Imaging the Earth
creative technologies for our changing world

Nicholas Arndt

- Emeritus professor, University Grenoble Alpes
- president of Sisprobe

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Plan of talk

1. Ambient noise seismology
   – what is it and how is it used?
2. Sisprobe – some information about our company
3. What we can do for you?

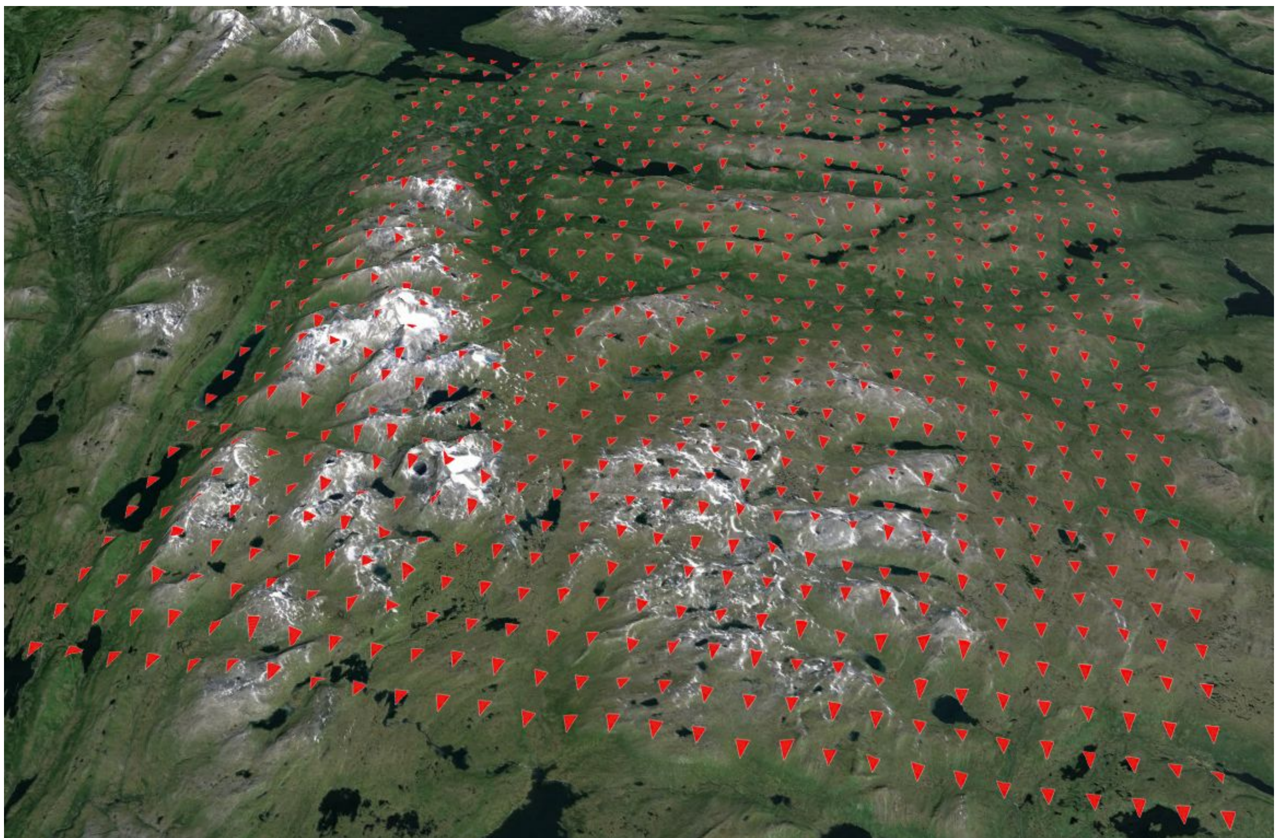
Passive seismic exploration

Passive noise-based seismic exploration is a new revolutionary approach for imaging and monitoring the underground.

- Used to obtain tomographic 3D images or to monitor the sub-surface
- No active source – explosions or vibrator trucks; instead we use ambient (natural or anthropogenic) seismic noise
- Common sources – traffic, wind in trees, ocean waves, small earthquakes

Passive seismic imaging

We deploy new technology seismic nodes in the field and **exploit surface wave seismic noise**



No costly and dangerous active seismic sources!!

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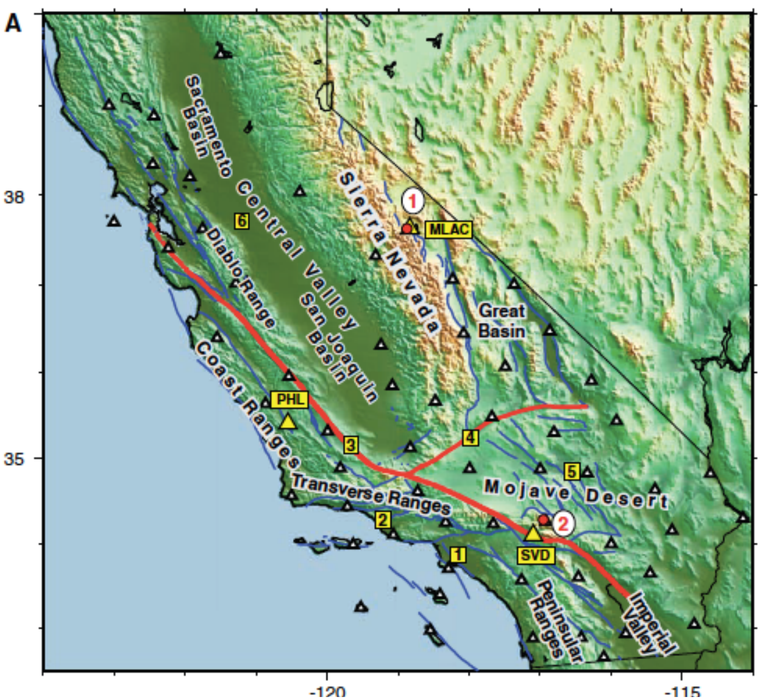
Passive seismic imaging as a research tool

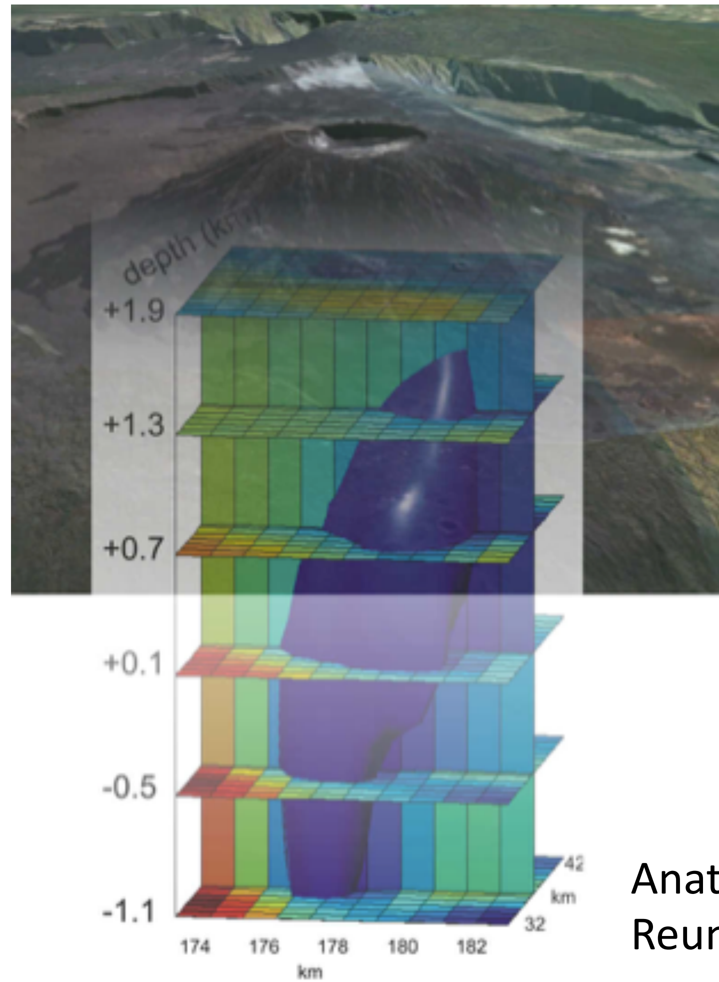
Passive seismic technology was developed by researchers at University Grenoble Alpes for fundamental research

- structure of continental crust, dynamics of fault zones, anatomy of volcanoes, etc

High-Resolution Surface-Wave Tomography from Ambient Seismic Noise
Shapiro et al, 2014



Imaging the San Andreas fault zone



Anatomy of La Reunion volcano

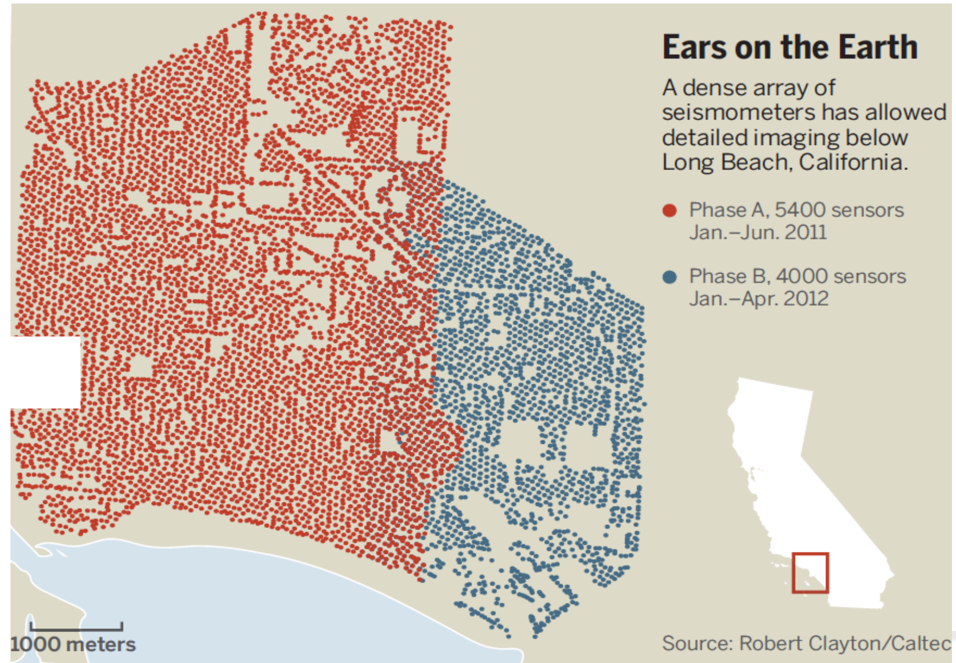
We made some of the first industrial applications

A boom in boomless seismology

Densely packed sensors eavesdrop on Earth's hum

Science, August 2014; vol 345

Imaging a gas field in California



Geophysical Research Letters

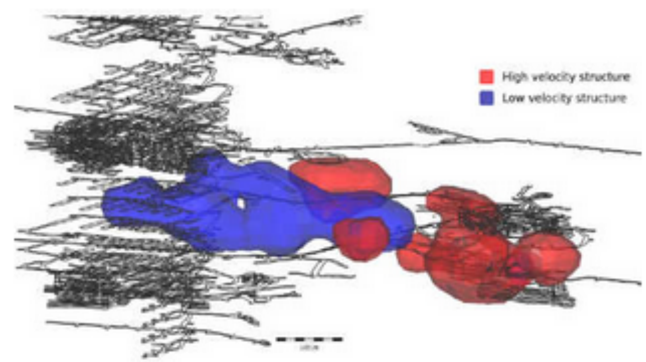
RESEARCH LETTER
10.1002/2015GL065975

Key Points:
- Seismic velocity variations were examined with seismic noise correlations in a mine during a blast
- A sudden decrease, gradual relaxation, and permanent changes in the seismic velocity are observed

Investigation of coseismic and postseismic processes using in situ measurements of seismic velocity variations in an underground mine

G. Olivier[1,2], F. Brenguier[1], M. Campillo[1], P. Roux[1], N. M. Shapiro[3], and R. Lynch[2]

[1]Institut des Sciences de la Terre, Université Joseph Fourier, Grenoble, France, [2]Institute of Mine Seismology, Kingston, Tasmania, Australia, [3]Institut de Physique du Globe de Paris, Paris, France



Body-wave tomography and monitoring

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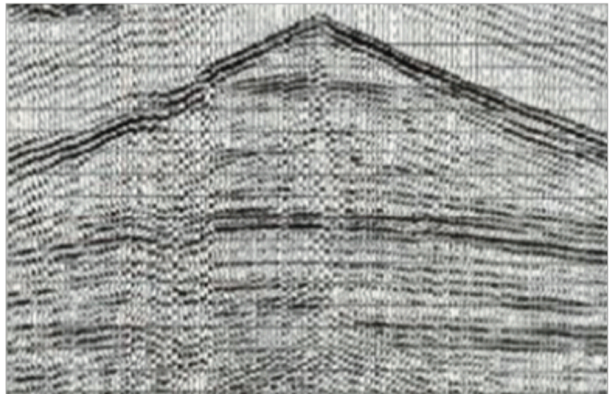
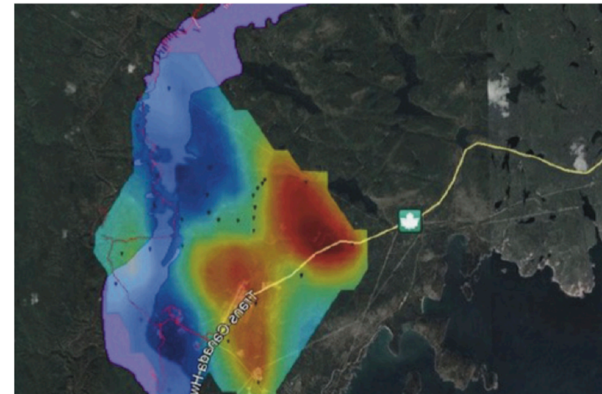
Current fields of application

Imaging & monitoring the subsurface from 10m to a few km depth



Oil & gas

Subsurface passive imaging. Velocity models for statics, NMO, migration, and anisotropy.



Mineral exploration

Brownfields and greenfields exploration. Environmentally friendly, low-cost way to de-risk full-scale seismic surveys.

Geothermal resource exploration, CO_2 storage

Imaging geological features; monitoring geothermal resources and sites of CO_2 sequestration.

Geotechnical engineering

Detection and monitoring of weak, unstable subsurface zones. Seismic risk assessment. Tunnels, dams, power stations, civil engineering projects.

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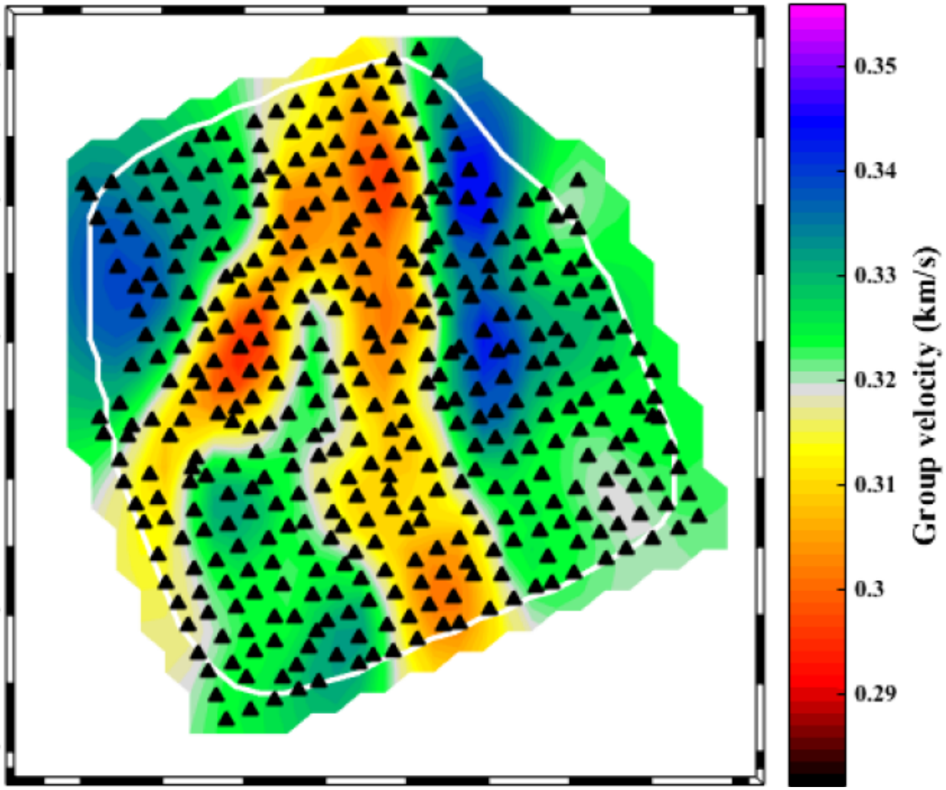
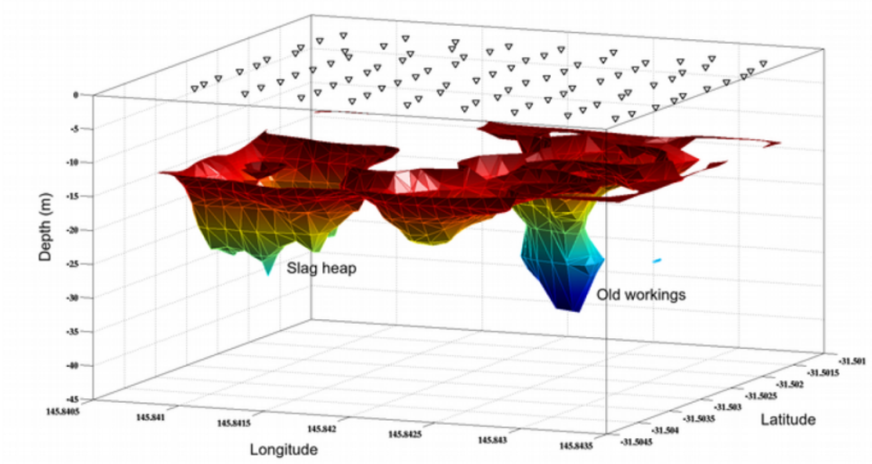
Ambient-noise seismic tomography – how does it work?

Passive surface wave tomography produces
3D S-wave velocity models



Each sensor behaves as a
receiver and
virtual seismic source



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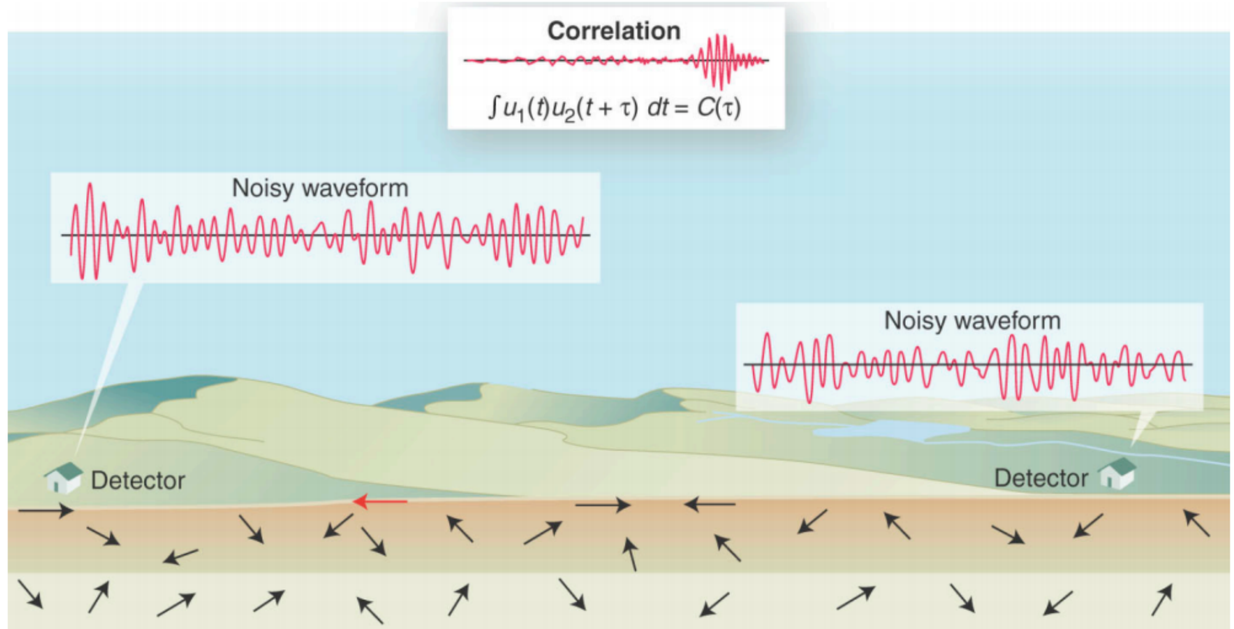
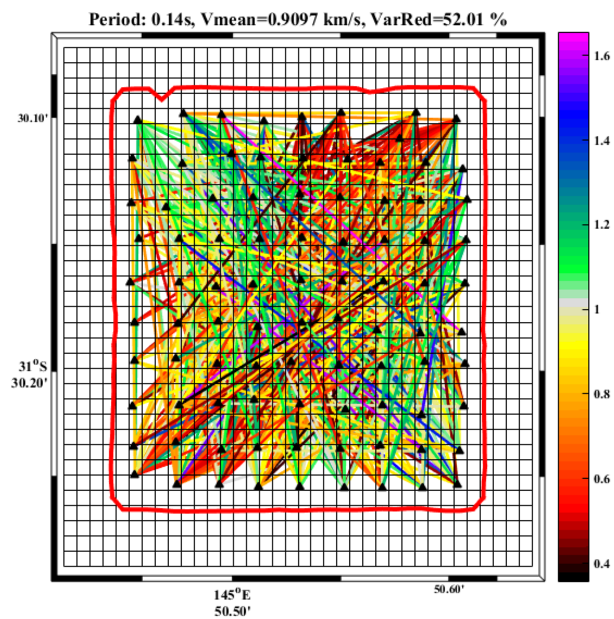
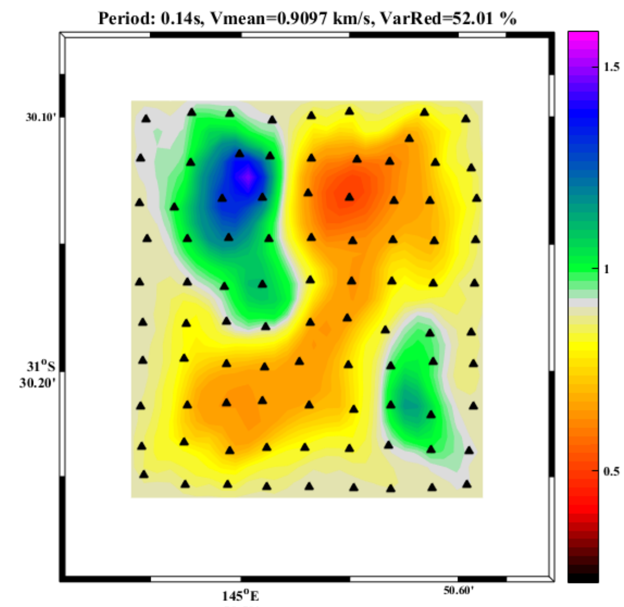
Ambient-noise seismic tomography – how does it work?

- Cross-correlating ambient seismic noise recorded at the surface turns each seismometer into a virtual source



Use of dense surface arrays provides detailed images of the subsurface





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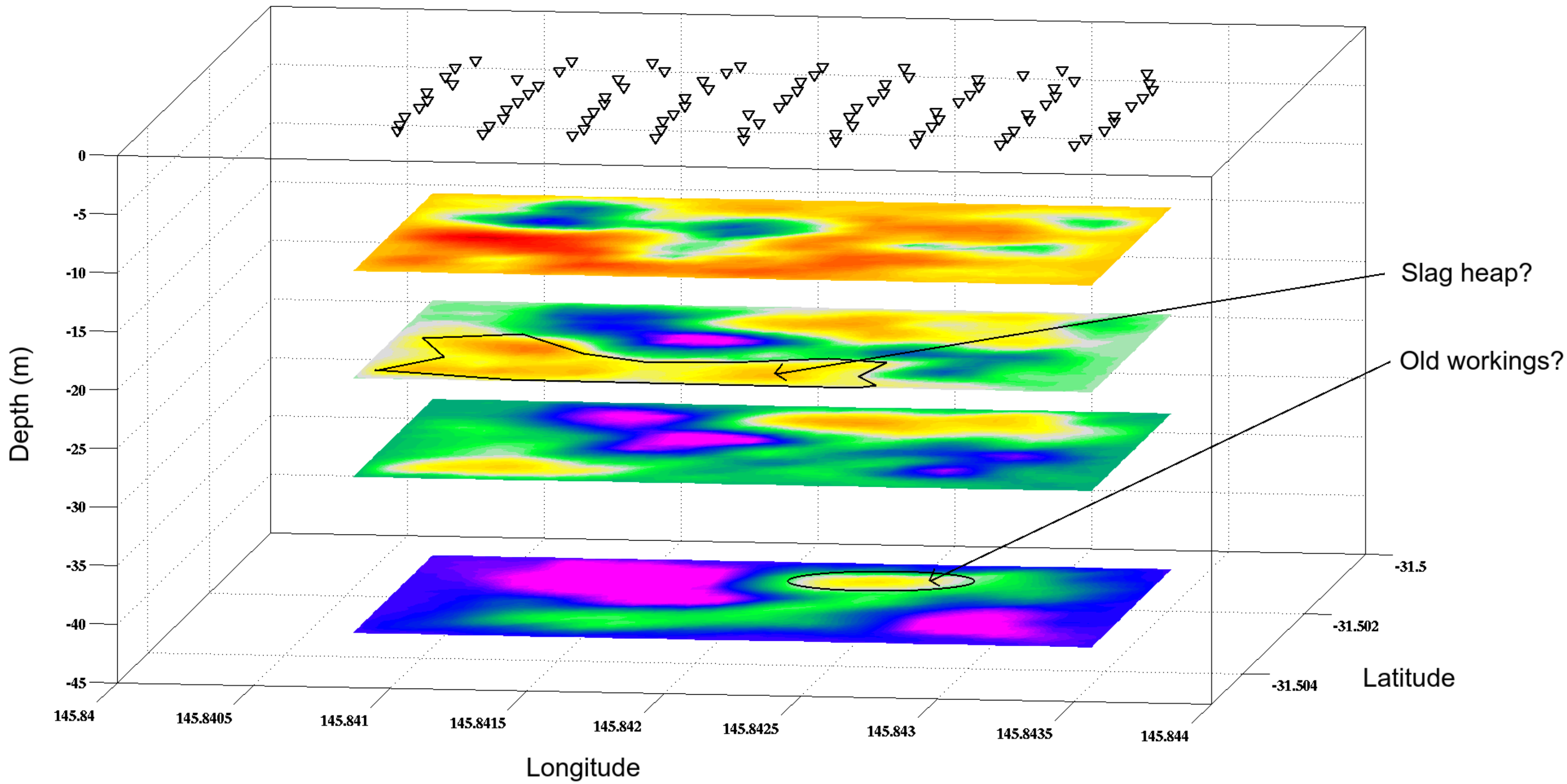
Ambient-noise seismic tomography – how does it work?

Different frequency surface waves sample different depths (low frequency → greater depth), so we can image the subsurface by looking at the wave velocities at different depths.



Seismic methods for mineral exploration – why aren't they used?

- Seismic surveys have been shown to be useful, but the minerals industry hesitates to adopt them
- This is partly due to cost: > $1M for a large active-source seismic survey
- For the method to be adopted more widely in the minerals industry, the cost must be reduced by an order of magnitude

How?

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Ambient seismic noise tomography

With new methods and technology, we can remove the costly active source and use only ambient noise to image deposits. We use autonomous nodes that do not need cables

DTCC SmartSolo nodes: 3 component, 30-day battery life; frequency: 10 Hz sensitivity: 78.7 V/m/s

This means:

- No active source
- No cables
- Less impact on the environment
- Less licencing and permitting
- Easy deployment

= massive reduction in cost

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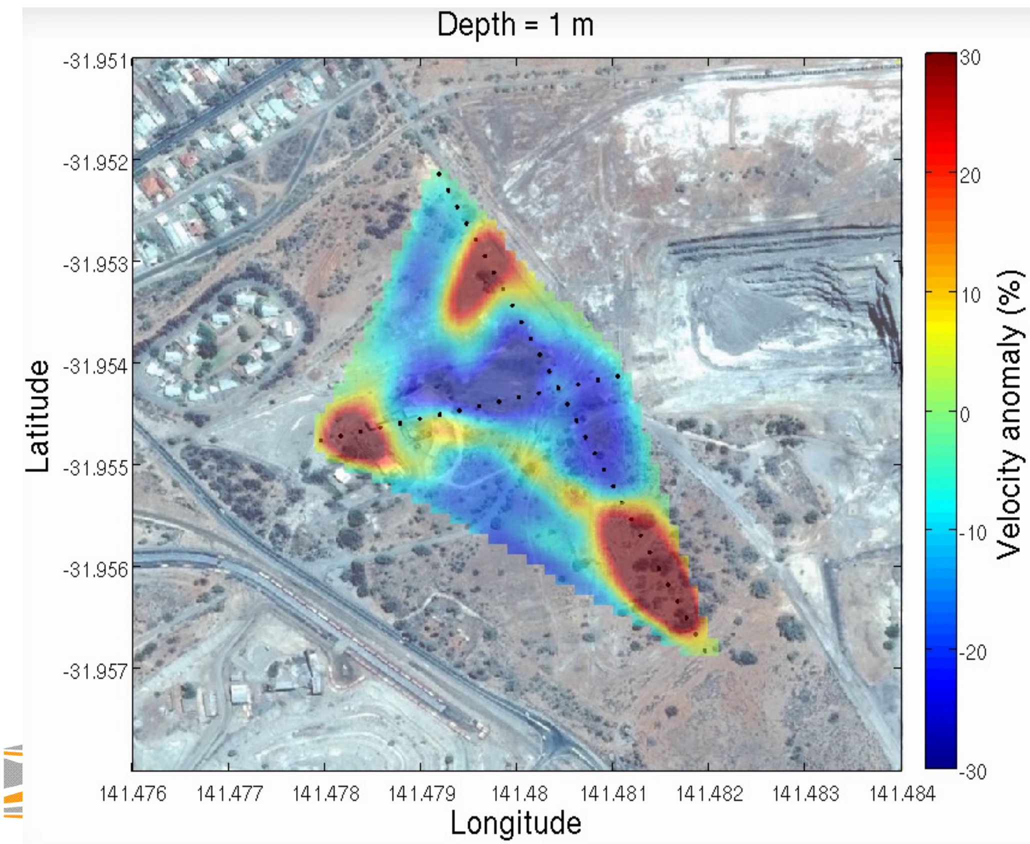
A survey in a zone of mine expansion

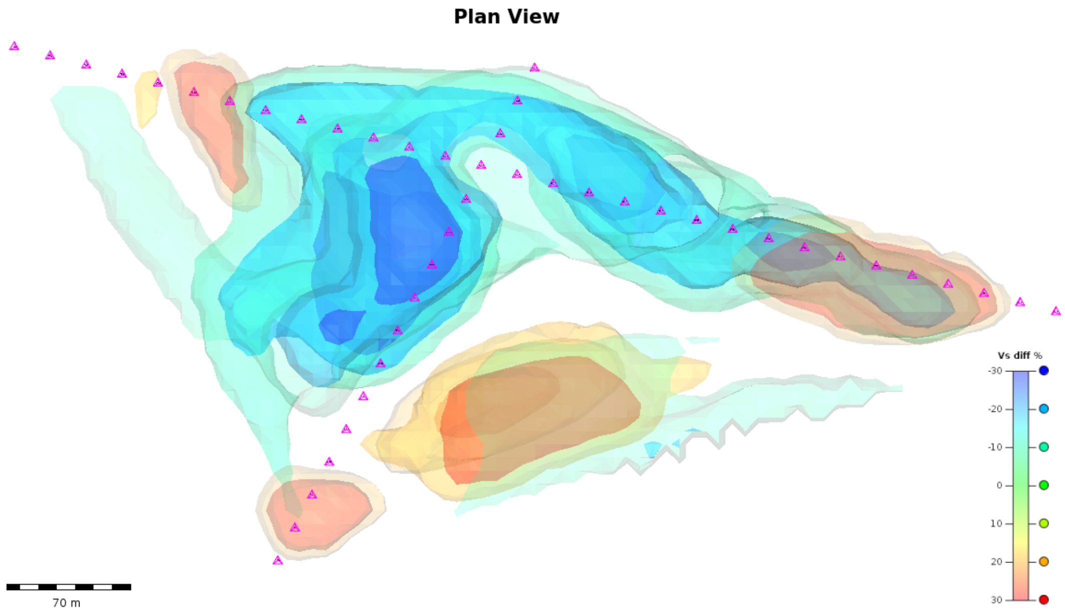
- Goal - to detect remnant zones of high grade ore amongst mined out and back-filled stopes
- 100 year old mine plans are not accurate enough to show the remnant zones

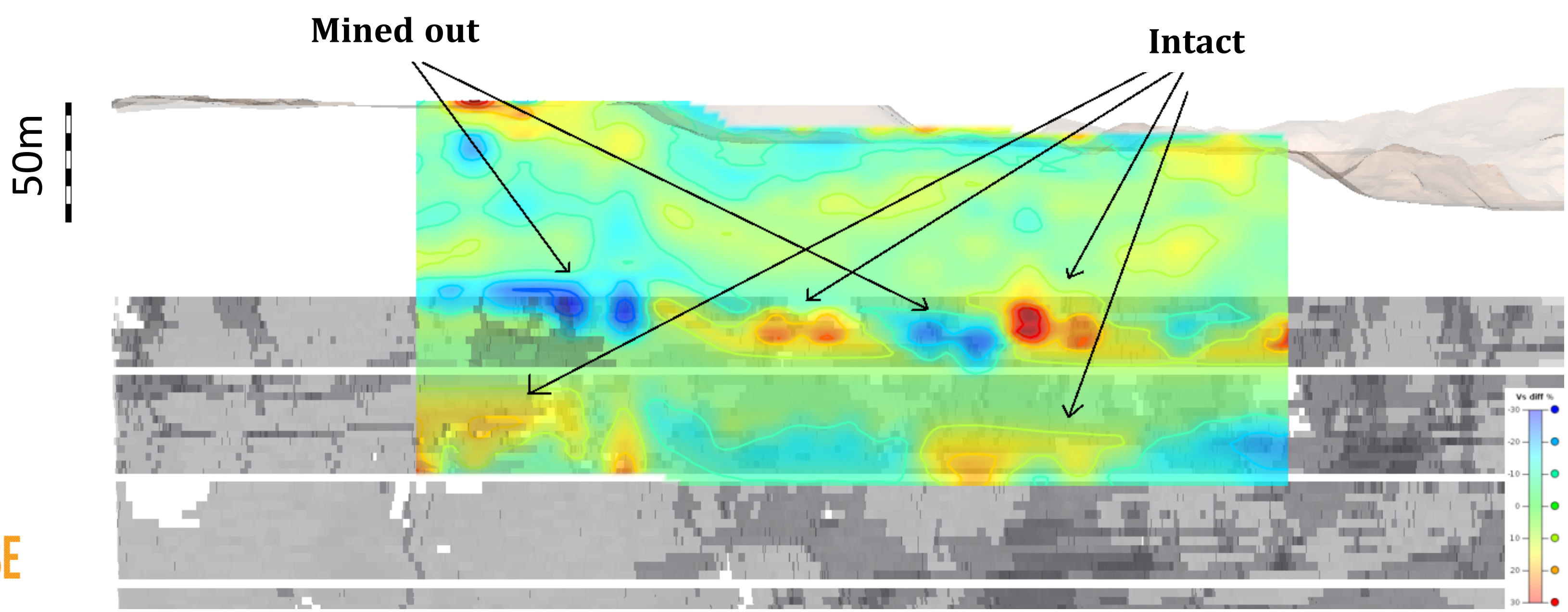


A survey in a zone of mine expansion

- We used 60 nodes to target two areas. Data was recorded for 5 days; total cost ca. $40k

- The results of the survey indicated the back-filled regions (low velocity) amongst the intact rock





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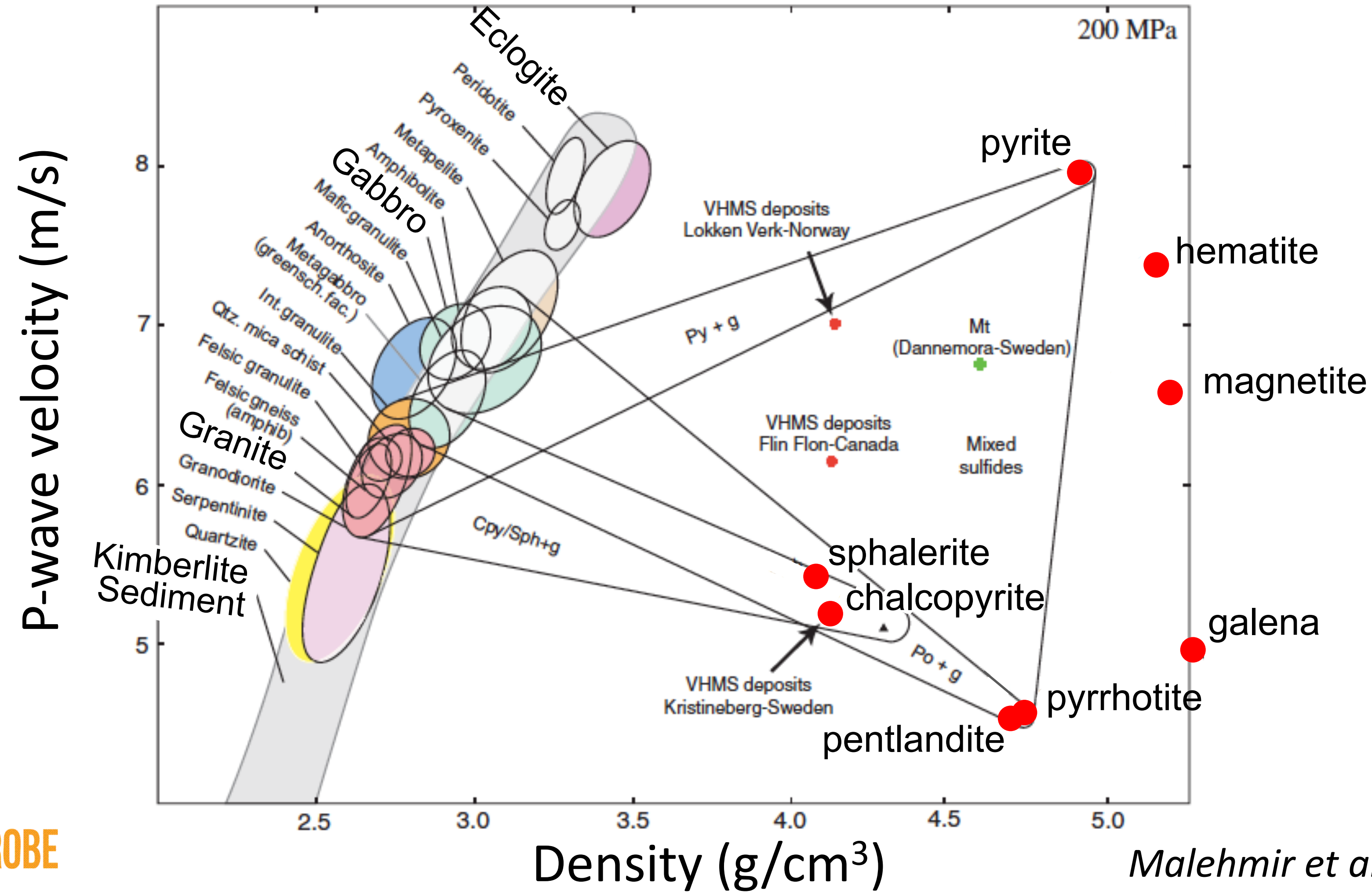
Seismic methods for mineral exploration– why do they work?

To use seismics to delineate ore bodies, we exploit differences in ore and rock properties (seismic velocity for transmission and accoustic impedance contrast for reflection tomography).



Malehmir et al 2012

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A Survey at an Exploration Site

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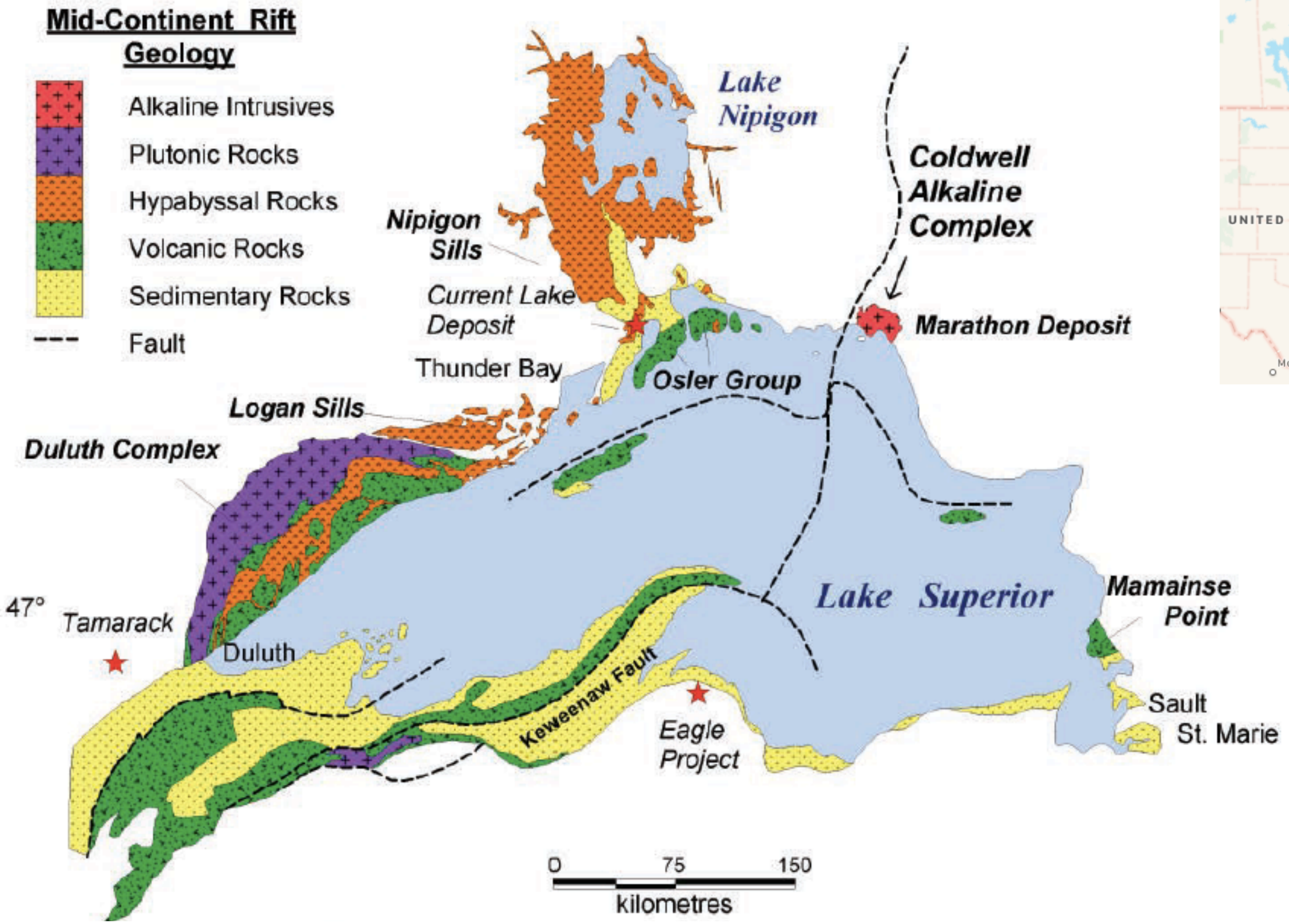
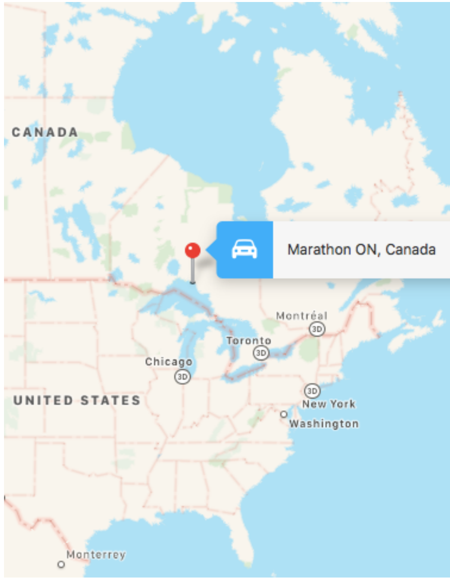
The Marathon PGM-Cu deposit, Ontario





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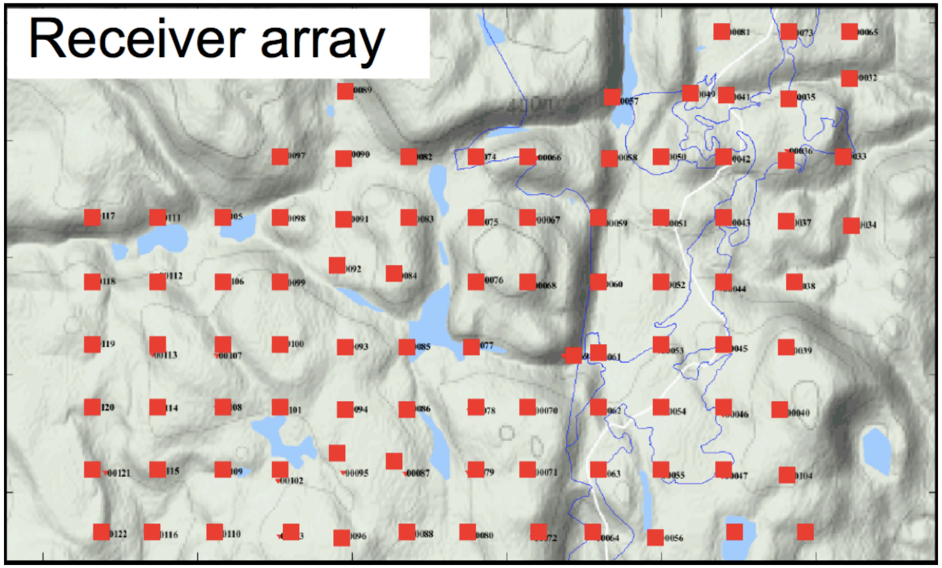
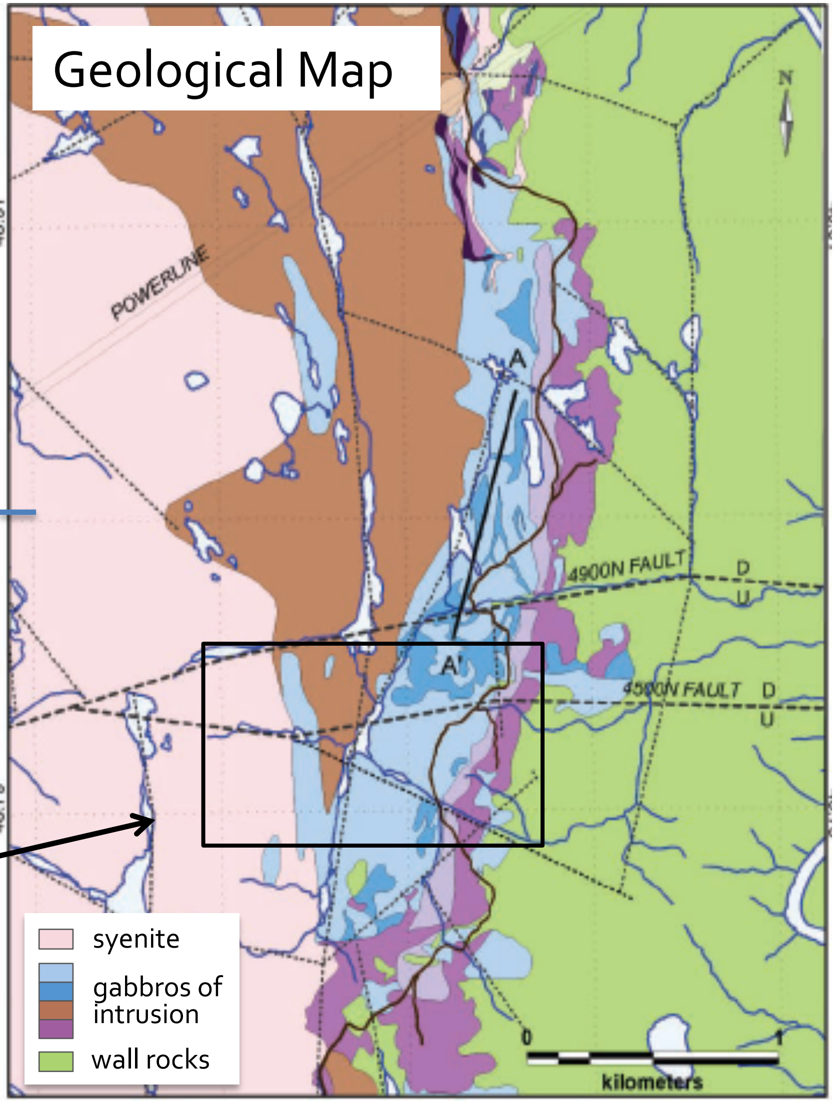
UNIVERSITÉ Grenoble Alpes
DIAS

The Marathon PGM-Cu deposit, Ontario

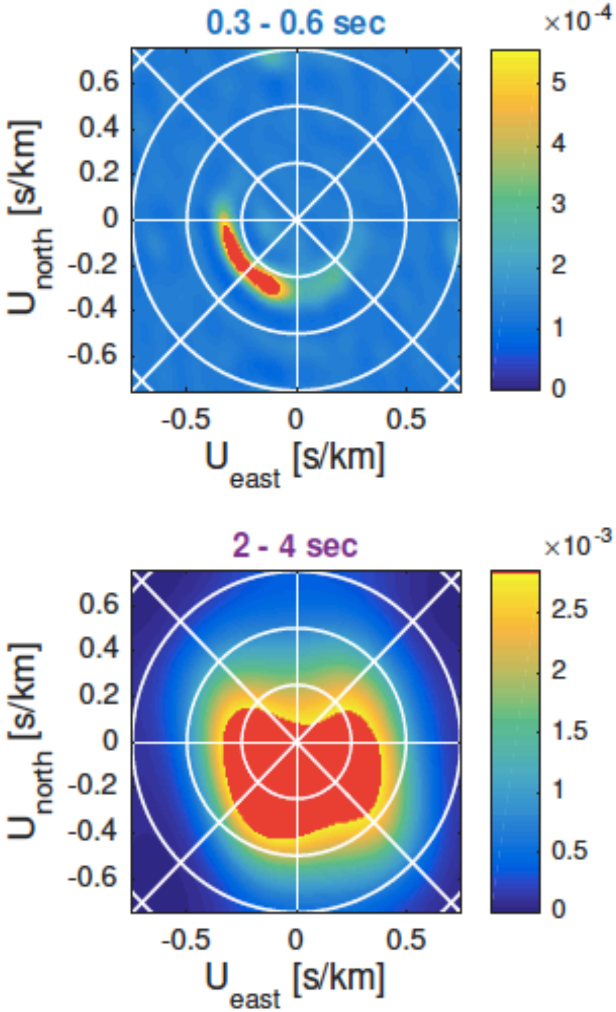
GENERATIONPGM

Target: magmatic PGM-Cu sulfides in a gabbroic intrusion
Method: surface wave ambient noise seismic tomography
Goals: 1) define the geometry of the intrusion contact 2) identify ore-localising structures
Approach: 90 receivers deployed for 30 days; treatment of surface waves; total cost about 70k$





Seismic noise at the Marathon Site



high frequency - from waves on Lake Superior

low frequency - from waves on the North Atlantic ocean

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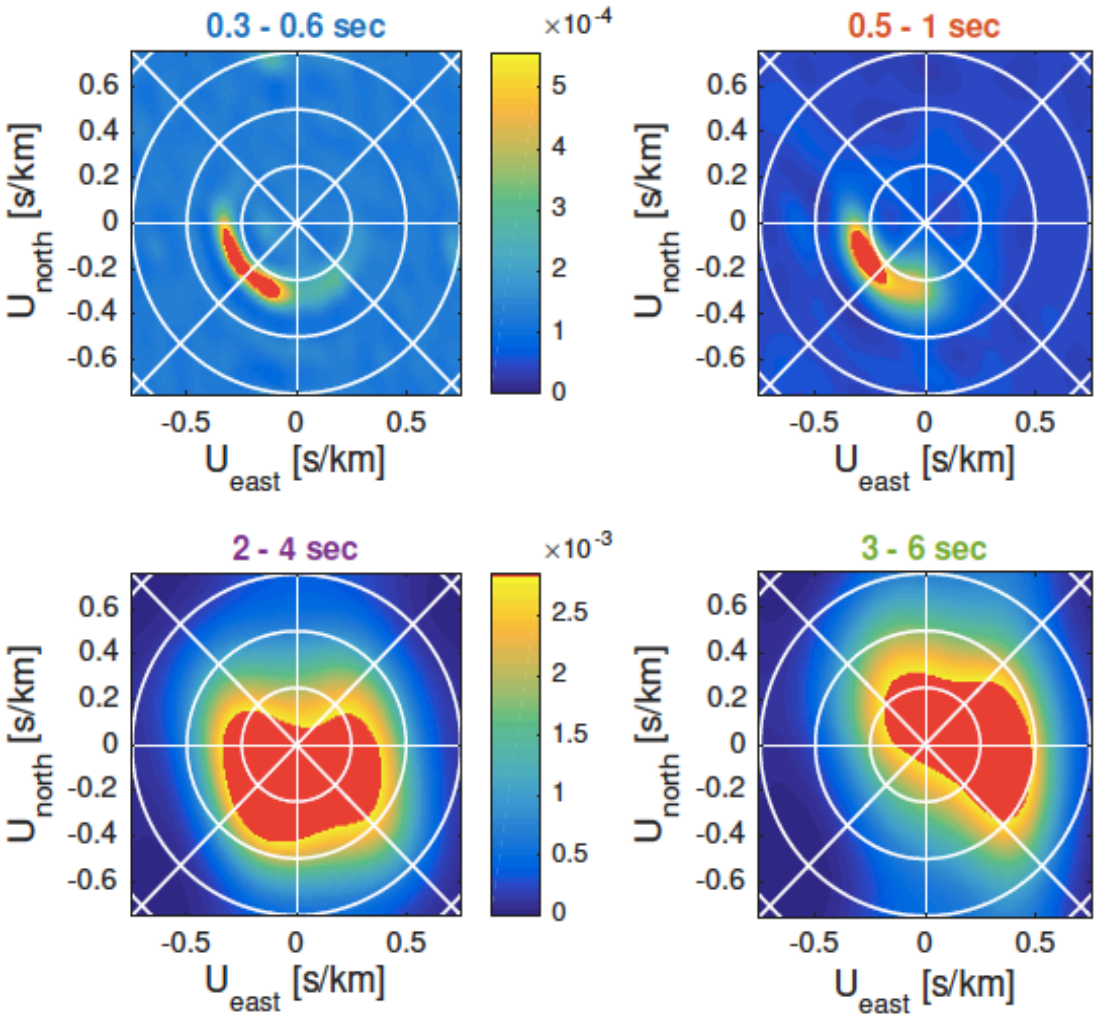
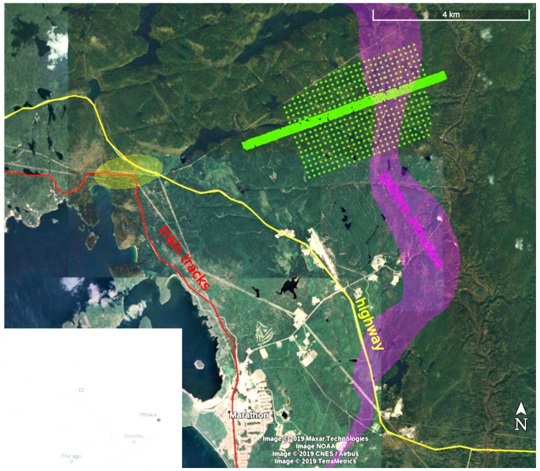
Seismic noise at the Marathon Site



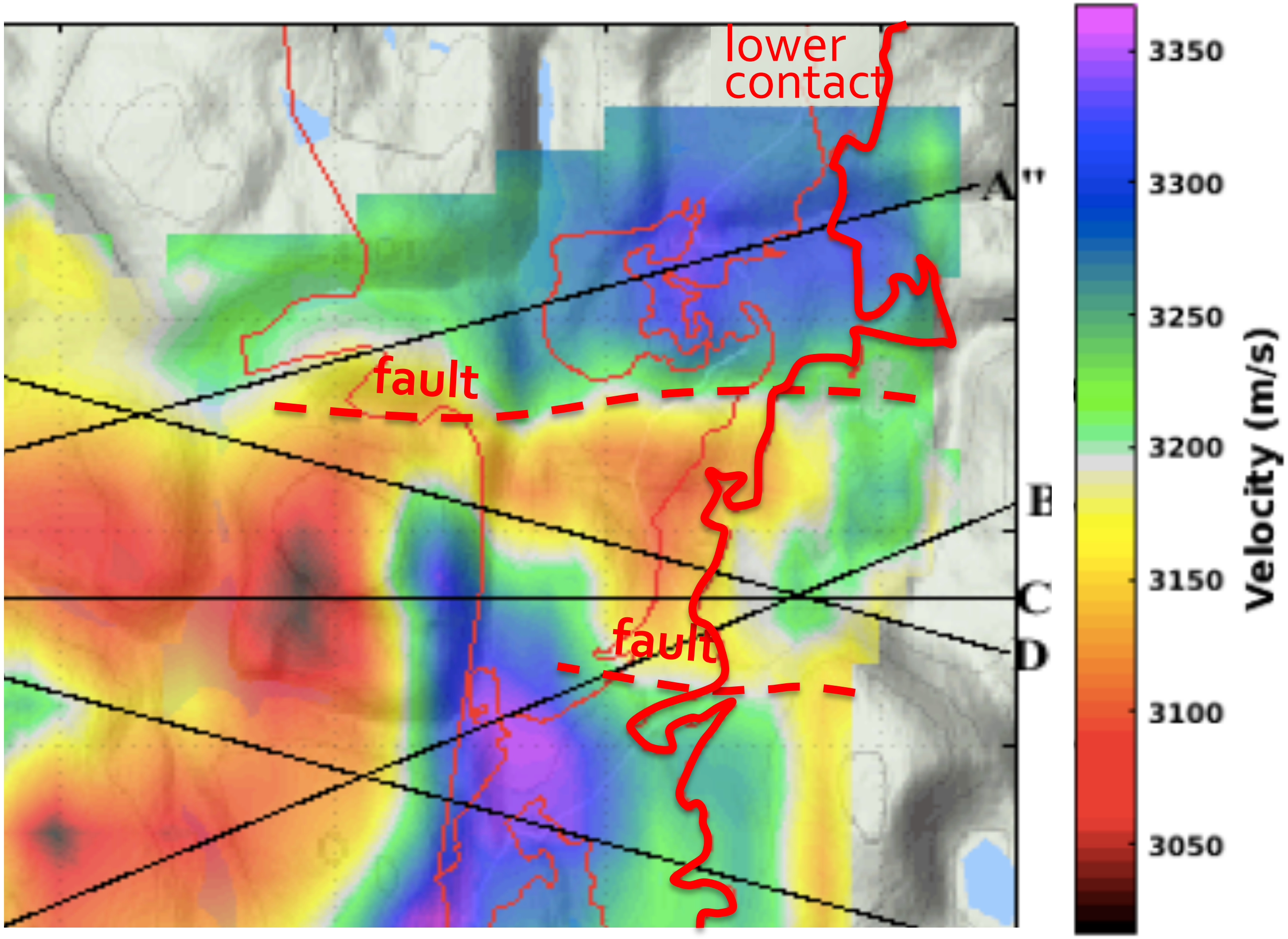
high frequency
~~- from waves on
Lake Superior~~

freight trains !



Velocity model (Vs) – a slice at 250 m depth - delineates:

- the lower gabbro contact of the intrusion
- a horst bounded by two faults
- the syenite layer to the west



The Marathon PGM-Cu deposit, Ontario

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But there are limits of the ambient noise surface wave method:

- poor depth penetration
- limited spatial resolution

In PACIFIC, a 3M$ project financed by the European Horizon 2020 program, we develop two new methods:

1. passive reflection body-wave seismology
2. multi-array approach – a surface array combined with a down-hole array

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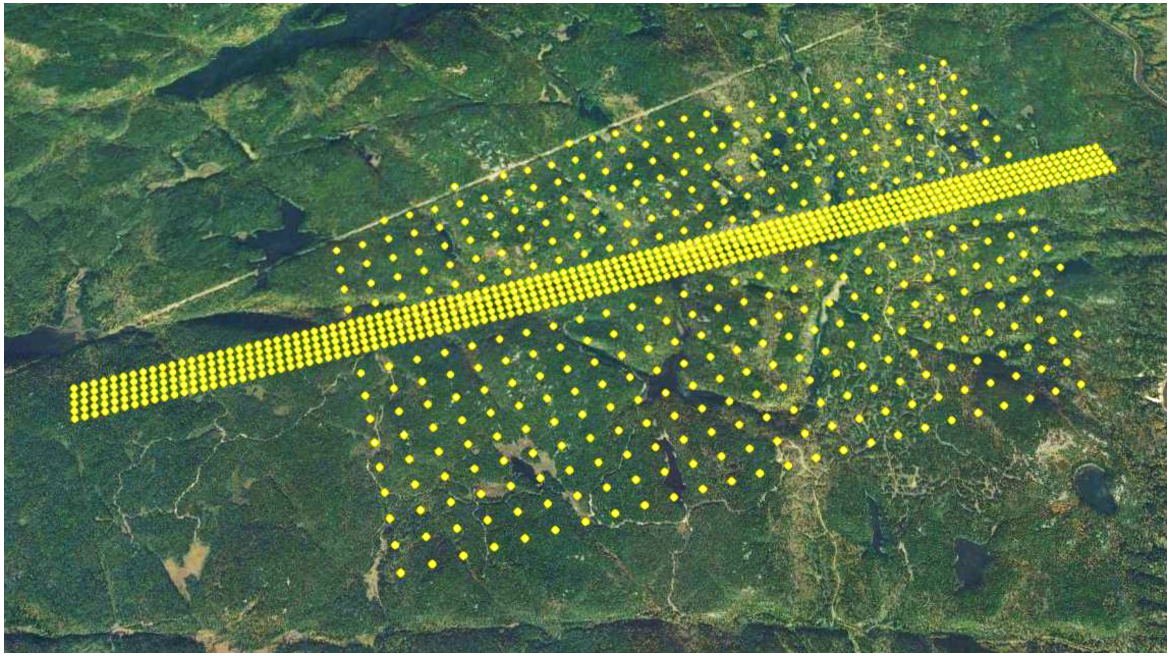
The Marathon PGM-Cu deposit, PACIFIC project

1) Passive reflection body-wave seismology

A dense 3D array and a “fat” 2D array was deployed for 30 days to obtain high-resolution images of the ore setting



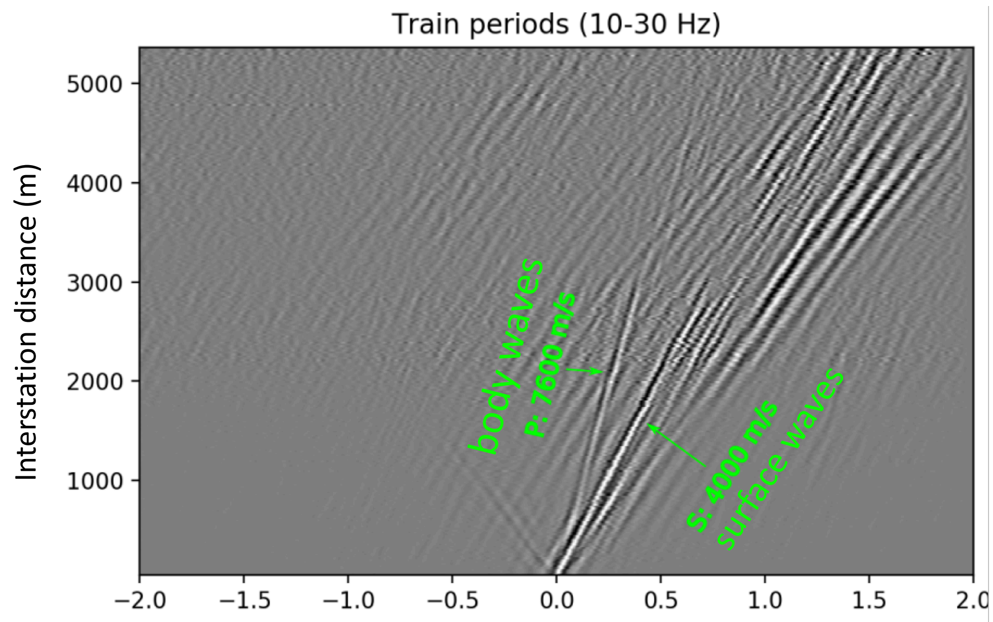
The 1100 node array at Marathon

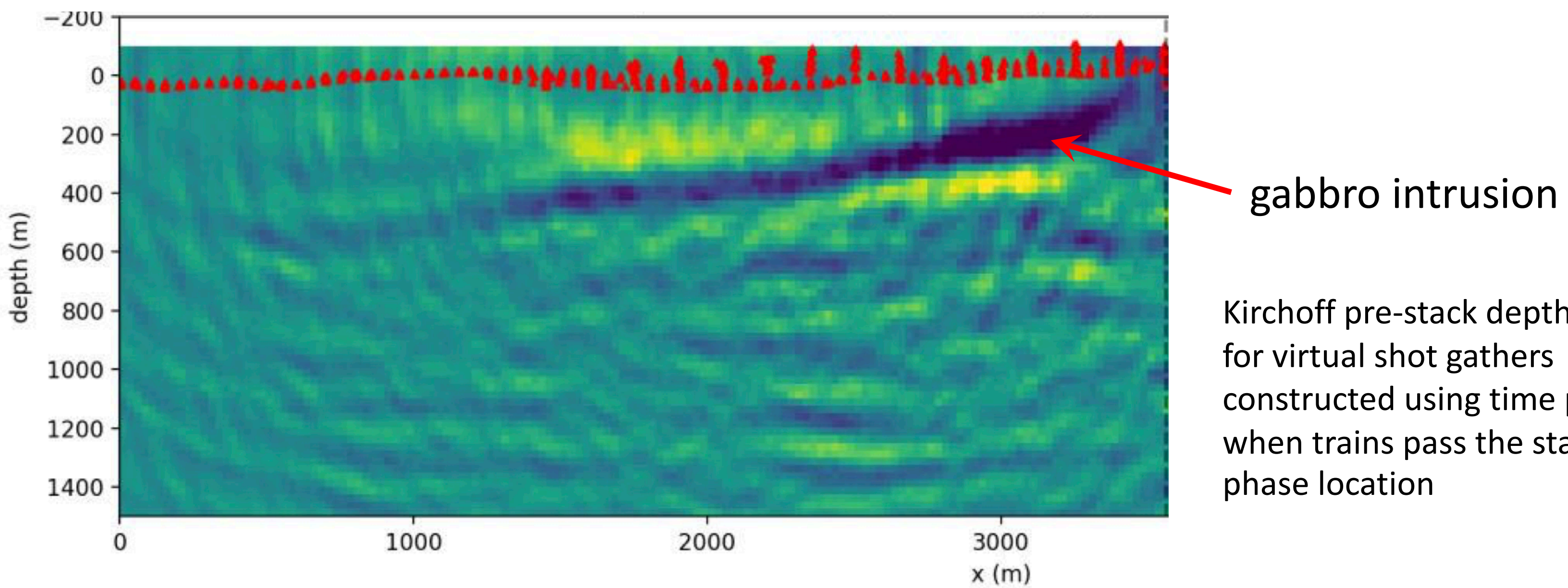
SISPROBE · institute of mine seismology · GENERATIONPGM · UNIVERSITÉ Grenoble Alpes · DIAS

The Marathon PGM-Cu deposit, PACIFIC project

Extraction of body waves from the ambient noise signal

Virtual common midpoint gathers selectively stacked for periods when rail or highway traffic passes the dense line



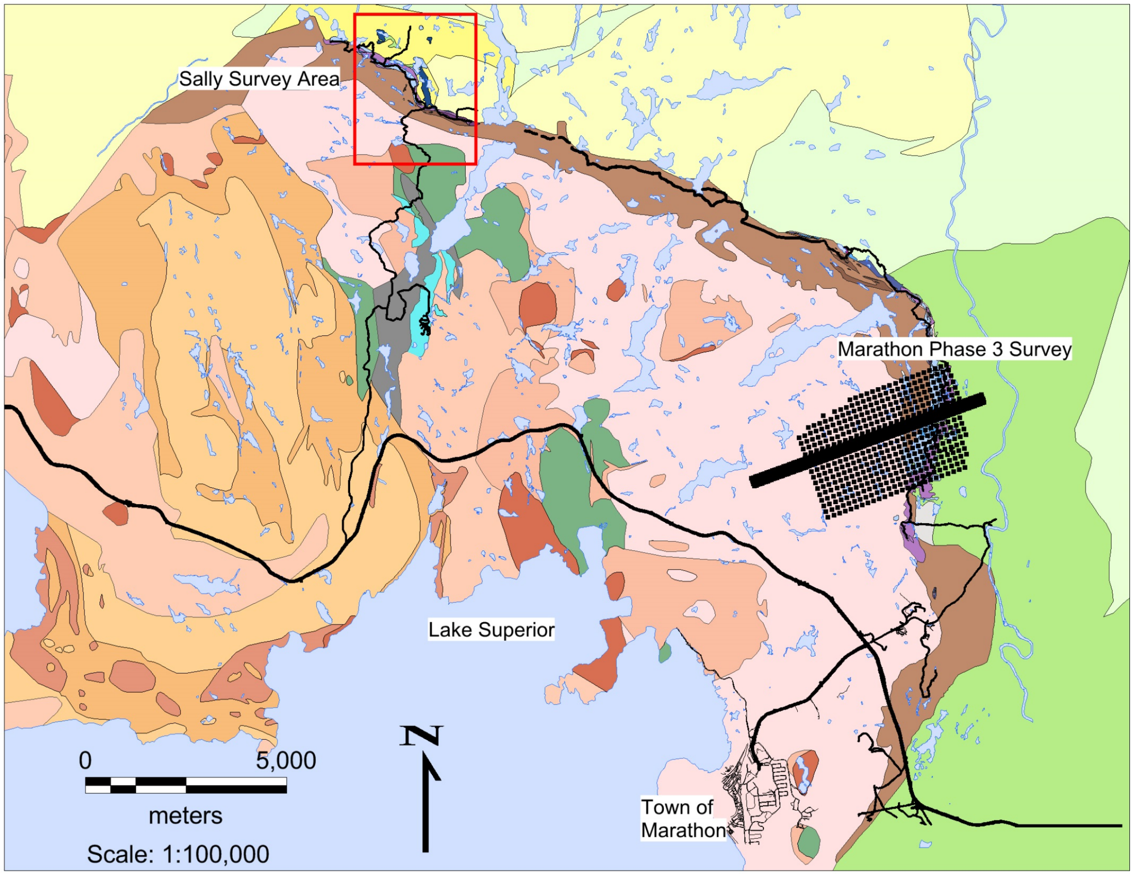


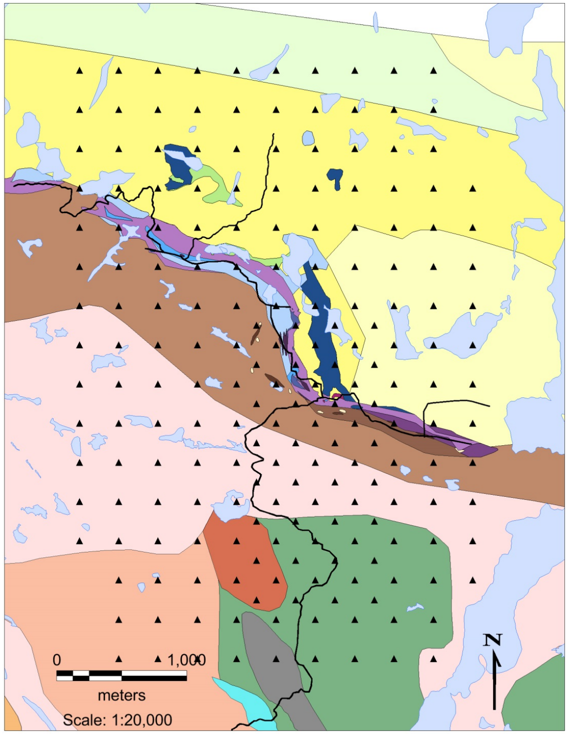
Kirchoff pre-stack depth migration for virtual shot gathers constructed using time periods when trains pass the stationary phase location

Sally, a commercial project

GENERATIONPGM

PGM-Cu mineralization in another part of the Caldwell complex





200 receivers over 3 x 4 km; 300m spacing; 30 days deployment; cost €70k

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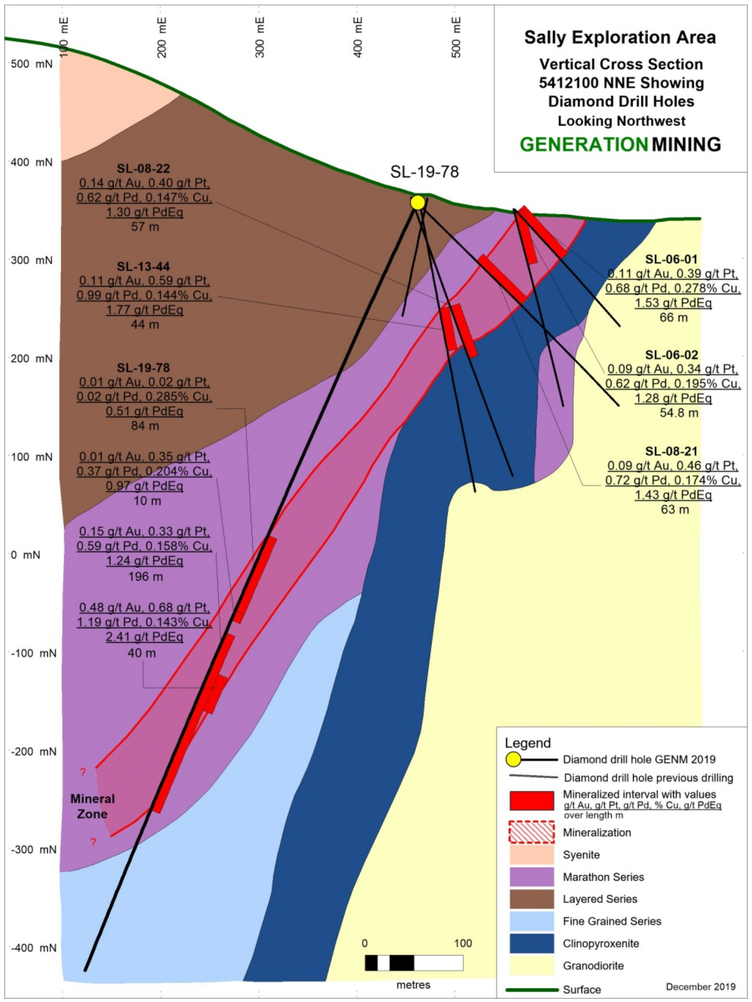
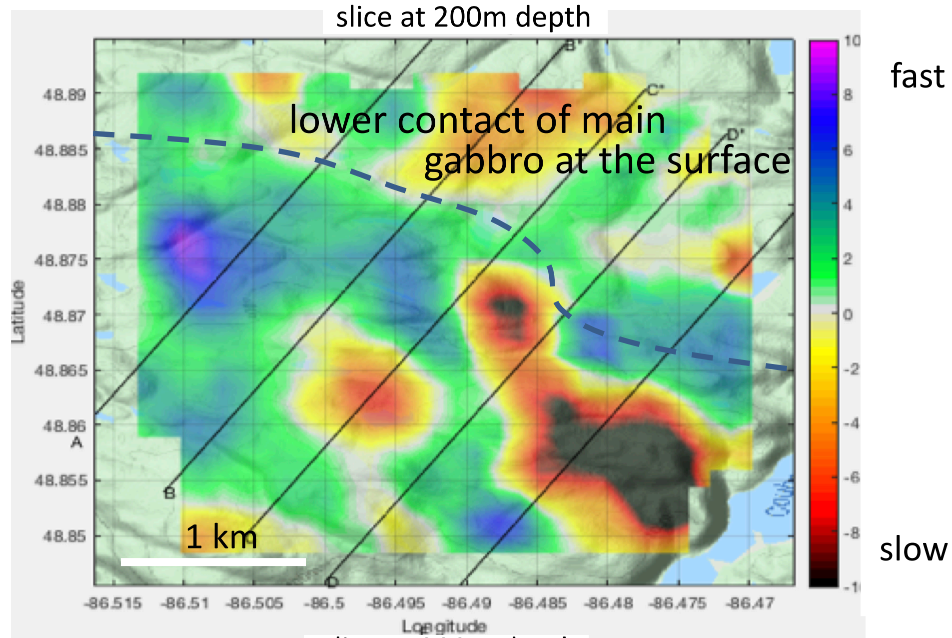
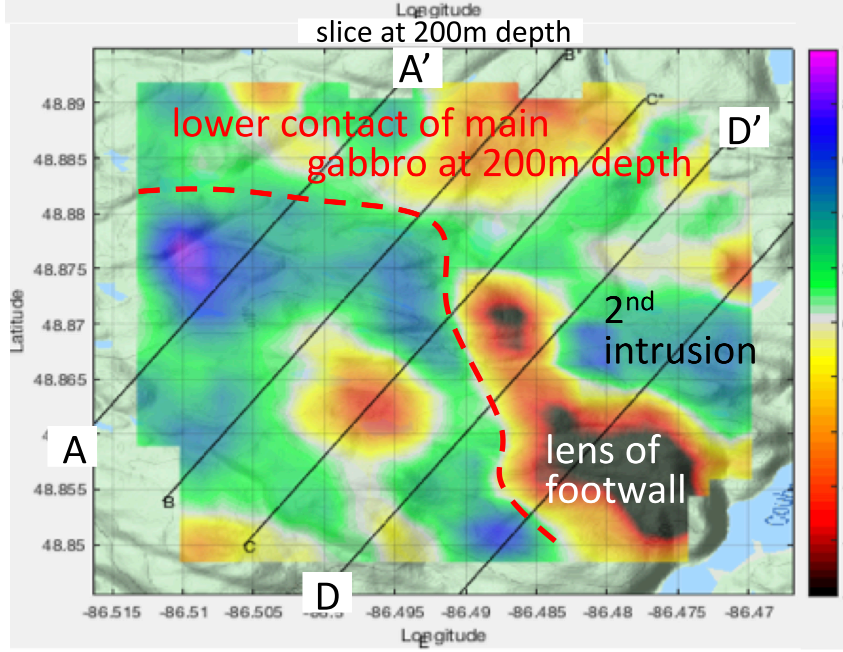
Sally PGM prospect

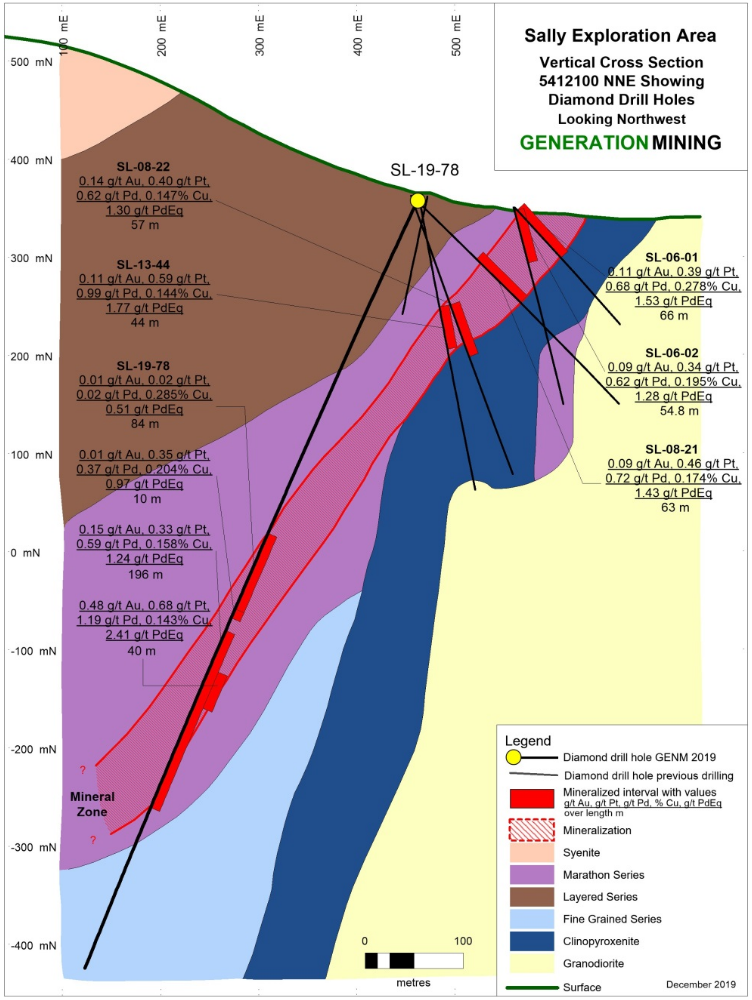


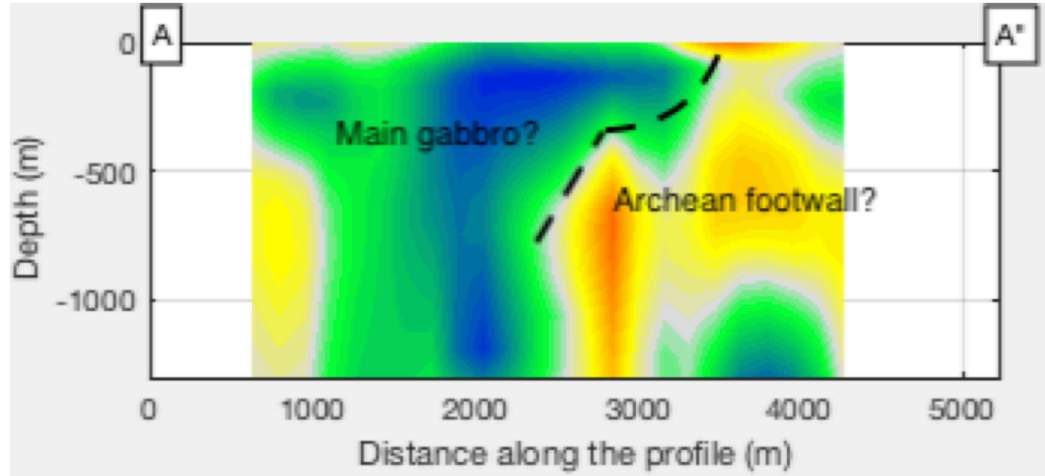


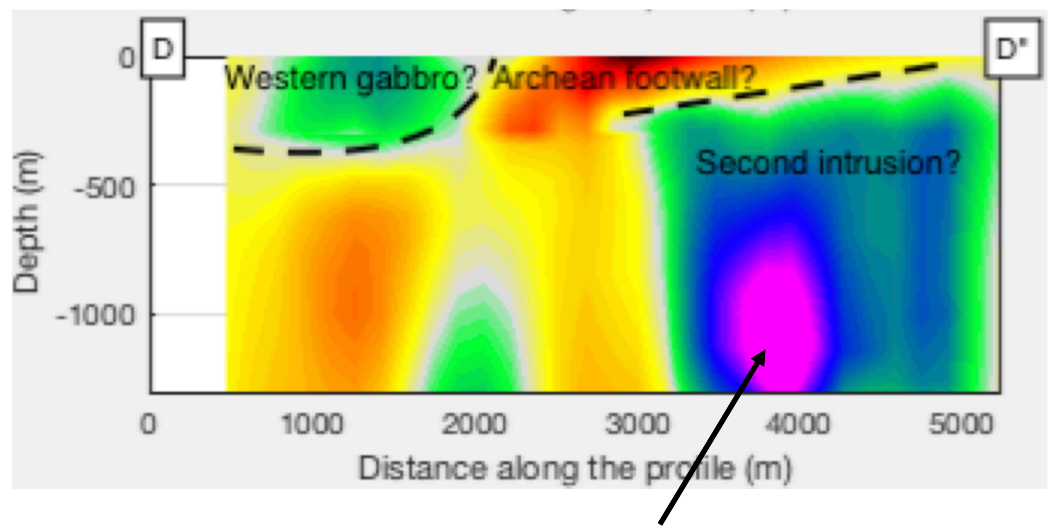


SISPROBE GENERATION PGM

Sally PGM prospect







very high velocity = pyroxenite like that which contains PGM mineralisation

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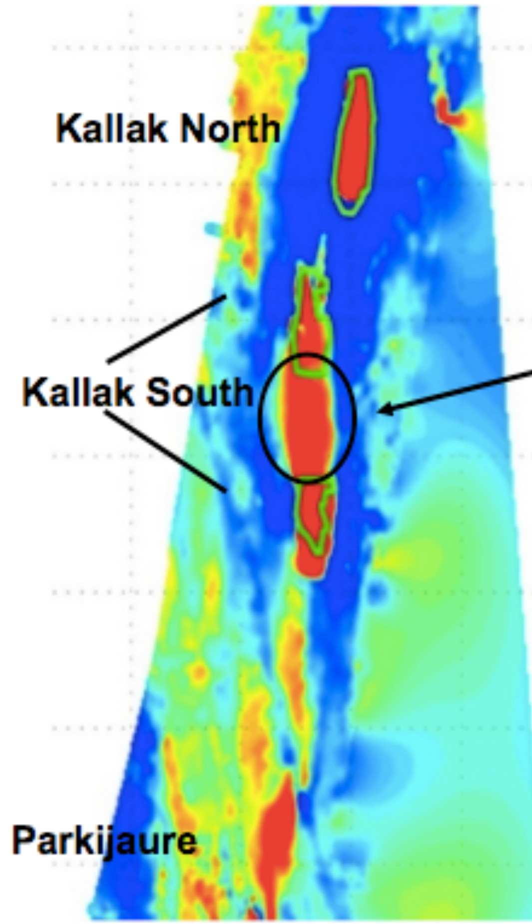
Kallak Iron Ore Project

Beowulf Mining PLC

2. Test of the multi-array method; a surface array combined with a down-hole array



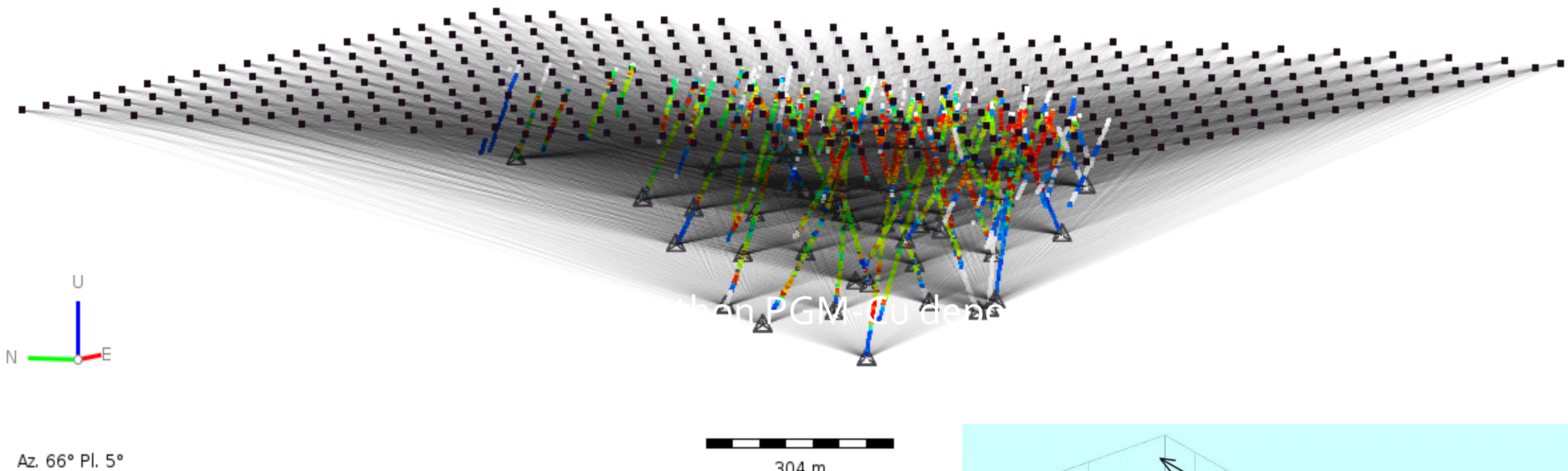
Exploration target

90-100Mt at 22-30% Fe

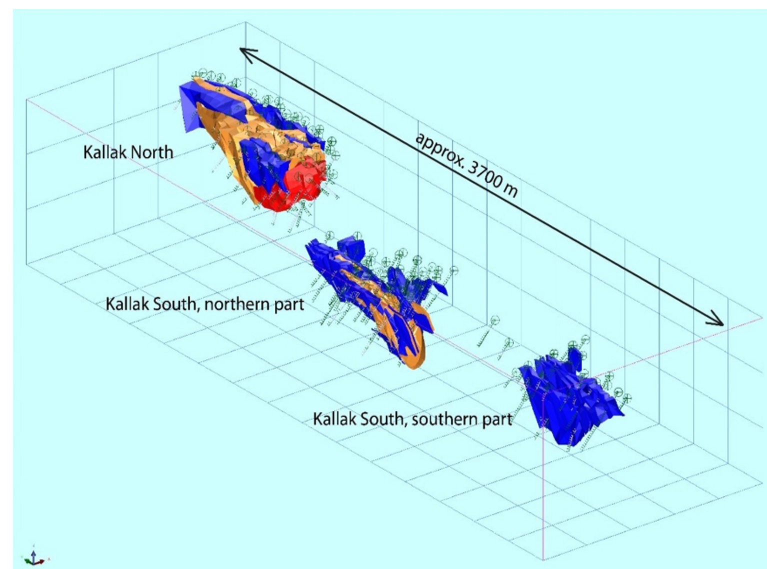
Source: Mineral Resource Update 28/11/14

Beowulf Mining PLC · institute of mine seismology · Université Grenoble Alpes · SISPROBE

2. Test of the multi-array method; a surface array combined with a down-hole array



- Borehole array will be used in conjunction with surface array
- ca. 400 nodes (100 m spacing between nodes) for 30 days
- direct body-wave transmission tomography (surface to borehole and borehole to borehole) in conjunction with ambient wave tomography from the surface array



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Other projects

- **Las Cruces Mine** – VMS Cu-Zn deposit in Spain: First Quantum
- **Kaiserstuhl** – alkaline complex containing REE and other high-tech elements, in Germany: Terratech
- **Schumann Lake** – hydrothermal Co-Ag mineralization in Canada: First Cobalt Inc.
- **Boulia** – sedimentary Zn-Pb-Cu deposits in Australia: Anglo American
- **Borax** – boron mine in USA:
- Porphyry deposits in USA, etc

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New techniques

- Extraction of body waves → reflection seismic
- Opportunistic-Noise Surface-Wave Tomography (ONSWT); use of nearby man-made sources such as:
    - freight trains
    - drilling
    - light sources

- Optic fibres as sensors. Many applications for monitoring of tailings dams, etc
- Full wave-form conversion

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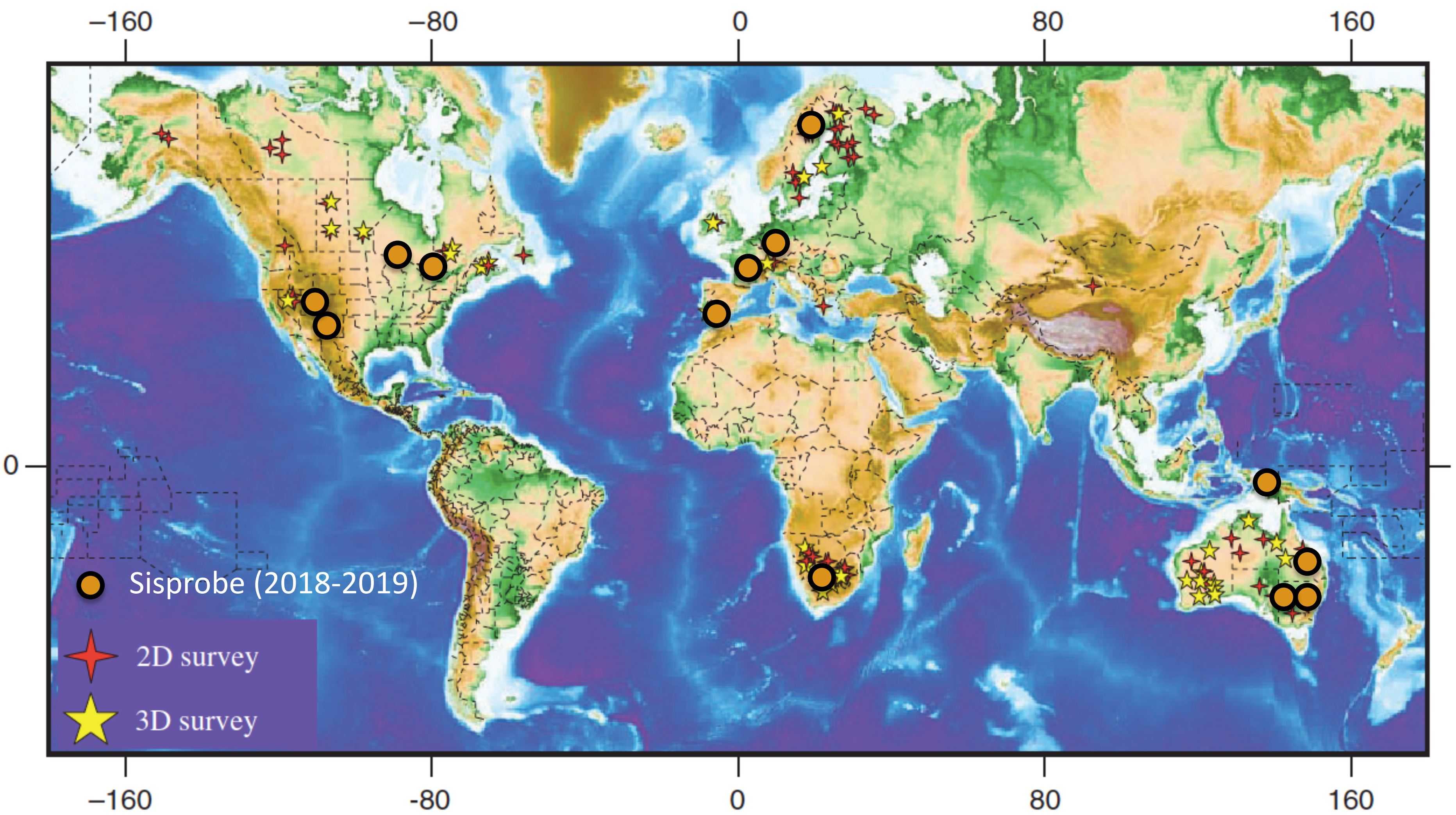
Seismic surveys in mineral exploration



Malehmir et al 2012

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An introduction to Sisprobe

A spin-off company from the University of Grenoble founded in January 2017

UNIVERSITÉ Grenoble Alpes

ISTerre
Institut des Sciences de la Terre

Based in Grenoble, France

We are the world leaders in **passive seismic imaging** and monitoring

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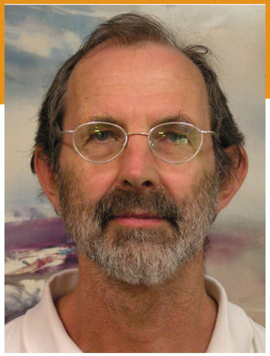
Who are we?



Nick Arndt,
President

Dan Hollis,
CEO

Richard Lynch,
COO

Gosia Chmiel,
engineer

Sophie Beaupretre
engineer

Roméo Courbis
engineer

Anaïs Boué
engineer

for more info:
www.sisprobe.com

+ a solid group of scientific experts from Univ. Grenoble Alpes

P. Roux

F. Brenguier

A. Mordret

M. Campillo

P. Boué

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Active vs Passive Seismic – comparison

Performance and cost

	Cost ($USk)	Resolution (m)	Environmental impact
Active	1000	>30	large
Passive	50-100	40-200	low

Passive seismic

Resolution	Dimensions	Deployment (# receivers)	Duration	Resolution		Cost ($kUS)		
				lateral	vertical	operation	treatment	total
Low	300 x 100 x 3km	40	2 months	10 km	400m	45	15	**60**
Medium	30 x 10 x 3 km	500	1 month	500 m	200m	100	50	**150**
High	3 x 1 x 0.5 km	200	15 days	100 m	40 m	45	35	**80**

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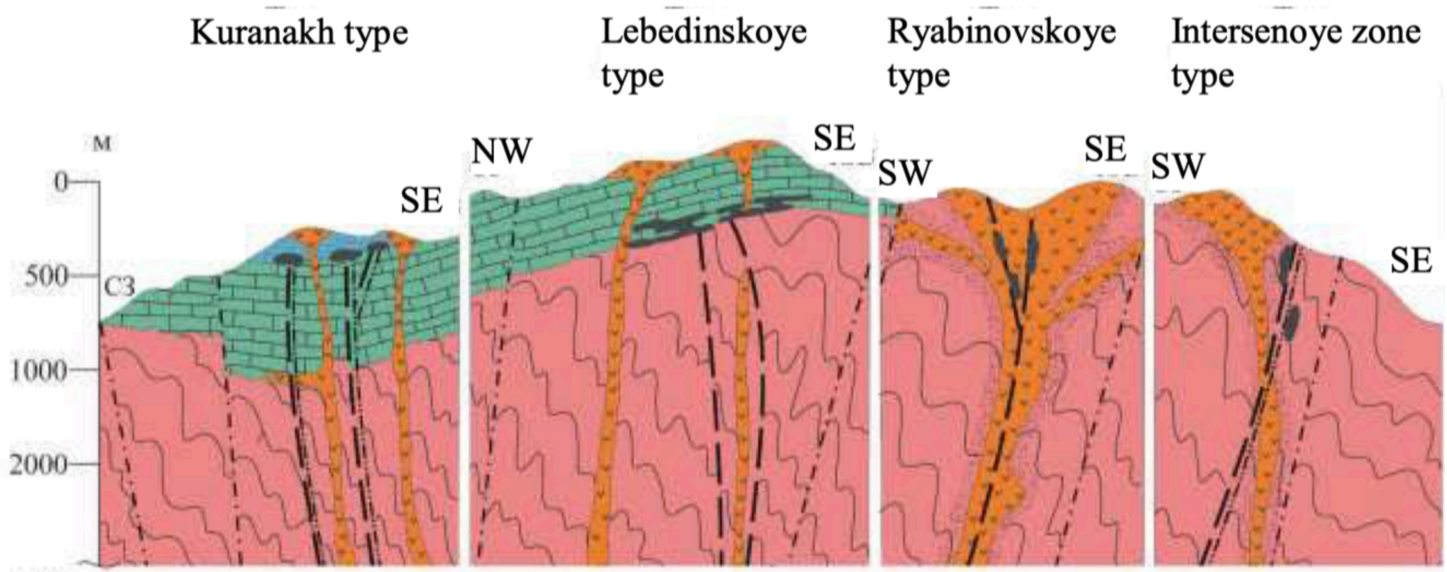
What can passive seismic reveal?



1. contacts between carbonates and basement
2. contacts between terrestrial sediments and carbonates
3. contacts and structures of karsts
4. contacts of alkaline intrusions and fenitised zones
5. faults - if they juxtapose different rock types
6. ore bodies – if big enough and if sufficient physical contrast

also

- voids in old mine areas
- monitoring of tailings dams
- exploration in natural reserves
- complementary to other geophysical techniques