transformed from the acquisition coordinate system into an orthogonal XYZ system to represent conventional seismic components: X (horizontal in the shot point direction), Y (perpendicular horizontal), and Z (vertical) (Figure 9).

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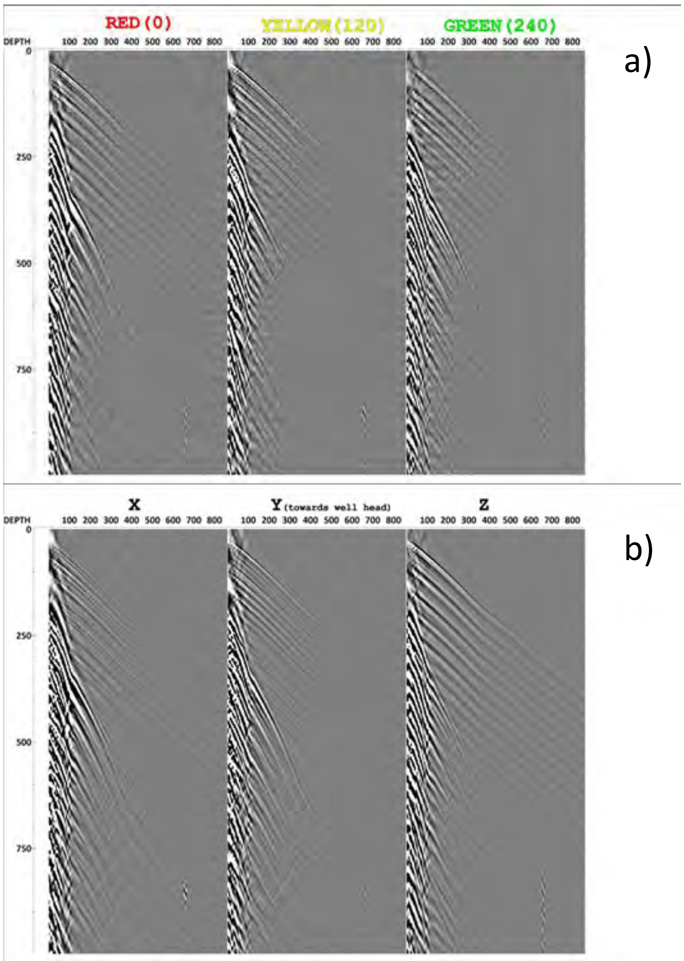

Figure 9 a) Raw data recorded for three orientations of the electromagnetic source. b) Raw data transformed into an orthogonal XYZ orientation.

The study successfully demonstrated the capability of the electromagnetic 3C vibroseis source to work with DAS sensors to acquire three-component seismic data. The transformed data showed clear separation of wavefield components. The results suggest that the source design is adaptable and scalable, capable of adjusting for varying depth investigations and operational requirements.

The findings highlight the potential of using a 3C electromagnetic vibroseis source with DAS for both surface and borehole seismic acquisitions, providing a flexible and scalable alternative for geophysical exploration. The field trial demonstrates that combining DAS with a 3C electromagnetic vibroseis source can effectively produce high-quality three-component seismic data. This approach could expand

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the use of DAS in more complex geophysical scenarios, enhancing its role in subsurface characterisation and monitoring applications.

2.8.6 Using Downhole DAS for Ambient Seismic Noise Analysis in Urban Environments

This study investigates the use of Distributed Acoustic Sensing (DAS) technology for monitoring ambient seismic noise in an urban environment. DAS technology allows for the continuous acquisition of seismic data using fibre optic cables as sensing elements, providing high spatial and temporal resolution. The research focused on the passive DAS data collected over 85 days in a deep well, revealing the ability of DAS to detect a range of natural and anthropogenic seismic events in a complex urban setting (Shulakova et al. 2022).

The primary aim was to evaluate the effectiveness of DAS in detecting and characterising various types of ambient seismic energy, including earthquakes, ocean swell, and urban noise, such as mine blasting, traffic, and machinery. The study utilised spectral analysis and kinematic assessment of the recorded seismic waves to identify and classify different sources of seismic noise. The events detected were categorised into local and distant earthquakes, mine blasts, traffic, and machinery noise, demonstrating the capability of DAS to capture a broad spectrum of seismic activities.

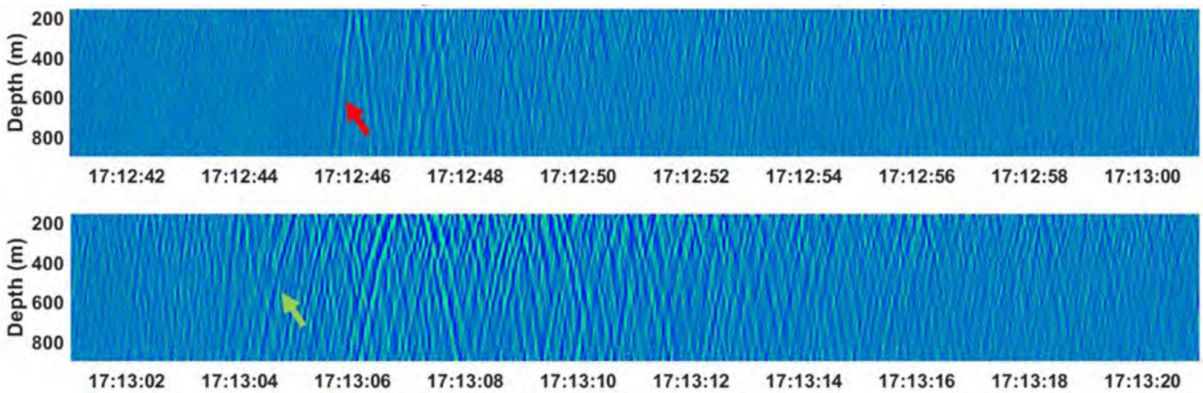

Figure 10 An example of the raw DAS record of the ML 2.9 earthquake occurred in Pingelly, Western Australia, 5/06/2018 at 17:12:21 UTC.

Sixteen earthquakes were detected (Figure 10), with epicentres ranging from 126 km to 900 km for local events and from 2300 km to 6400 km for distant events. The DAS system also recorded a

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consistent ocean swell signal at frequencies below 0.9 Hz, as well as various types of urban noise. The study highlights the potential of DAS technology for continuous passive seismic monitoring in urban environments, offering insights into both natural and human-induced seismic events. The findings suggest that DAS can be a powerful tool for continuous seismic monitoring, reducing the costs and environmental impact associated with traditional seismic surveys.

2.8.7. Comparative Study on the Sensitivity of DAS Cables to Acoustic Waves

This study investigates the sensitivity of different Distributed Acoustic Sensing (DAS) cable constructions to acoustic waves in water, highlighting the impact of cable materials, especially the Poisson ratio of the cable jacket, on DAS measurements. The research, conducted as part of the CRC MinEx project, provides the first detailed analysis of how the physical properties of DAS cables influence their sensitivity to seismic waves, particularly in the borehole and marine environments where fluid coupling plays a significant role (Bona, A. and Lebedev, M. 2022)

The primary aim was to compare the sensitivity of four different types of fibre optic cables to pressure waves generated in water. The study focused on understanding how the Poisson ratio of cable materials affects the transfer of fluid pressure to the fibre, which is crucial for applications involving loose deployments in boreholes and marine settings. Four types of fibre optic cables (bare single-mode fibre, simplex patch cord, tactical cable, and loose tube telecommunication cable) were tested in a water tank. The cables were arranged in loops and connected in series, with acoustic waves generated by speakers through a signal generator. The sensitivity was measured by recording the relative energy of the seismic waves using DAS (Figure 11).

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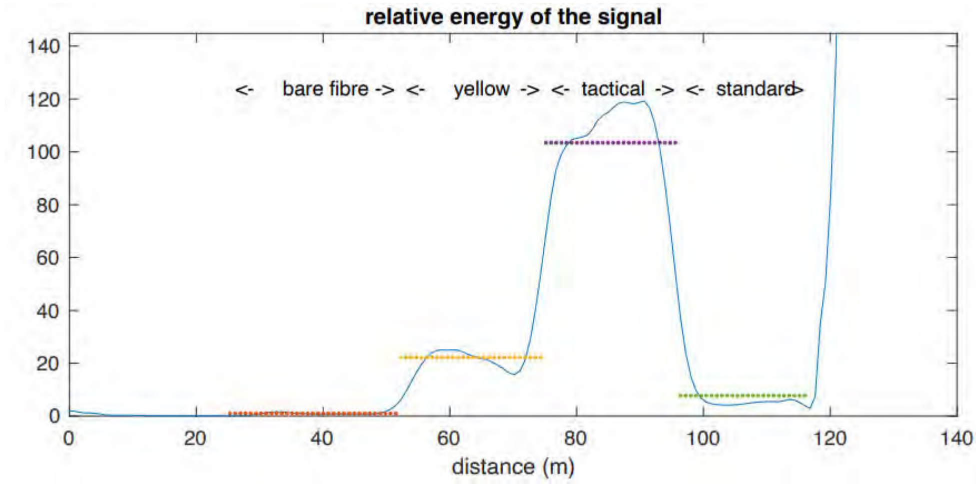

Figure 11 Relative energy of the recorded wavefield on different cables. The relative energy is computed with respect to the bare fibre energy (red dots). While the standard telecommunication loose-tube cable (green) and the yellow patch cord (yellow) perform better that the bare fibre, they still significantly lack in sensitivity in comparison with the tactical cable (purple).

The results showed significant differences in sensitivity among the cables. The tactical cable exhibited the highest sensitivity, with a 20.15 dB increase over the bare fibre. The simplex patch cord and standard telecommunication cable also demonstrated higher sensitivity than the bare fibre, with increases of 13.46 dB and 8.87 dB, respectively. The study confirmed that the Poisson ratio of the cable jacket material plays a critical role in sensitivity; however, the coupling of fibres within the cable structure is also a significant factor. The findings of this research provide valuable insights for selecting DAS cables based on their sensitivity characteristics, especially in borehole and marine applications where fluid coupling is a critical consideration. The results will aid in optimising DAS field acquisition planning and enhancing the effectiveness of subsurface monitoring using fibre optic technologies.

2.8.8. Comparative Analysis of DAS Cable Directivity and Interrogator Sensitivity for Seismic Applications

This study presents a comparative analysis of Distributed Acoustic Sensing (DAS) technologies, focusing on the directivity patterns of different DAS cable configurations and the influence of interrogator design on DAS sensitivity. The work was conducted as part of the CRC MinEx project, aimed at advancing DAS applications for subsurface exploration and monitoring in diverse geological settings (Sidenko et al. 2020; Sidenko et al. 2021).

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Influence of Interrogator Design on DAS Sensitivity:

The first study compares the sensitivity of two DAS interrogators—the Terra15 Treble, which measures deformation-rate, and the Fotech Helios Theta, which measures dynamic strain. Data were acquired using these two interrogators connected to a fibre optic cable cemented behind the casing of a 900 m deep well. The results demonstrated that the directional sensitivity of DAS measurements is significantly influenced by the design of the interrogator. Specifically, the Terra15 Treble shows a directivity pattern similar to geophones, with a cosine function relationship between amplitude and incidence angle. Meanwhile, the Fotech Helios Theta's measurements, when adjusted for P-wave velocity, showed a consistent relationship, confirming that the choice of interrogator affects the recorded seismic signal (Figure 12).

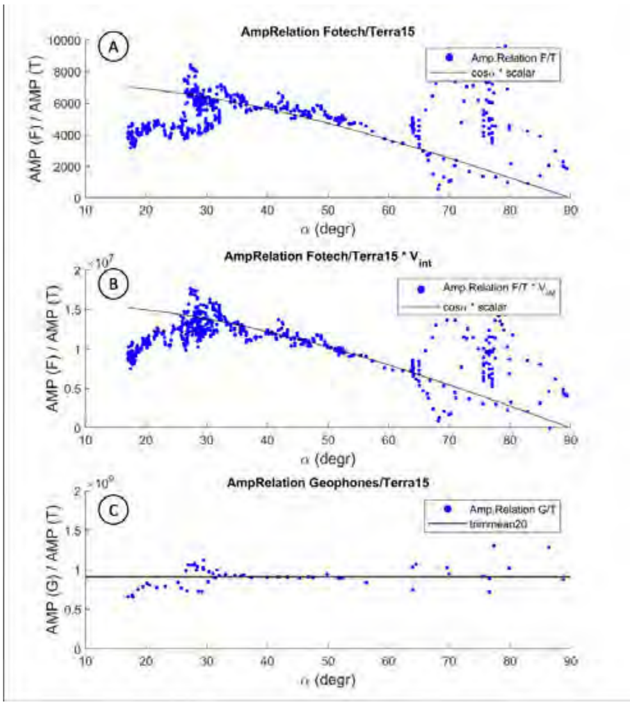

Figure 12 Direct wave amplitude relation plotted against raytraced angles. Fotech to Terra15 relation (A), Fotech to Terra15 relation multiplied by the interval velocity function (B); Geophones to Terra15 (C).

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Comparative Study of Straight and Helically Wound DAS Cables:

The second study examines the directivity patterns of standard straight DAS cables versus helically wound (HW) DAS cables with a 60° winding angle. The HW cable was designed to overcome the limitations of straight DAS cables, which are less sensitive to seismic waves arriving at 90° to the cable axis. The experimental results confirmed that while the amplitude of seismic signals recorded by straight DAS fibres diminishes as a function of the cosine squared of the incidence angle, the HW DAS cable shows an almost flat response across all angles, providing near-omnidirectional sensitivity. This makes HW DAS cables particularly useful for applications where uniform sensitivity is required (Figure 13).

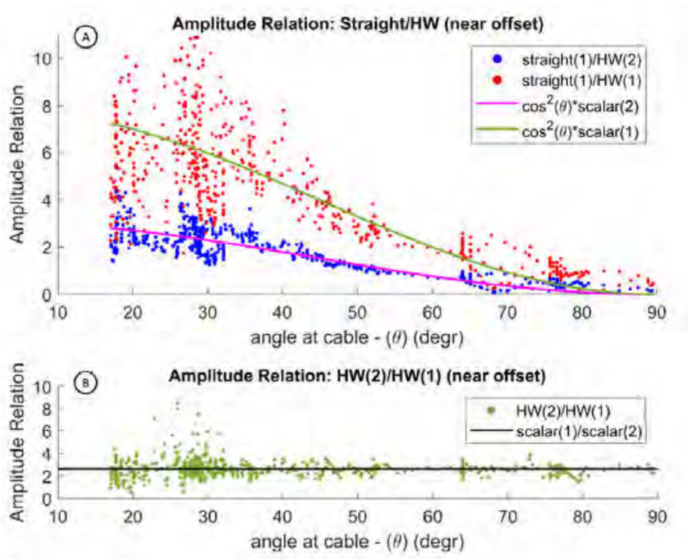

Figure 13 Direct wave amplitude ratio plotted against raytraced angles. Straight (parameters set 1) to HW DAS obtained with parameters set 1 and 2 (A). HW DAS with parameters set 1 to HW DAS with parameters set 2 (B).

The studies highlight the importance of both interrogator design and fibre optic cable configuration in optimising DAS for seismic applications. The findings demonstrate that the directivity and sensitivity of DAS systems can be tailored through careful selection of hardware, enhancing their applicability in various geophysical and mineral exploration scenarios. The research contributes to the ongoing development of DAS technologies, providing valuable insights for their deployment in complex geological environments.

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2.9 CO2CRC Otway instrumented site: An Advanced Testing Facility for DAS, DTS, and DSS Technologies

The CO2CRC Otway Project, located in Victoria, Australia, is a globally recognised carbon capture and storage (CCS) research site that also serves as an advanced testing facility for validating cutting-edge monitoring technologies such as Distributed Acoustic Sensing (DAS), Distributed Temperature Sensing (DTS), and Distributed Strain Sensing (DSS). The facility provides a unique environment for field-scale experimentation and validation of fibre optic sensing systems in complex geological settings, supporting the development and optimisation of these technologies for a variety of subsurface monitoring applications beyond CCS.

Site Overview:

The Otway Project is situated in the Otway Basin, a region with diverse geological features, making it an ideal location for testing advanced sensing technologies under real-world conditions. The site includes eight wells, seven of which are equipped with optical fibre cables. In six of these wells, the fibre optic cables are installed behind the casing, ensuring they are well-protected while allowing for optimal data acquisition. The installed fibre optic cables comprise a combination of single-mode, multi-mode, and engineered fibres, enabling comprehensive testing and validation of DAS, DTS, and DSS technologies.

Advanced Well Instrumentation for DAS, DTS, and DSS Testing:

The Otway Project’s wells are meticulously instrumented to facilitate the testing, validation, and optimisation of DAS, DTS, and DSS technologies. These advanced fibre optic sensing systems provide continuous data on various subsurface parameters, such as acoustic signals, temperature variations, and strain changes, which are essential for CCS applications and broader geophysical research, including mineral exploration.

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Distributed Acoustic Sensing (DAS):

The site is equipped with fibre optic cables installed along the entire length of several wells to enable DAS monitoring. DAS technology converts fibre optic cables into continuous acoustic sensors capable of detecting seismic waves, microseismic events, and flow-induced vibrations in real-time. The facility allows the combination of DAS with controlled seismic sources (e.g., vibroseis trucks, weight drops) and passive sources to validate DAS capabilities in capturing both active and passive seismic data. The Otway site provides an ideal testing environment to validate DAS performance for various conditions, helping to refine its application in reservoir monitoring, subsurface imaging, and mineral exploration.

Distributed Temperature Sensing (DTS):

Fibre optic cables are also used for DTS along the wellbore to monitor temperature variations continuously. The CO2CRC Otway site's wells provide a controlled environment to test DTS performance in detecting thermal anomalies associated with fluid migration, potential leakage pathways, and geothermal studies. The facility enables the calibration of DTS systems and optimisation of sensor configurations to enhance sensitivity and accuracy in temperature monitoring.

Distributed Strain Sensing (DSS):

DSS technology uses fibre optic cables to measure strain changes along the wellbore. The Otway Project's wells offer an excellent platform for validating DSS capabilities in detecting geomechanical responses, such as reservoir compaction, subsidence, deformation, and fault reactivation. This validation helps refine DSS for monitoring well integrity, formation stability, fault movement, and applications in mining operations. The site allows for long-term testing of DSS systems, providing continuous data on strain variations and enabling the development of predictive models for subsurface stress changes.

The CO2CRC Otway Project serves as an instrumented field site laboratory for validating and optimising DAS, DTS, and DSS technologies in a real-world setting. Its advanced infrastructure,

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including eight wells (with seven equipped with fibre optics featuring single-mode, multi-mode, and engineered fibres), makes it an unparalleled testing ground for developing next-generation fibre optic sensing solutions. The insights gained from these experiments are crucial for advancing the deployment of fibre optic technologies in complex geological environments.

2.9.1. Integrating Distributed Acoustic Sensing with Seismic While Drilling (SWD) Techniques

This study explores the integration of Distributed Acoustic Sensing (DAS) technology with Seismic While Drilling (SWD) to enhance subsurface imaging by recording drill-bit generated seismic signals in boreholes. SWD has traditionally been limited by low signal-to-noise ratios (SNR) due to contamination from surface noise, especially from the drilling rig itself. By deploying DAS cables in boreholes, this study demonstrates that the recorded drill-bit signals are less affected by such noise, resulting in higher quality data (Qin, Z. et al. 2020). The work was conducted as part of the CRC MinEx project and represents a significant milestone as it is the first dataset available where drilling activity was recorded on fibre optic cables installed in neighbouring wells. During the experiment at the CO2CRC Otway site, new boreholes were drilled while DAS cables in adjacent wells recorded the seismic signals generated by the drill-bit. This setup allowed for a unique cross-well recording configuration, providing a novel perspective for subsurface characterisation.

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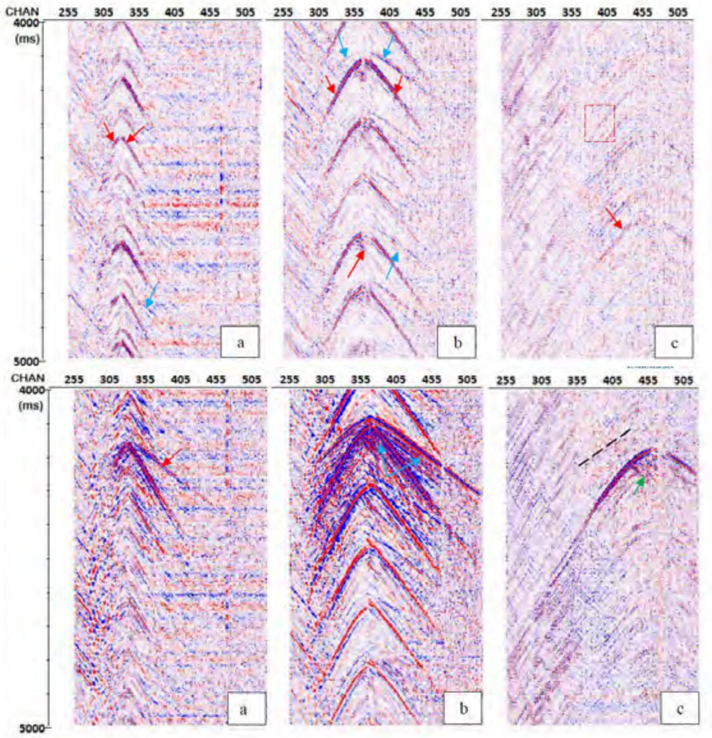

Figure 14 Top row: Drill-bit data recorded by observation of DAS cable when drill-bit was at elevations of -649m (a), - 842m (b), -1329m (c), respectively, in a well being drilled. Direct P and S-wave arrivals are denoted by downward pointing blue and red arrows, while upward arrows denote reflected P and S-wave energy, respectively. Bottom row: Results after a "shift and stack" technique applied at selected template impulse position over gathers above.

To enhance the SNR, a "shift and stack" technique was developed, capitalising on the repetitive nature of drill-bit impulses. This method significantly improved the quality of the recorded waveforms, enabling clearer identification of seismic events. The DAS recordings showed high-definition waveforms after processing, demonstrating their potential to be integrated with conventional surface or Vertical Seismic Profiling (VSP) surveys. The results suggest that combining DAS with SWD can provide a powerful tool for more accurate velocity models and better subsurface imaging. The encouraging outcomes of this study offer new exploration opportunities, particularly in sectors like mining, where drilling frequency is higher than in other industries.

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2.9.2. Supervised Deep Learning for Detecting and Locating Passive Seismic Events with DAS

The research explores the use of supervised deep learning to detect and locate passive seismic events captured using Distributed Acoustic Sensing (DAS). The study addresses the challenges of handling large datasets generated by DAS systems in seismic monitoring applications, where passive seismic events need to be tracked efficiently. DAS offers a flexible and cost-effective solution for continuous seismic monitoring by using fibre optic cables to capture seismic data along their entire length. However, the volume of data generated, combined with the noise levels present in DAS recordings, presents significant challenges for real-time analysis.

The study proposes using a convolutional neural network (CNN), specifically the ResNet50 architecture, to detect and locate passive seismic events from DAS data automatically. The network is trained on synthetic data generated to mimic seismic events, which is paired with real noise recordings to create a realistic dataset for training the model. The study uses seismic data from the Otway CO_2 injection site in Australia, where DAS-equipped wells recorded induced seismic events before and during CO_2 injection. Synthetic data is generated based on known subsurface properties at the site, and noise from real DAS recordings is added to simulate realistic conditions. The preparation of synthetic datasets is crucial for training the neural network, mainly due to the differences between synthetic and field-recorded data, including mismatches in acquisition geometry and signal-to-noise ratios (SNR).

The trained model is tested on both synthetic and field datasets. The results demonstrate that the model can accurately detect seismic events and estimate their location despite the challenges posed by low SNR and geometry mismatches. The study also highlights the importance of handling time shifts in the data, as passive seismic events can occur at unpredictable times, unlike active seismic sources. Incorporating time shifts into the training process improves the model's accuracy in detecting events. The trained network is applied to real DAS data from the Otway site, showing promising results in distinguishing noise from seismic events (Figure 15). The methodology can generalise to nearby wells, even with slightly different geometries, though further refinement is needed to improve performance in more complex settings (Al-Hemyari et al. 2024).

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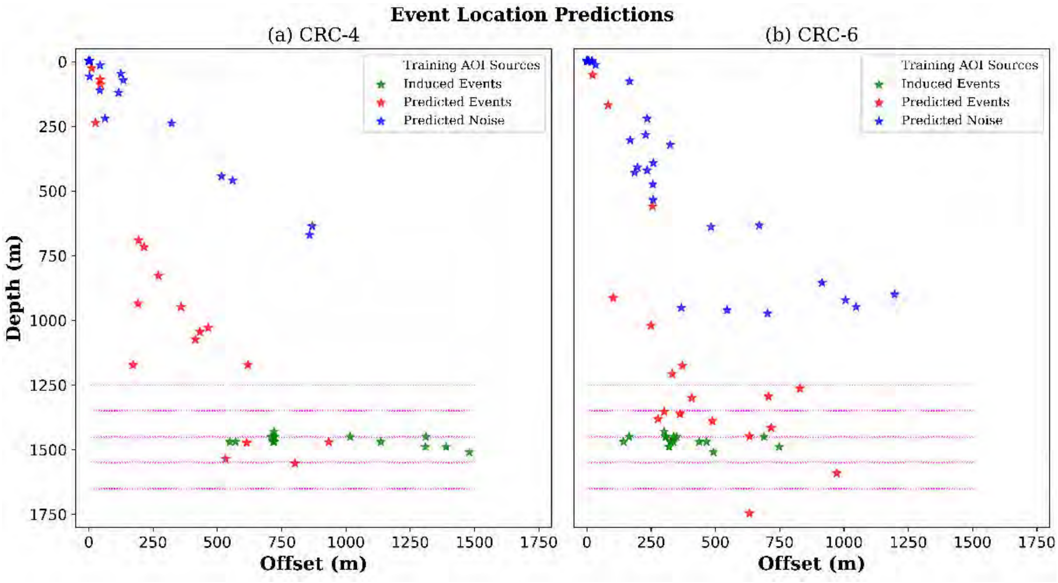

Figure 15 Predictions of event and noise locations for data from slightly deviated (a) CRC-4 and (b) CRC-6 wells. Green stars represent the actual locations of induced events relative to the well positioned at zero offset.

This study demonstrates the potential of using supervised deep learning to automate the detection and location of passive seismic events in DAS data. The proposed workflow shows that, with sufficient training on synthetic data and consideration of challenges such as time shifts and noise, neural networks can provide accurate event detection in real-world monitoring scenarios. The research highlights opportunities for extending this approach to other applications, such as seismic while drilling (SWD), and underscores the need for further exploration of deep learning models tailored to seismic data processing.

3. Comparative Analysis of DAS Interrogators for Seismic Applications

Distributed Acoustic Sensing (DAS) technology has become an essential tool for subsurface monitoring, geophysical surveys, and seismic applications. Various DAS interrogators, such as the Silixa iDAS v2, iDAS v3 (Carina), iDAS MG, Terra15 Trebble+, and ASN OptoDAS, have been developed with different capabilities and optimal use cases. This chapter provides a detailed comparison of these DAS interrogators based on key performance parameters, including gauge length, minimum channel spacing, maximum sensing range, and optimal cable length for seismic applications. The analysis is based on extensive testing and field experience to help users select the most suitable DAS system for their specific needs.

3.1. Comparison of DAS Interrogators

The following table summarises the capabilities of each DAS interrogator, highlighting their strengths and limitations for seismic applications:

Interrogator	Gauge Length	Minimum Channel Spacing	Maximum Sensing Range	Optimal Cable Length for Seismic Applications	Notes
iDAS v2	Fixed	0.25 m	50 km	Up to 20 km	"Excellent frequency sensitivity across a wide seismic band
iDAS v3 (Carina)	Selectable from several settings	0.25 m	Up to 60 km	Up to 20 km (can be significantly increased with engineered fibres)	"Paired with Constellation fibre for enhanced performance. Great for permanent monitoring and cross-hole induced seismicity studies."
iDAS MG	Selectable from several settings	0.25 m	Up to 50 km	Up to 20 km	"Suitable for conventional borehole or surface seismic applications
Treble+	Can be defined after the acquisition	0.82 m	Up to 40 km	Up to 10 km	"Exceptional sensitivity at very high frequencies (>300-400 Hz). Ideal for cross-hole surveys with high-frequency sources
OptoDAS	Selectable	1.021 m	150 km	Up to 120 km	"Outperforms others in sensing range and maintains high-quality data acquisition with 10 m gauge length on cables up to 100 km. Best for long-range monitoring

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					with a minimal number of interrogators."

1. **Gauge Length Flexibility:**

   - The iDAS v2 has a fixed gauge length, while the iDAS v3 (Carina) and iDAS MG allow for gauge length selection from several settings, providing flexibility in adjusting the spatial resolution to suit specific applications. The Treble+ offers the unique capability to define gauge length after data acquisition, which is beneficial for high-frequency applications and fine-tuning data quality. The OptoDAS also provides selectable gauge lengths, balancing between sensitivity and sensing range.

2. **Sensing Range and Data Quality:**

   - The OptoDAS has the highest maximum sensing range of up to 150 km, making it ideal for long-distance monitoring and large-scale seismic surveys. It maintains excellent sensitivity with shorter gauge lengths (e.g., 10 m), even on cables as long as 100 km, which is advantageous for remote operations with minimal infrastructure.

   - The iDAS v3 (Carina), optimised with Constellation fibres, has an extended sensing range of up to 60 km and is suitable for cross-hole and permanent monitoring applications. iDAS v2 and iDAS MG offer sensing ranges of up to 50 km, providing a good balance for conventional seismic applications.

3. **Optimal Cable Length for Seismic Applications:**

   - The optimal cable length for seismic applications varies by interrogator and use case. For example, the OptoDAS can handle cable lengths up to 120 km effectively, while the iDAS v2, iDAS v3 (Carina), and iDAS MG are optimal up to 20 km but can be extended with engineered fibres. The Treble+ is more suited for shorter cable lengths (up to 10 km) but excels in high-frequency and low-magnitude event monitoring, especially in cross-hole applications using high-frequency sources like sparkers.

4. **Specialised Applications:**

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- Each DAS interrogator has unique advantages for specific applications:
  - Silixa iDAS v2: Best for conventional borehole and surface seismic, as well as passive seismic monitoring in environments with ultra-low frequencies.
  - Silixa iDAS MG: Effective for higher frequency seismic sources and monitoring induced seismicity.
  - Silixa Carina (iDAS v3): Paired with Constellation fibres, ideal for permanent installations and cross-hole seismic monitoring.
  - Treble+: Highly sensitive to very high-frequency signals, making it suitable for cross-hole surveys with high-frequency sources such as sparker sources (kHz range) and monitoring very low-magnitude seismic events.
  - OptoDAS: Best for long-range monitoring scenarios requiring minimal infrastructure and optimal data quality over extended distances.

Conclusion

The choice of DAS interrogator depends on the specific requirements of the seismic application, such as the desired sensing range, spatial resolution, frequency sensitivity, and operational environment. The comparative analysis highlights the strengths and limitations of each interrogator, providing valuable guidance for selecting the most suitable system for diverse subsurface monitoring needs. As the DAS technology evolves, understanding these factors will help maximise data quality, optimise deployment strategies, and ensure successful geophysical surveys and subsurface monitoring operations.

4. Types of fibre and cable designs for acquisitions

4.1 Common types of fibre used in DAS

Standard Single Mode Fibres

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- **Description**: Traditionally used in DAS systems, these fibres have low loss but limited reflection or scattering of Rayleigh light, which is critical for DAS functionality.
- **Challenges**: The amount of scattering varies along the fibre, leading to inconsistent signal-to-noise ratio (SNR). This issue, known as "fading," can affect the quality of measurements in seismic acquisition.

Enhanced Backscatter Fibres (EBF)

- **Description**: These fibres are designed to enhance Rayleigh scattering, providing a higher signal level for DAS applications.
- **Types**:
  - **Highly Doped Fibres**: These create more reflection but significantly increase optical loss, making them suitable only for short distances.
  - **Continuously Enhanced Fibres**: These provide more signal than doped fibres with lower loss but lack control over the phase relationship of multiple scatterers, limiting their effectiveness in improving SNR.

Engineered Fibres

- **Description**: Engineered fibres are custom-designed to optimise their reflection properties along the length of the fibre. This allows precise control over Rayleigh scattering and SNR enhancement, leading to significantly better performance than standard fibres (Naldrett, G. 2021).
- **Key Advantages**:
  - **SNR Improvement**: Engineered fibres offer up to a **20 dB improvement in SNR** compared to standard single-mode fibres.
  - **Customization**: The location and reflectivity of scatterers can be tailored to meet specific requirements, such as seismic acquisition, well integrity monitoring.
- **Design**: These fibres are integrated into downhole cables with mechanical protection and pressure isolation, ensuring they can withstand harsh operational conditions.

Fibre Longevity and Hydrogen Darkening

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- **Challenge**: A major concern with fibres in downhole environments is **hydrogen darkening**, where free hydrogen atoms bond with the silica glass, increasing optical loss and rendering the fibre ineffective.
- **Mitigation**: Enhanced or engineered fibres must be resistant to hydrogen darkening. Manufacturers address this issue with specialised glass chemistry, hermetic barriers, or other proprietary methods. These fibres are tested in accelerated lifetime tests to ensure their durability.

4.2. Sensitivity of different fibre optic cables to Acoustic Waves

This study investigates the sensitivity of different Distributed Acoustic Sensing (DAS) cable constructions to acoustic waves in water, highlighting the impact of cable materials, especially the Poisson ratio of the cable jacket, on DAS measurements. The research, conducted as part of the CRC MinEx project, provides the first detailed analysis of how the physical properties of DAS cables influence their sensitivity to seismic waves, particularly in the borehole where fluid coupling plays a significant role (Bona, A. and Levbedev, M. 2022).

The primary aim was to compare the sensitivity of four different types of fibre optic cables to pressure waves generated in water. The study focused on understanding how the Poisson ratio of cable materials affects the transfer of fluid pressure to the fibre, which is crucial for applications involving loose deployments in boreholes and marine settings. Four types of fibre optic cables (bare single-mode fibre, simplex patch cord, tactical cable, and loose tube telecommunication cable) were tested in a water tank. The cables were arranged in loops and connected in series, with acoustic waves generated by speakers through a signal generator. The sensitivity was measured by recording the relative energy of the seismic waves using DAS. The results showed significant differences in sensitivity among the cables. The tactical cable exhibited the highest sensitivity, with a 20.15 dB increase over the bare fibre. The simplex patch cord and standard telecommunication cable also demonstrated higher sensitivity than the bare fibre, with increases of 13.46 dB and 8.87 dB, respectively. The study confirmed that the Poisson ratio of the cable jacket material plays a critical role in sensitivity; however, the coupling of fibres within the cable structure is also a significant factor.

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The findings of this research provide valuable insights for selecting DAS cables based on their sensitivity characteristics, especially in borehole and marine applications where fluid coupling is a critical consideration. The results will aid in optimising DAS field acquisition planning and enhancing the effectiveness of subsurface monitoring using fibre optic technologies.

4.3 Different DAS cables performance in surface seismic acquisition

The research investigates the application of Distributed Acoustic Sensing (DAS) technology in conducting high-definition (HD) weathering and surface seismic surveys in sand dune environments. The study aims to explore the potential of DAS as an alternative to conventional seismic acquisition methods, particularly in conditions where near-surface complexities present significant challenges to traditional techniques (Bakulin et al. 2022).

Surface seismic acquisition on land, especially in environments with complex near-surface conditions , requires high trace density and fine spatial sampling to resolve imaging and near-surface challenges. Conventional seismic acquisition systems, which rely on point sensors such as geophones, struggle to meet these requirements due to limitations in their ability to handle complex wavefields caused by significant vertical and lateral velocity variations near the surface. Distributed Acoustic Sensing (DAS) has emerged as a promising alternative to traditional point sensors for surface seismic acquisition. DAS uses fiber optic cables to measure acoustic signals along their entire length, offering the potential to capture multiscale seismic data with denser spatial sampling at a lower cost. Additionally, DAS provides flexibility in its ability to acquire "shallow," "deep," and Full-Waveform Inversion (FWI) data using the same cable infrastructure, whereas conventional point sensors would require separate receiver layouts for each application. However, one of the key challenges for DAS is its directivity, as conventional straight DAS cables primarily detect horizontally polarised wave energy, making them less sensitive to vertical seismic signals.

A comprehensive field trial was conducted in Western Australia to assess the effectiveness of DAS in addressing these challenges. The field trial focused on evaluating the performance of different DAS cable designs and comparing them with conventional 3C geophones.

Cable Types and Configurations:

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The field trial utilised a range of DAS cable configurations, each designed to address the specific challenges posed by surface seismic acquisition. The following cables were tested:

- Straight DAS Cable: A standard telecom cable with an 11-degree pitch, which is typically used for DAS applications.
- Helical DAS Cables: Three helical cables with varying wrapping angles of 20°, 30°, and 60°. These cables were designed to enhance the directivity of the DAS system by making it more sensitive to vertical displacements, which are essential for capturing refracted arrivals and reflections in seismic data.

The cables were deployed in a 500-meter-long shallow trench (approximately 20 cm deep), with geophones placed alongside the DAS cables for comparison. The trenching provided good coupling to the ground, which is necessary for high-quality signal detection.

Three different seismic sources were used during the field trial:

1. A 26,000-pound Vibroseis Truck: This source is commonly used in land seismic acquisition due to its ability to generate strong, controlled seismic waves.
2. A Large 720-kg Weight Drop: This impulsive source was used for shallow surveys to measure near-surface characteristics.
3. A Small 45-kg Accelerated Weight Drop: This source was also used for shallow weathering surveys, offering an operationally simpler and more cost-effective alternative to vibroseis.

The field trial provided valuable insights into the performance of DAS cables for surface seismic:

- Helical DAS Cables Outperform Straight Cables: The trial demonstrated that helical DAS cables, particularly those with a 60-degree wrapping angle, were more effective at capturing vertical seismic signals, including refracted arrivals and reflections. In contrast, the straight DAS cable showed weaker signal performance, particularly in detecting near-vertical wavefields.
- Near-Surface Noise Suppression: The helical cables with higher wrapping angles also showed better suppression of near-surface noise than straight cables, which is consistent with theoretical predictions. This makes helical DAS cables more suitable for capturing clean seismic data in environments with strong near-surface noise.

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- Comparison with Geophones: The helical DAS cables performed comparably to traditional geophones in detecting seismic arrivals. However, further analysis is needed to understand the differences in signal quality and sensitivity fully (Figure 16).
- Shallow Trenching Improves Data Quality: Shallow trenching proved effective in coupling the DAS cables to the ground, significantly improving data quality compared to surface-laid cables.

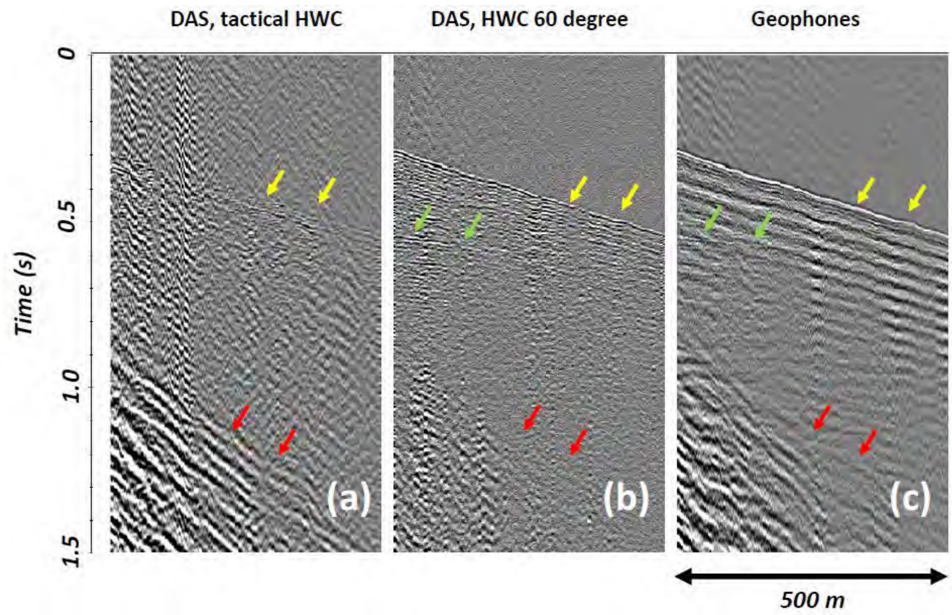

Figure 16 Vibroseis shot records obtained with two omnidirectional DAS cables and geophones: (a) H1, tactical helical (dr=~1 m); (b) H4, 60- degree helical (dr=~0.5 m); (c) vertical geophones covering the same extent as DAS (dr=2 m). Refracted arrival (yellow arrows) is clearly seen on (b) and (c). Shallow reflection event (green arrows) is seen on (b) and (c), but not detectable on (a). Red arrows show the reduced amplitude of near-surface arrivals on (b). All panels have the same spatial extent (~ 500 m) but differ in the number of traces caused by different spacing. In the case of DAS cables, variable sampling is caused by different wrapping angles.

The study concludes that **Distributed Acoustic Sensing (DAS)** offers significant advantages for surface seismic acquisition, particularly in challenging environments. The use of **helical DAS cables** with optimised wrapping angles can overcome the directivity challenges associated with straight cables, making DAS a viable alternative to conventional geophones. Additionally, DAS's ability to acquire multiscale data with a single cable infrastructure provides operational flexibility and cost savings. The results from this field trial lay the groundwork for further development and optimisation of DAS technology for land-based seismic applications. By integrating various cable designs and seismic

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sources, this research provides a comprehensive evaluation of DAS's capabilities and demonstrates its potential for surface seismic acquisition in complex near-surface environments.

5. DAS cable deployments

5.1 Downhole deployments

The studies reviewed here focus on the deployment strategies of fibre optic cables for Distributed Acoustic Sensing (DAS) in various seismic applications, including borehole monitoring and mineral exploration (Gurevich et al. 2023; Tertyshnikov et al. 2022).

1. Cementing Behind the Casing:

- One of the most effective deployment methods for DAS is cementing fibre optic cables behind the casing in a well. This approach provides excellent coupling with the formation, resulting in high-quality seismic data.
- Advantages: This method offers near-complete immunity from noise, particularly tube waves (acoustic noise generated along the tubing). Cemented DAS cables allow clear recordings of both direct seismic waves and reflected signals.
- Disadvantages: The process of cementing cables can be expensive and is typically used in permanent monitoring scenarios.

2. Tubing-Conveyed Deployment:

- In some cases, fibre optic cables are deployed on production tubing. Although this method provides decent data quality, it suffers from increased noise levels due to the tubing's interaction with seismic waves. Tube waves generated by surface impacts can travel along the borehole and interfere with the signal.
- Advantages: Tubing-conveyed cables are easier to deploy than cemented cables and allow for retrievability, making them suitable for temporary or exploration purposes.
- Disadvantages: Coupling with the formation is weaker, and the presence of tubing reverberations can degrade data quality unless sophisticated noise-reduction techniques are applied.

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3. Wireline and Retrievable Deployments:

- In exploration settings where permanent installations are not feasible or cost-effective, wireline deployment of fibre optic cables is commonly used. This method allows the cable to be temporarily suspended in the well, and it can be retrieved after data acquisition is complete.
- Advantages: Wireline deployment is highly flexible for short-term surveys. It is widely used in mineral exploration and coal seam exploration.
- Disadvantages: The quality of data from wireline deployment can vary significantly depending on how well the cable couples with the formation, and it may be affected by noise such as tube waves.

4. Suspended Fibre Deployment in Borehole Fluids:

- An alternative to cementing or tubing-conveyed methods is suspending fibre optic cables in the borehole fluid. This method was tested in trials where the cable was left hanging in liquid-filled boreholes. Surprisingly, the data quality was comparable to that of cemented cables under certain conditions, especially when the well had a slight deviation, which improved coupling by adding tension to the cable.
- Advantages: This method is less expensive and quicker to deploy, and it is particularly useful in exploration settings where fast and non-permanent installation is required.
- Disadvantages: Suspended cables are susceptible to noise from the wellbore fluid, and the data quality can deteriorate significantly if the borehole is filled with gas instead of liquid.

5. FibreLine Intervention (FLI) Tool:

- The FibreLine Intervention (FLI) tool is a rapid deployment method of bare fibreinto a borehole. The tool unspools fibre from a bobbin as it descends into the borehole. This approach was tested in a highly inclined uncased mineral borehole and found to be efficient, with the fibre successfully populating the entire bore length.
- Advantages: This method is fast, safe, and requires minimal personnel. The lightweight probe can be deployed quickly, making it an ideal choice for time-sensitive mineral exploration projects.

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- Disadvantages: The fibre is not retrievable after deployment, as it is left in the borehole. Additionally, coupling with the formation is entirely dependent on the borehole's fluid, which can introduce noise or data quality issues depending on the well's conditions.

Different fibre optic cable deployment strategies for DAS offer varying trade-offs between data quality, cost, and ease of installation. Cemented deployments provide the highest data quality but at a higher cost, making them suitable for long-term monitoring. Tubing-conveyed and wireline deployments are more flexible but may suffer from higher noise levels. The suspended cable method offers a balance between cost and quality, particularly in liquid-filled wells, while the FLI tool demonstrates a fast and efficient method for deploying DAS in exploration settings.

5.1.1 Supporting Numerical Modelling

In addition to the practical field trials, we conducted significant modelling studies to understand the effects of fibre optic deployment strategies on Distributed Acoustic Sensing (DAS) performance (Gurevich et al. 2023). These modelling efforts are essential for explaining some of the observed phenomena and optimising deployment methods.

The modelling studies focus on the effects of various borehole environments and fibre deployment methods on DAS measurements. These simulations aim to understand better how seismic waves propagate in and around boreholes and how they interact with fibre optic cables deployed in different configurations.

1. Borehole Environment Effects:

The numerical simulations used a 1.5D full wave reflectivity method, which models seismic wave propagation in a simplified 1D layer representation of boreholes. This approach allows researchers to evaluate how factors such as cement layers, casing, and the presence of borehole fluids affect the DAS response. A cement layer around the fibre optic cable slightly affects the vertical strain amplitude (less than 5%). The interference between direct seismic waves and reflections from the casing or cement layers can influence signal quality but not significantly. In a liquid-filled borehole, the strain amplitude in the liquid is comparable to that in the surrounding formation, making it feasible to deploy DAS cables in such environments. However, in an air-filled borehole, the strain in the cable decreases drastically, as air cannot efficiently transfer seismic energy.

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2. Cable Design and Sensitivity:

The modelling also examined how the Poisson's ratio of the cable material impacts the strain recorded by DAS. Poisson's ratio describes how much a material deforms in directions perpendicular to the compression direction. A higher Poisson's ratio improves the coupling between the cable and seismic waves in the surrounding formation or fluid. The simulations demonstrated that cables with a higher Poisson's ratio are more sensitive to seismic waves, especially when suspended in liquid-filled boreholes. Conversely, cables with low Poisson's ratio materials, such as quartz glass, show reduced sensitivity, making them less suitable for DAS.

The simulations highlight the importance of cable material properties (e.g., Poisson's ratio) and borehole conditions (liquid vs. air) in optimising DAS performance. These findings complement the practical field trials and suggest that combining optimised deployment strategies and advanced noise management can lead to successful DAS applications across various environments.

5.2 Distributed Acoustic Sensing (DAS) while Coil Tubing (CT) Drilling with a Coil Tubing Rig

The MinEx opportunity fund OP4 has showcased a significant advancement in real-time seismic data acquisition by successfully recovering seismic measurements from fibre optics through a technology known as distributed acoustic sensing (DAS). These results were achieved by integrating DAS within the tubing of a minerals coil tubing (CT) drill rig. The real-time seismic data was collected via an interrogator, specifically a Terra 15 interrogator, which was situated on the surface of the drilling site.

This innovative integration involved collaboration between teams from MinEx Projects 2, 4, and 5. A key component that made DAS possible during drilling operations with a CT rig was the inclusion of an optical slip ring—also known as a fibre optic rotary joint (FORJ)—which was incorporated into the spool of the CT rig. The role of the FORJ was crucial—it allowed continuous fibre optic measurements along the entire length of the tubing, even while the coil was rotating during drilling operations. This meant that the seismic data could be acquired without interruption as the tubing moved and turned, greatly improving the ability to monitor and assess conditions in real time during drilling activities.

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The DAS system was deployed and tested in a variety of field conditions to assess its functionality under different operational scenarios. The data acquisition scenarios included:

- Stationary conditions, where no drilling was taking place,
- Active drilling operations, where the rig was in full operation, and
- Tripping operations, where the drill tubing was being inserted into or removed from the drill hole.

These different conditions allowed the team to evaluate the system's performance and capabilities in real-world drilling scenarios, confirming the effectiveness of DAS technology in capturing valuable seismic data throughout various stages of the drilling process. This advancement in distributed acoustic sensing for CT drilling holds promise for improving the accuracy and efficiency of subsurface monitoring and exploration in mineral extraction projects.

6. DAS data quality enhancement workflows

6.1. High quality DAS VSP data acquisition with low energy sources

The study focuses on how DAS can provide cost-effective and efficient data acquisition for VSP surveys by using smaller, less powerful sources than traditionally required.

The experiment was conducted at Curtin University's research well facility. The well is instrumented with a fibre optic cable, cemented behind the fibreglass casing, and connected to a DAS interrogator. Instead of using high-energy sources, the study tested a 45 kg accelerated weight drop as a seismic source to determine if smaller sources could provide acceptable data quality when combined with DAS. The source was placed 165 meters away from the well, and 205 shots were fired.

The findings demonstrate that stacking multiple shots from the low-energy weight drop significantly improved the data quality, as seen in the vertical seismic profiling (VSP) records. A cumulative average seismogram was computed from 1, 50, 100, and 200 shots, showing that both the direct P-wave and reflected seismic waves became more pronounced as the number of stacked shots increased. This improvement follows the theoretical prediction that noise reduction improves with the square root of the number of stacked shots.

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Using smaller sources like weight drops in combination with DAS offers a more cost-effective and flexible solution for seismic surveys. Traditional methods involving large vibroseis trucks or explosives require significant logistical effort and costs, whereas low-energy sources can be deployed easily with fewer personnel. The study shows that even in offset VSP geometries, where fewer source locations are available, the ability to stack multiple excitations compensates for the lower power of the source.

While the study used a well with pre-installed optical fibre, the authors note that DAS cables can be deployed via other methods, such as wireline, slackline units, and suspended cables, without requiring heavy logging trucks. The study suggests that this approach could replace or complement traditional high-energy sources in many VSP applications, with the potential to streamline operations while maintaining high-quality seismic data acquisition.

6.2. Denoising of DAS data using Deep Learning Approaches

DAS, a technology used for seismic acquisition and monitoring, often faces the issue of low signal-to-noise ratio (SNR) due to the noise introduced by the DAS interrogators. This study compares two machine learning-based approaches to denoise DAS data: Supervised Learning (SL) and Noise2Noise (N2N) methods, offering insights into their effectiveness for seismic data applications (Gu et al. 2024).

DAS is gaining popularity in seismic applications due to its ability to provide high spatial sampling, low maintenance costs, and resilience under varying environmental conditions. However, DAS data often suffers from instrument-specific noise generated by the DAS interrogators, which can significantly reduce the SNR, affecting the quality of seismic data. Traditional denoising techniques such as low-pass filtering and advanced methods like fk-filters and principal component analysis have been applied but are often insufficient in addressing the specific noise patterns present in DAS data.

The Supervised Learning (SL) approach involves generating training data pairs composed of clean/noisy data. In this study, semi-synthetic datasets are created by adding real DAS instrumental noise, recorded from an acoustically isolated fibre coil, to synthetic clean data. This method enables the neural network to learn how to distinguish between signal and noise. The SL-trained network uses convolutional neural network (CNN) architectures, particularly the U-Net design, which is effective for image-based denoising tasks applied here to seismic data.

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The N2N method involves training the network using noisy/noisy data pairs, eliminating the need for clean data. This approach is based on the assumption that two noisy datasets contain independent realizations of noise. By using the downgoing and upgoing signals from a looped fibre-optic cable installed in the Curtin research well as training data, the neural network learns to denoise by recognizing underlying patterns in the noisy signals. The N2N method has the advantage of being trained on real noisy field data, reducing the potential mismatch between synthetic training data and real-world conditions.

Semi-synthetic data is created for the SL approach by combining synthetic seismic waveforms with real instrumental noise. For the N2N approach, data is generated from field-recorded DAS data using a looped fibre. Both methods utilize a CNN-based U-Net architecture to perform the denoising task. The neural networks are trained on patches of the DAS data to optimise computational efficiency and improve the denoising capability for large datasets. Both neural networks are trained and tested on synthetic and field DAS data, including vertical seismic profile (VSP) datasets and microseismic event recordings. The effectiveness of the networks is measured by comparing the signal-to-noise ratio (SNR) before and after denoising, as well as by analysing the spectral density of the input, denoised, and removed noise data.

The SL-trained neural network significantly improved the SNR in both synthetic and field datasets. The network successfully removed the majority of instrumental noise while preserving the useful seismic signal. However, the network struggled with low-amplitude events, where noise and signal have similar magnitudes.

The N2N network also achieved substantial noise reduction, with improvements in SNR similar to the SL approach. One advantage of N2N was its ability to preserve more high-frequency content compared to the SL method, making it more effective for denoising data with high-frequency components. However, the N2N approach sometimes exhibited signal leakage, especially in the case of complex noise patterns.

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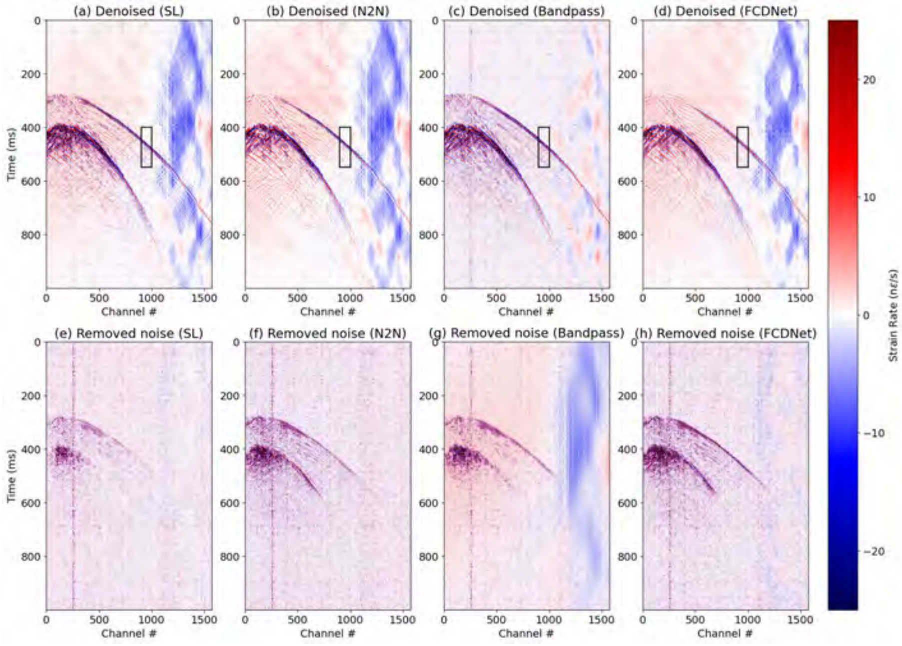

Figure 17 Comparison of the denoising results obtained for a microseismic event recorded in a deep well using (a, e) the SL approach, (b, f) N2N trained neural network, (c, g) band-pass filtering, and (d, h) FCDNet. The upper row shows the denoised sections, while the lower row shows the removed noise sections.

Both methods outperformed traditional denoising techniques such as bandpass filtering. The SL approach showed better performance in structured noise removal, while N2N demonstrated strength in preserving signal features and handling real noisy datasets (Figure 17). The results suggested that both methods could be beneficial depending on the specific dataset and noise characteristics.

The study shows that deep learning-based denoising methods are effective in removing instrumental noise in DAS data. Both the supervised learning and Noise2Noise approaches have their respective strengths: the SL approach benefits from clean/noisy data pairs and works well in structured environments, while N2N is better suited for real-world noisy data where clean data is unavailable. Future work will focus on optimising these approaches for specific use cases, such as higher-frequency datasets or passive seismic monitoring. The paper emphasises that incorporating real instrumental noise into the training datasets is critical to enhancing the effectiveness of these machine learning techniques for seismic data applications.

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7. Recommendations and Conclusions

This report underscores the transformative value of instrumenting field sites with a large number of sensors, offering significant benefits to the industry. The deployment of advanced sensing systems, such as fibre optic sensors, allows for a deeper understanding of subsurface conditions, effective hazard detection, and efficient monitoring of mine operations. The integration of multiple sensors at field sites enhances data acquisition capabilities and supports real-time data acquisition. Effective collection of rich datasets advances exploration efforts, and such data will contribute to improving the safety of operations.

Fibre optic sensing has emerged as an enabling technology with distinct advantages for instrumented field sites. The unique properties of optical sensors, such as their longevity, small spatial footprint, and the potential to leverage existing telecom infrastructure, make them a preferable choice for long-term monitoring and data collection. The ease of installation and adaptability of optical fibre arrays further enhance their suitability for a wide range of field conditions, providing high-resolution, continuous data over large areas.

One of the most notable strengths of fibre optic sensing is its ability to fuse multiple data types, such as Distributed Acoustic Sensing (DAS), Distributed Temperature Sensing (DTS), and Distributed Strain Sensing (DSS), using a single fibre optic cable. This capability enables efficient, cost-effective data collection of multiple parameters simultaneously and their monitoring, offering comprehensive insights into subsurface conditions and operational performance.

The report also highlights key considerations in selecting optimal fibre optic sensing solutions for specific site configurations. These considerations include:

- Choice of interrogator: Selecting the suitable interrogator based on factors such as sensitivity, range, and specific application is critical to ensuring accurate data acquisition.
- Choice of fibre optic cable: The type of cable used plays a vital role in the quality and reliability of the data. Factors such as cable material, design, and deployment environment must be evaluated for a particular task.

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- Choice of deployment strategy: The deployment method (e.g., cemented, suspended, tubing-conveyed) significantly impacts data quality and operational efficiency and should be tailored to the site's specific geological and operational conditions.

In addition to these technical insights, it should emphasise the importance of education and training in fibre optic technology. Developing dedicated courses and educating both students and industry professionals is crucial for advancing this technology's adoption and ensuring its potential is fully realised across various applications.

Lastly, the value of accessible testing field facilities has to be stressed. These facilities play a critical role in advancing fibre optic sensing technology by providing a real-world environment for testing, calibration, and innovation. Such facilities are essential for ensuring continuous technological improvements and training the next generation of geophysical professionals.

In conclusion, fibre optic sensing technology offers substantial advantages for instrumented field sites, enabling more efficient data acquisition in different settings and subsequent accurate subsurface characterisation and monitoring.

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The Open-Source Library Of Pre-Trained Neural Networks For De-Noising DAS Data

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MinEx CRC, Curtin University

Open-Source Library of Pre-Trained Neural Networks for DAS Data Denoising

- Removing DAS noise could enhance passive data and allow for the use of low power active sources which are cheaper to deploy.
- We have been exploring the use of Machine Learning to remove DAS instrumental noise:
  - Noise2Noise approach (noisy/noisy data pairs),
  - Traditional supervised learning approach (clean/noisy data pairs).
- Some of the pre-trained models are now publicly available on GitHub.

GitHub Repository

https://github.com/CEGCurtin/DASDenoisingML_RemoteSensing/tree/main

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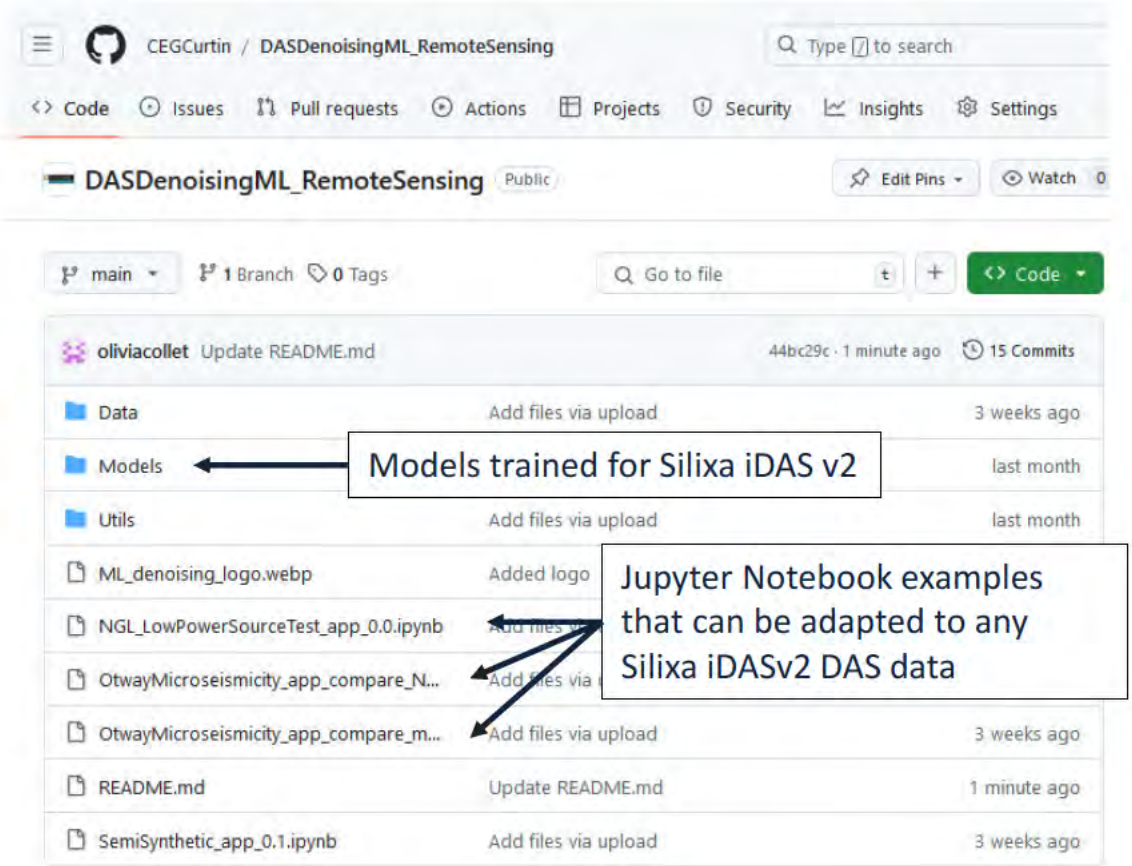
Open-Source Library of Pre-Trained Neural Networks for DAS Data Denoising



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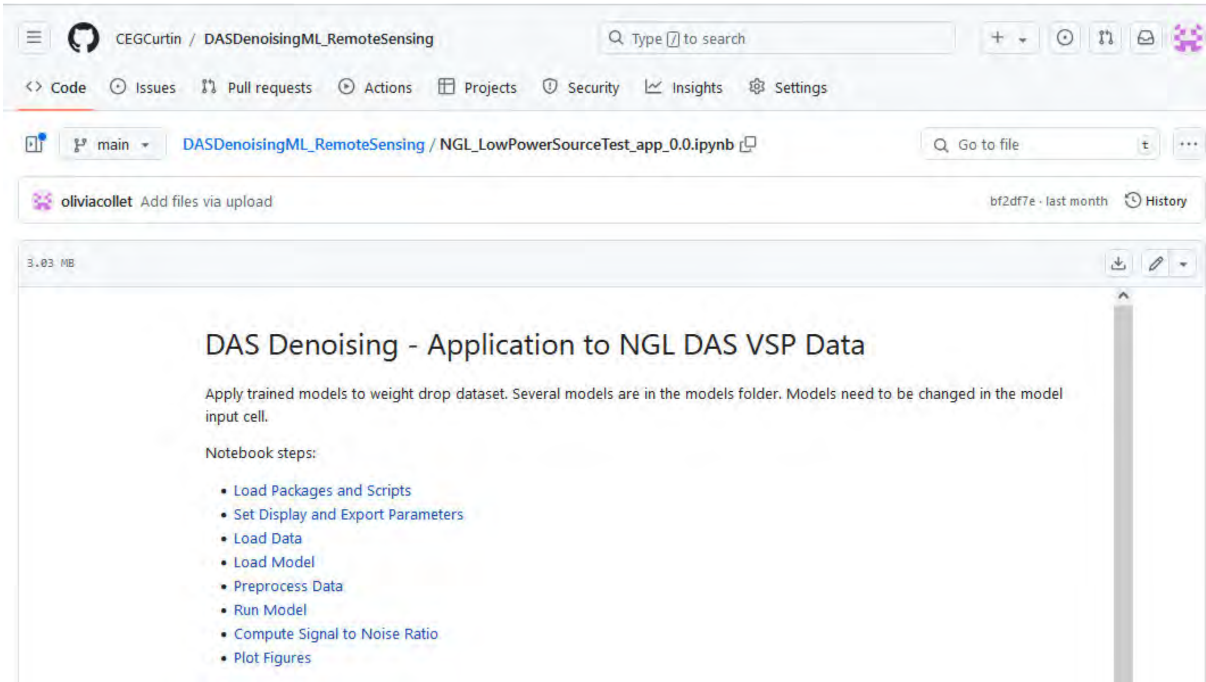
Jupyter Notebook Example



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Application of Denosing ML approach during the data acquisition

During acquisition of DAS data with a small weight drop using fibre optic cable installed in the Curtin research well, we have been applying denoising approaches during data collection. We used RadEx Pro seismic software for the test. The software is dedicated for seismic data QC during acquisitions and seismic data processing. It has an option (as many other modern seismic software packages) to integrate into QC or processing workflow external codes and algorithms implemented in Python. An example of a denoised single short excitation at a near offset location is demonstrated in Figure 1 below. Using the open-source library, such option could be realised and tested for any DAS acquisition contributing to further development of the ML approaches and extending the library models.

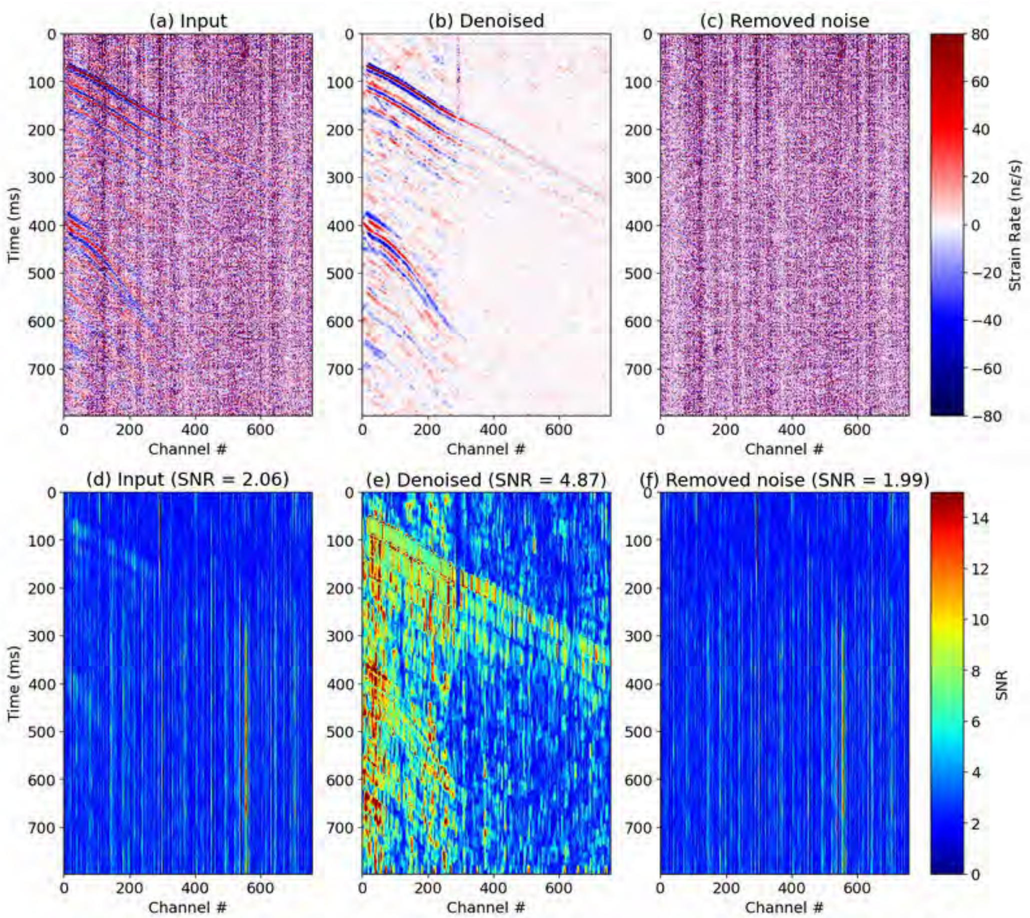

Figure 1. Example of a denoised single shot using ML approache.

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