Monitoring Tailings Dams using Ambient Seismic Noise Interferometry

Tjaart de Wit
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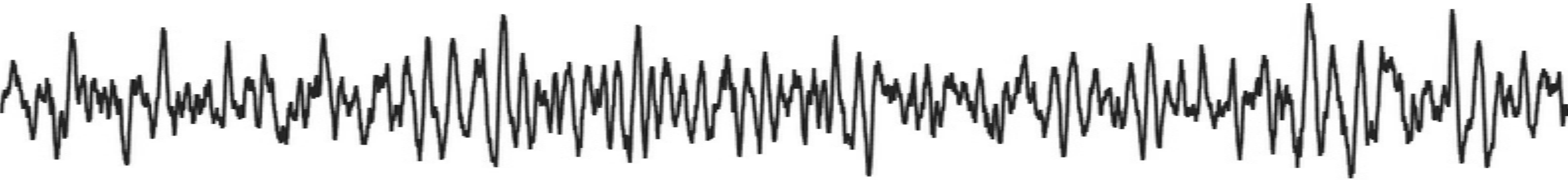
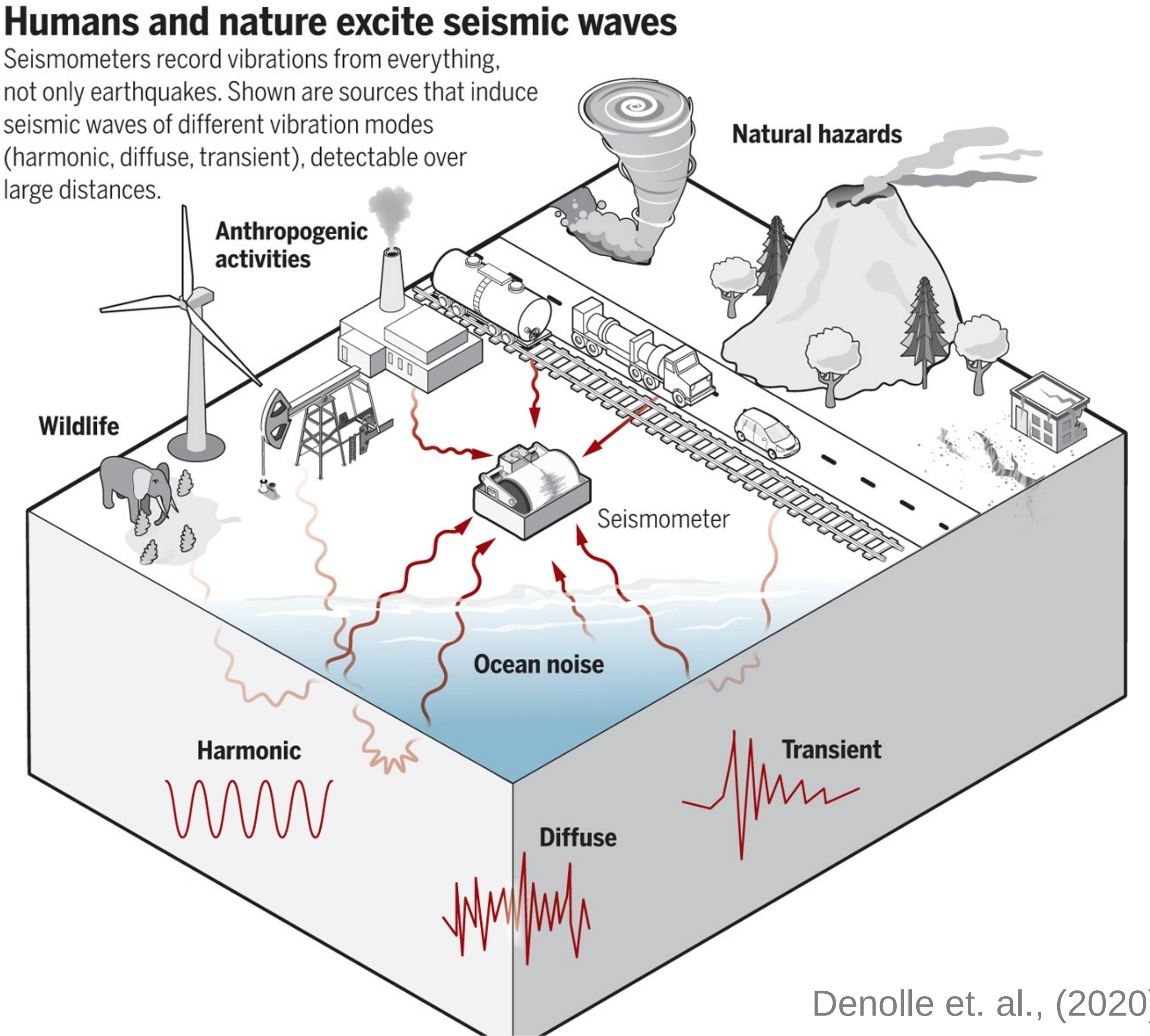


Collaborators:
Roel Snieder, Gerrit Olivier, Florent Brenguier, Marco Braga

Sources of seismic noise



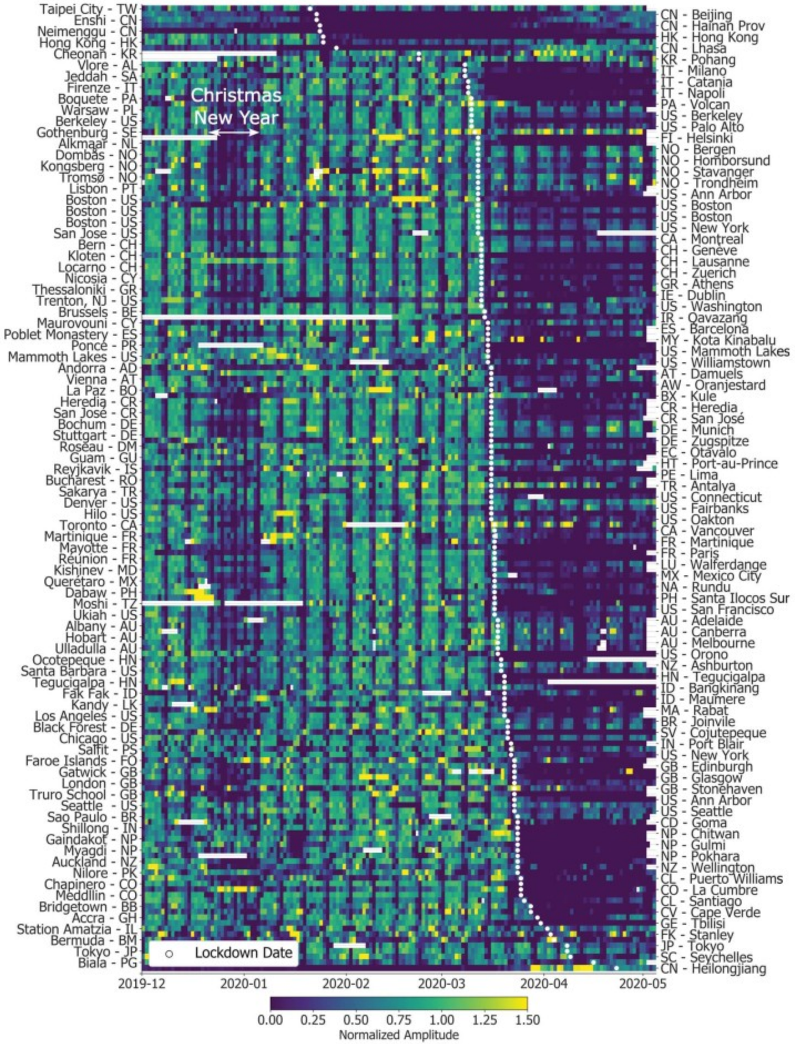
Denolle et. al., (2020)

SEISMOLOGY

Global quieting of high-frequency seismic noise due to COVID-19 pandemic lockdown measures

Thomas Lecocq[1*], Stephen P. Hicks[2], Koen Van Noten[1], Kasper van Wijk[3], Paula Koelemeijer[4], Raphael S. M. De Plaen[5], Frédérick Massin[6], Gregor Hillers[7], Robert E. Anthony[8], Maria-Theresia Apoloner[9], Mario Arroyo-Solórzano[10], Jelle D. Assink[11], Pinar Büyükakpınar[12,13], Andrea Cannata[14,15], Flavio Cannavo[15], Sebastian Carrasco[16], Corentin Caudron[17], Esteban J. Chaves[18], David G. Cornwell[19], David Craig[20], Olivier F. C. den Ouden[11,21], Jordi Diaz[22], Stefanie Donner[23], Christos P. Evangelidis[24], Läslo Evers[11,21], Benoit Fauville[25], Gonzalo A. Fernandez[26], Dimitrios Giannopoulos[27,28], Steven J. Gibbons[29], Társilo Girona[30], Bogdan Grecu[31], Marc Grunberg[32], György Hetényi[33], Anna Horleston[34], Adolfo Inza[35], Jessica C. E. Irving[34,36], Mohammadreza Jamalreyhani[37,13], Alan Kafka[38], Mathijs R. Koymans[11,21], Celeste R. Labedz[39], Eric Larose[17], Nathaniel J. Lindsey[40], Mika McKinnon[41,42], Tobias Megies[43], Meghan S. Miller[44], William Minarik[45,46], Louis Moresi[44], Víctor H. Márquez-Ramírez[5], Martin Möllhoff[20], Ian M. Nesbitt[47,48], Shankho Niyogi[49], Javier Ojeda[50], Adrien Oth[51], Simon Proud[52], Jay Pulli[53,38], Lise Retailleau[54,55], Annukka E. Rintamäki[7], Claudio Satriano[54], Martha K. Savage[56], Shahar Shani-Kadmiel[21], Reinoud Sleeman[11], Efthimios Sokos[57], Klaus Stammler[23], Alexander E. Stott[58], Shiba Subedi[33], Mathilde B. Sørensen[59], Taka'aki Taira[60], Mar Tapia[61], Fatih Turhan[12], Ben van der Pluijm[62], Mark Vanstone[63], Jerome Vergne[64], Tommi A. T. Vuorinen[7], Tristram Warren[65], Joachim Wassermann[43], Han Xiao[66]

Human activity causes vibrations that propagate into the ground as high-frequency seismic waves. Measures to mitigate the coronavirus disease 2019 (COVID-19) pandemic caused widespread changes in human activity, leading to a months-long reduction in seismic noise of up to 50%. The 2020 seismic noise quiet period is the longest and most prominent global anthropogenic seismic noise reduction on record. Although the reduction is strongest at surface seismometers in populated areas, this seismic quiescence extends for many kilometers radially and hundreds of meters in depth. This quiet period provides an opportunity to detect subtle signals from subsurface seismic sources that would have been concealed in noisier times and to benchmark sources of anthropogenic noise. A strong correlation between seismic noise and independent measurements of human mobility suggests that seismology provides an absolute, real-time estimate of human activities.



SEISMOLOGY

Global quieting of high-frequency seismic noise due to COVID-19 pandemic lockdown measures

Thomas Lecocq[1]*, Stephen P. Hicks[2], Koen Van Noten[1], Kasper van Wijk[3], Paula Koelemeijer[4], Raphael S. M. De Plaen[5], Frédérick Massin[6], Gregor Hillers[7], Robert E. Anthony[8], Maria-Theresia Apoloner[9], Mario Arroyo-Solórzano[10], Jelle D. Assink[11], Pinar Büyükakpınar[12,13], Andrea Cannata[14,15], Flavio Cannavo[15], Sebastian Carrasco[16], Corentin Caudron[17], Esteban J. Chaves[18], David G. Cornwell[19], David Craig[20], Olivier F. C. den Ouden[11,21], Jordi Diaz[22], Stefanie Donner[23], Christos P. Evangelidis[24], Läslo Evers[11,21], Benoit Fauville[25], Gonzalo A. Fernandez[26], Dimitrios Giannopoulos[27,28], Steven J. Gibbons[29], Társilo Girona[30], Bogdan Grecu[31], Marc Grunberg[32], György Hetényi[33], Anna Horleston[34], Adolfo Inza[35], Jessica C. E. Irving[34,36], Mohammadreza Jamalreyhani[37,13], Alan Kafka[38], Mathijs R. Koymans[11,21], Celeste R. Labedz[39], Eric Larose[17], Nathaniel J. Lindsey[40], Mika McKinnon[41,42], Tobias Megies[43], Meghan S. Miller[44], William Minarik[45,46], Louis Moresi[44], Víctor H. Márquez-Ramírez[5], Martin Möllhoff[20], Ian M. Nesbitt[47,48], Shankho Niyogi[49], Javier Ojeda[50], Adrien Oth[51], Simon Proud[52], Jay Pulli[53,38], Lise Retailleau[54,55], Annukka E. Rintamäki[7], Claudio Satriano[54], Martha K. Savage[56], Shahar Shani-Kadmiel[21], Reinoud Sleeman[11], Efthimios Sokos[57], Klaus Stammler[23], Alexander E. Stott[58], Shiba Subedi[33], Mathilde B. Sørensen[59], Taka'aki Taira[60], Mar Tapia[61], Fatih Turhan[12], Ben van der Pluijm[62], Mark Vanstone[63], Jerome Vergne[64], Tommi A. T. Vuorinen[7], Tristram Warren[65], Joachim Wassermann[43], Han Xiao[66]

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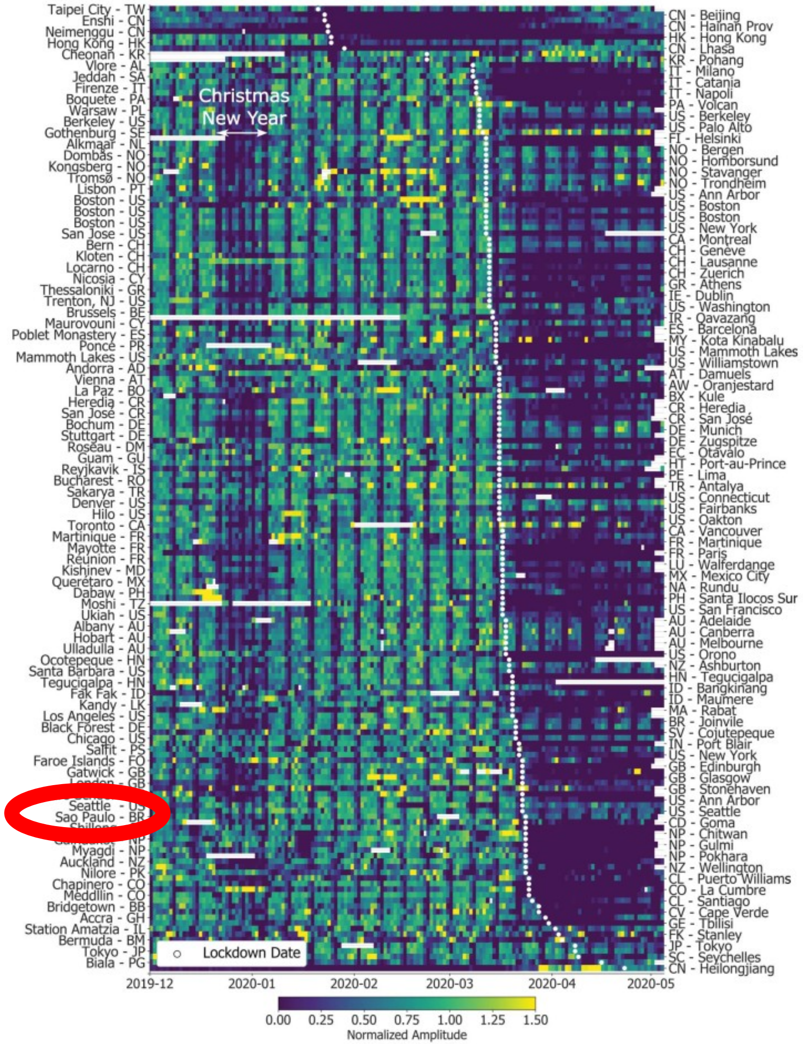
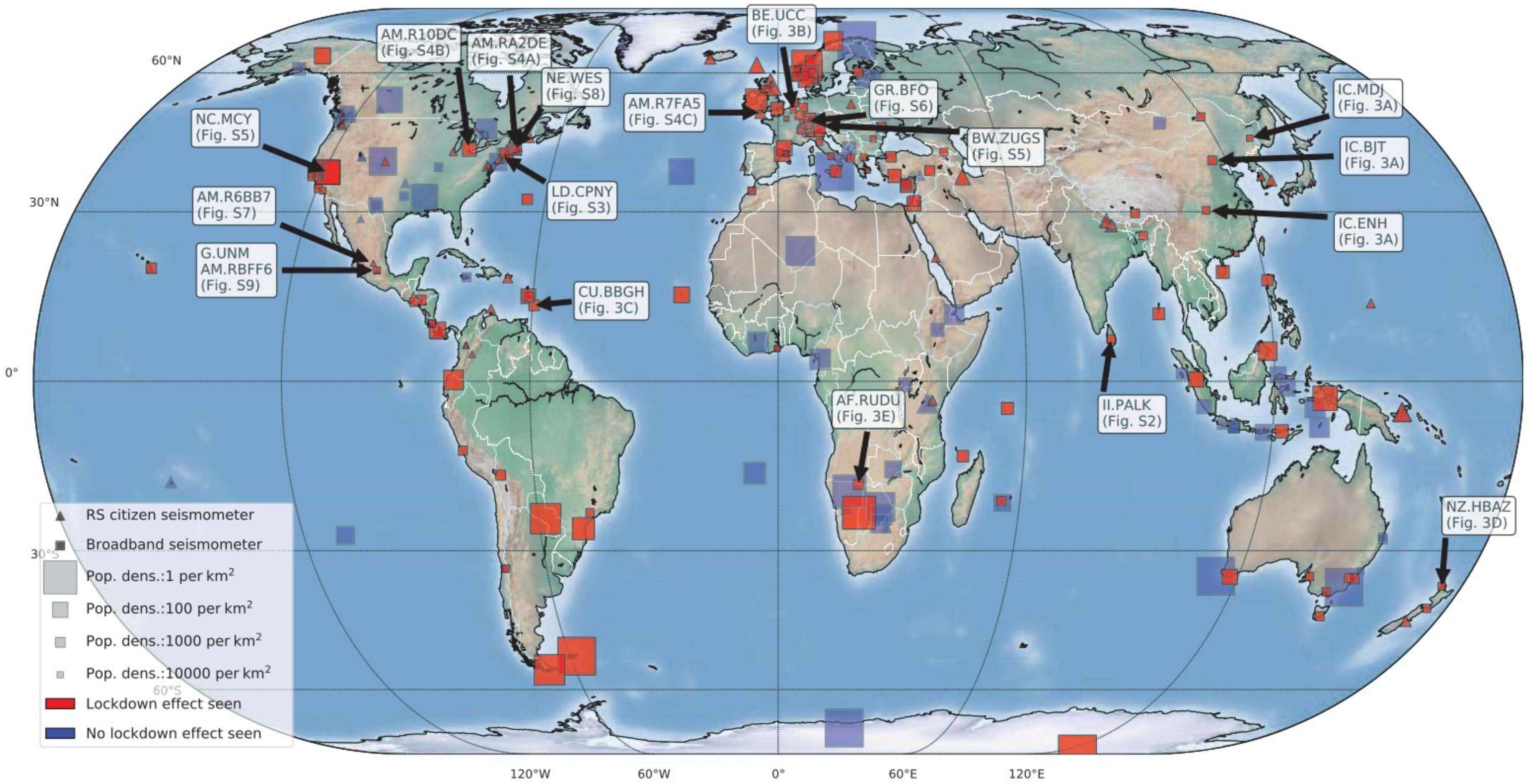
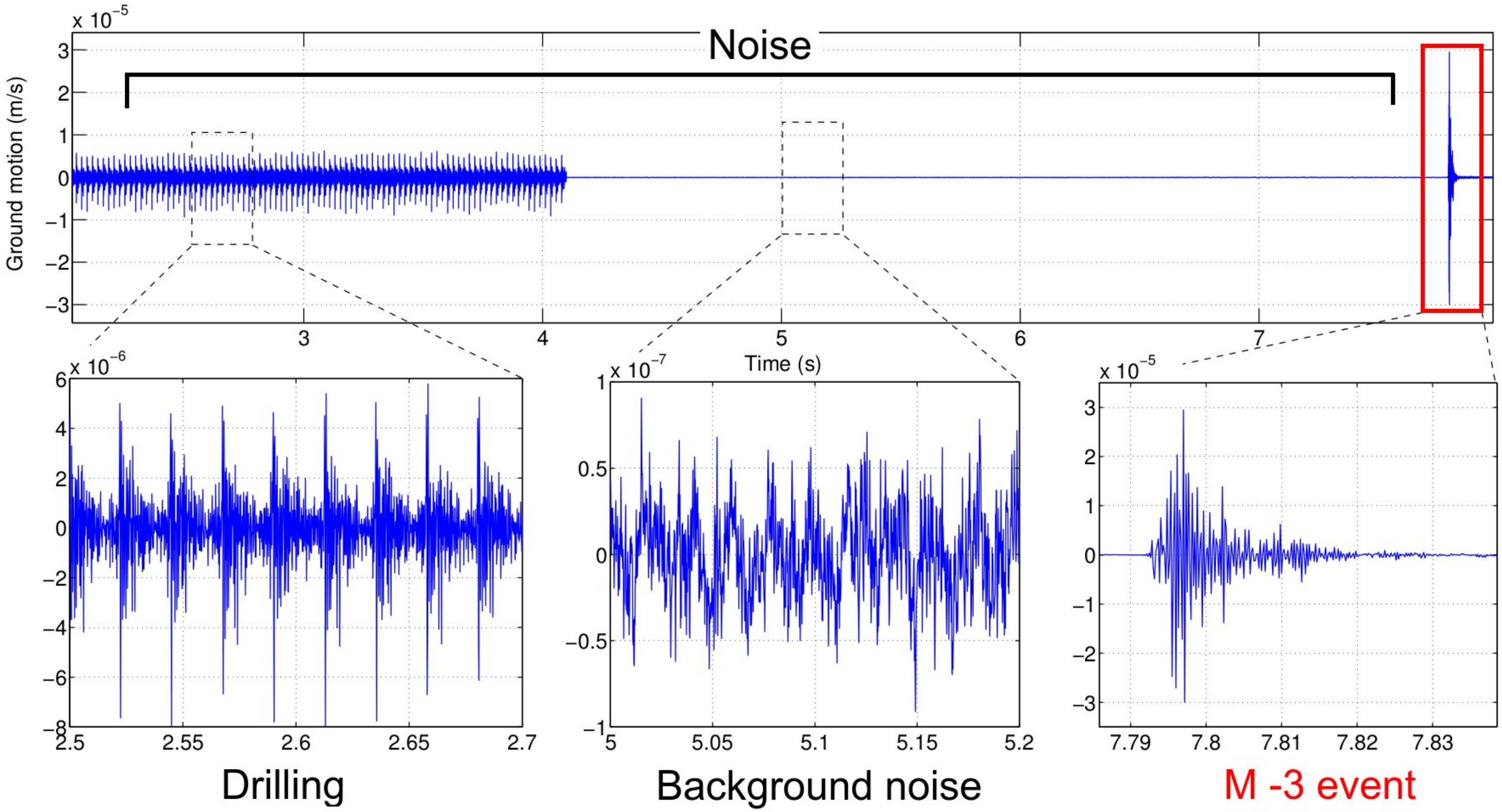




Lecocq et al., (2020)

What is seismic noise?



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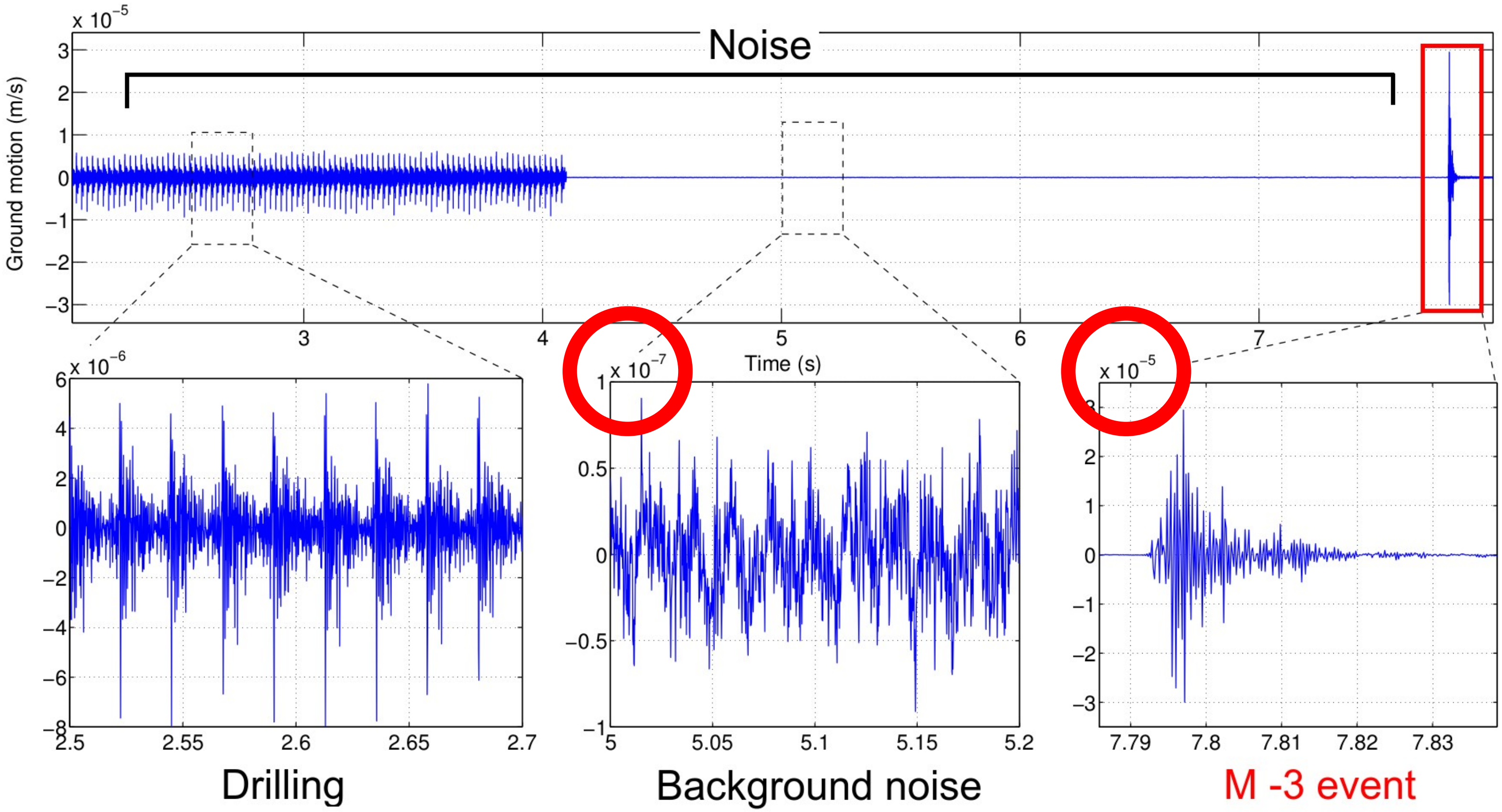

What is seismic interferometry?

Seismic interferometry—turning noise into signal

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KEES WAPENAAR, Delft University of Technology, The Netherlands

Turning noise into useful data—every geophysicist's dream? And now it seems possible. The field of seismic interferometry has at its foundation a shift in the way we think about the parts of the signal that are currently filtered out of most analyses—complicated seismic codas (the multiply scattered parts of seismic waveforms) and background noise (whatever is recorded when no identifiable active source is emitting, and which is superimposed on all recorded data). Those parts of seismograms consist of waves that reflect and refract around exactly the same subsurface heterogeneities as waves excited by active sources. The key to the rapid emergence of this field of research is our new understanding of how to unravel that subsurface information from these relatively complex-looking waveforms. And the answer turned out to be rather simple. This article explains the operation of seismic interferometry and provides a few examples of its application.

A simple thought experiment. Consider an example of a horizontally stratified (one-dimensional) acoustic medium, and for the moment let us imagine that it has only a single internal interface. Now, say horizontally planar pressure waves are emitted by two impulsive sources, one after the other, and that one source is above the interface and one below. Vibrations from the resulting propagating waves are recorded at two receivers which can be placed anywhere between the two sources (Figure 1, left).

The recordings are shown in the center of the figure. At each receiver a direct and a reflected wave is recorded for source 1, whereas only one transmitted wave is recorded for source 2.

Seismic interferometry of these data involves only two simple steps: The two recorded signals from each source are crosscorrelated and the resulting crosscorrelograms are summed (stacked). The result, shown on the right of Figure 1, is surprising; for positive times it is the seismogram that would have been recorded at either receiver if the other receiver had in fact been a *source*, and at negative times it is the time reverse of this seismogram. In other words, by this simple, two-step operation we have constructed the seismic trace from a virtual source—a source that did not exist in our initial experiment, and a source that is imagined to be at the location of one of our receivers.

To generalize, this simple example placed no constraint on where the receivers were placed, provided they were between the sources. By moving either or both of them (or by using many distributed receivers from the start), it is therefore possible to construct the trace from an infinite number of virtual source and receiver pairs placed at any locations, by recording the signal from only two actual sources. What is more, provided one of the active sources is above the interface and receivers and the other is below, the location of the active sources is also arbitrary, and in order to carry out the process above we do not even need to know where these sources are.

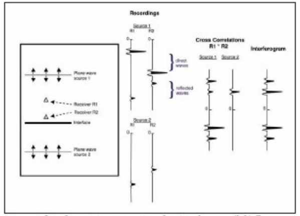

Figure 1. Interferometric construction of a virtual source. (left) One-dimensional acoustic medium consisting of single interface between two half-spaces, with two plane-wave sources and two receivers. (center) Traces recorded at each receiver for each source. (right) crosscorrelations between pair of traces for source 1 and for source 2, and the sum of these crosscorrelations. At positive times, the final summed trace turns out to be the trace that would be recorded at one receiver if the other had been a source. (Note that the virtual source wavelet in the three traces on the right should in fact be the autocorrelation of the recorded source wavelet shown in the center; we have omitted this change in source wavelet in the figure for simplicity.)

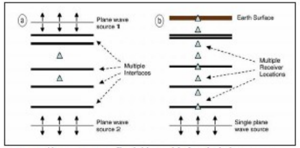

Figure 2. Alternative, more Earth-like models for which the process in Figure 1 works equally well. (left) Multiple layers with no free surface—still two sources required. (right) Multiple layers with a free surface—only one source required. The right plot also shows that any receiver locations can be used for the virtual source and receiver reconstruction.

Seismic interferometry steps. The fundamental steps of the operation are simple: crosscorrelation (we can understand this operation as detecting the traveltime difference of the recorded waves between the pair of receivers), then stacking (i.e., integration over all actual sources; a few details required to get the dynamics correct have been omitted for clarity). Yet, the technique is powerful and so far we have barely scratched the surface.

The result above holds for any horizontally stratified medium, still using only two actual sources (Figure 2a). The important criterion for the distribution of actual sources is that they completely surround the medium of interest (a portion of a one-dimensional medium is "surrounded" by two

Seismic interferometry—turning noise into signal

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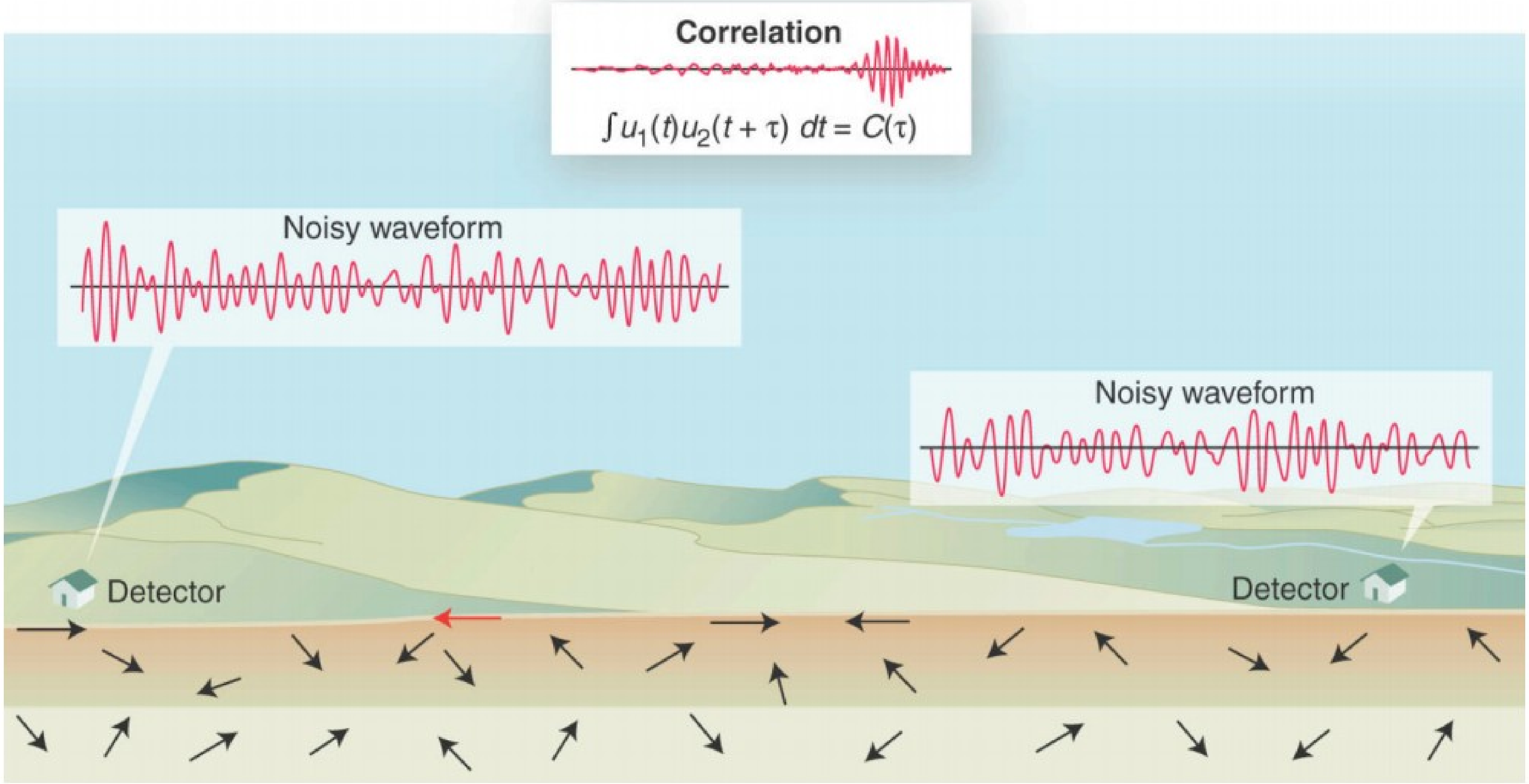
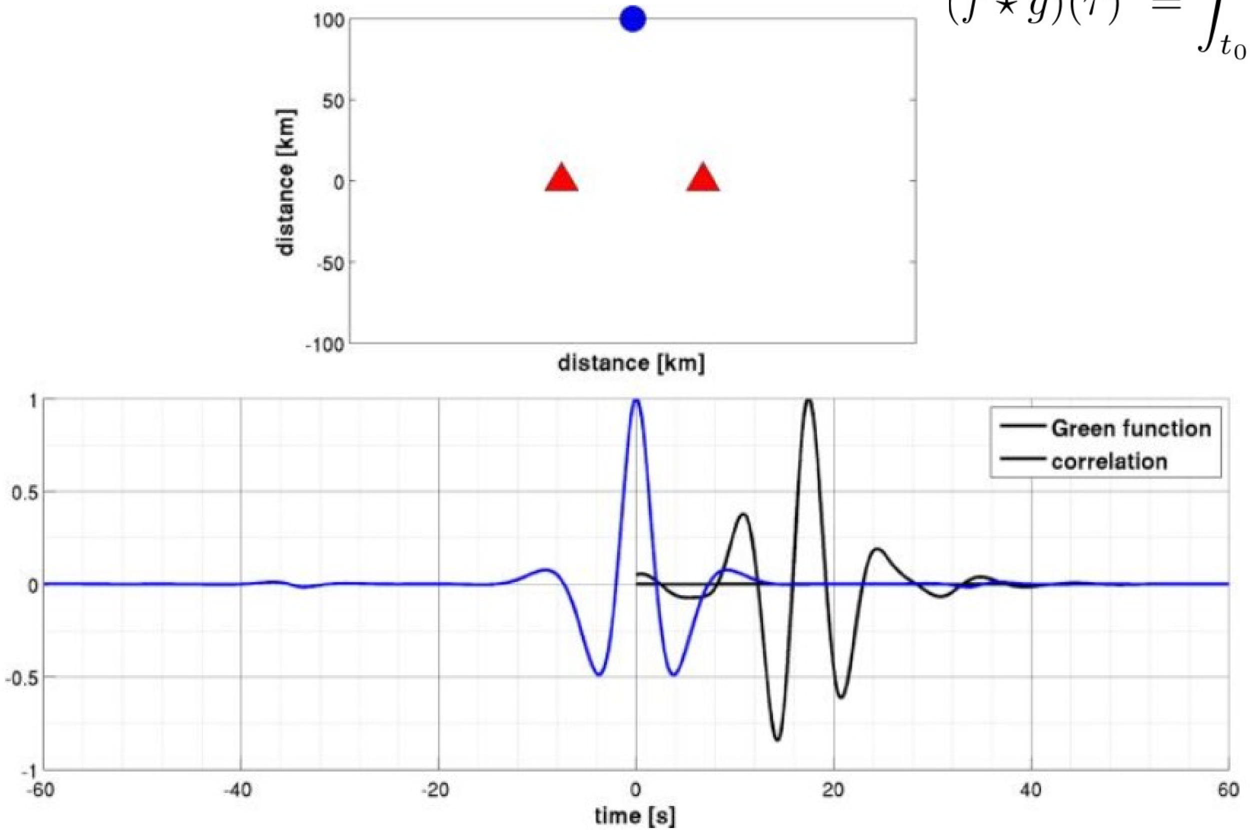
Definition of seismic interferometry. The term *interferometry* generally refers to the study of interference phenomena between pairs of signals in order to obtain information from the differences between them. Seismic interferometry simply refers to the study of interference of seismic-related signals. The principal mathematical operation used to study this interference is crosscorrelation of pairs of signals, but one could equivalently consider convolution as the principal operation because crosscorrelation is simply convolution with the reverse of one of the two signals. The signals themselves may come from background-propagating waves or reverberations in the Earth, from earthquakes, from active artificial seismic sources, from laboratory sources, or from waveforms modeled on a computer—examples of using all of these data types will be given below.

What is seismic interferometry?



Retrieving the Green's function

$$(f \star g)(\tau) \triangleq \int_{t_0}^{t_0+T} \overline{f(t)} g(t+\tau)\, dt$$



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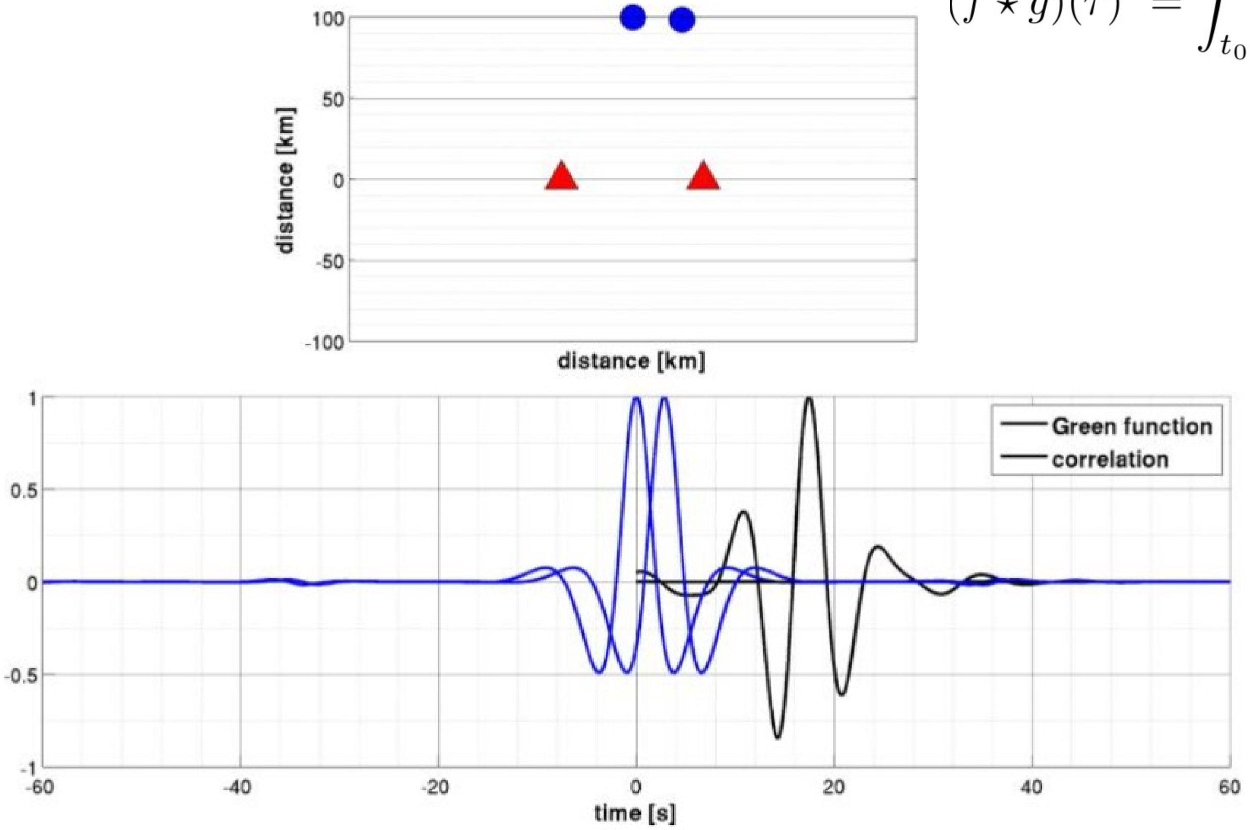

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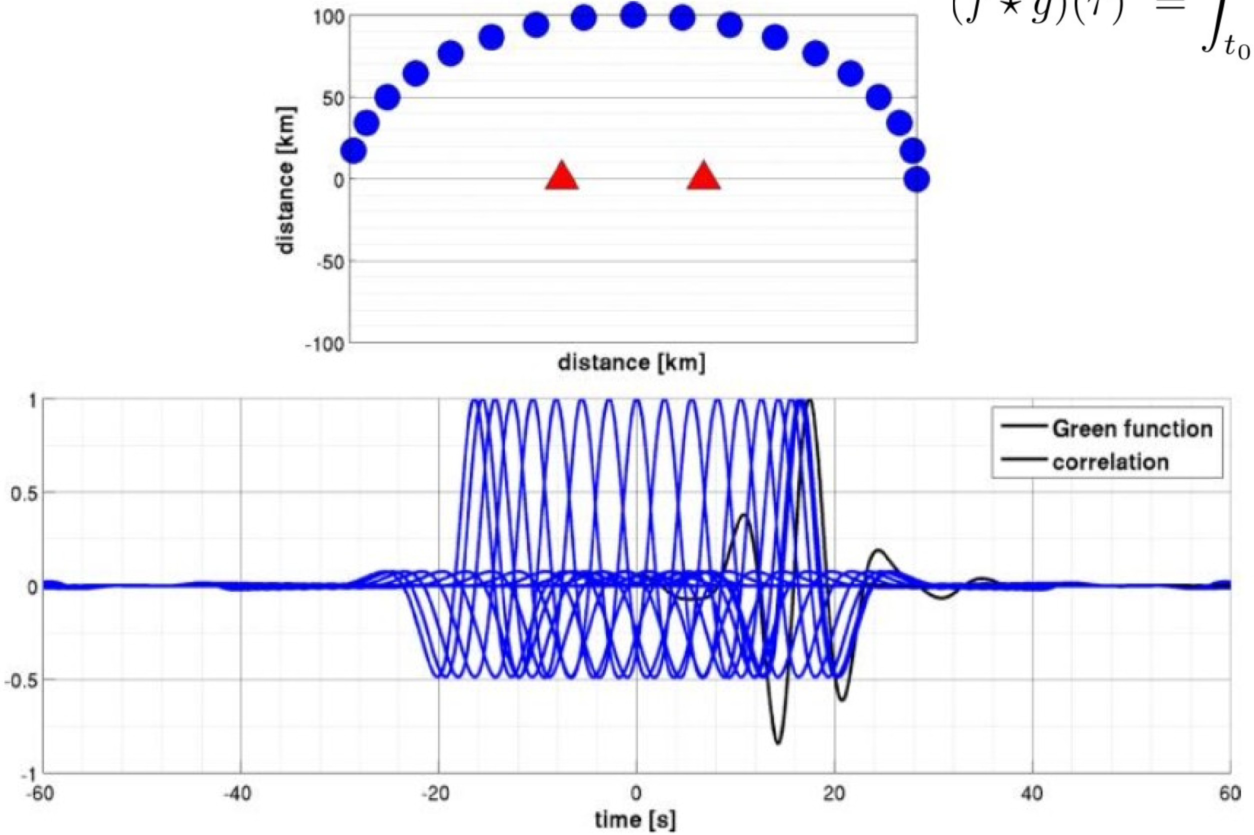
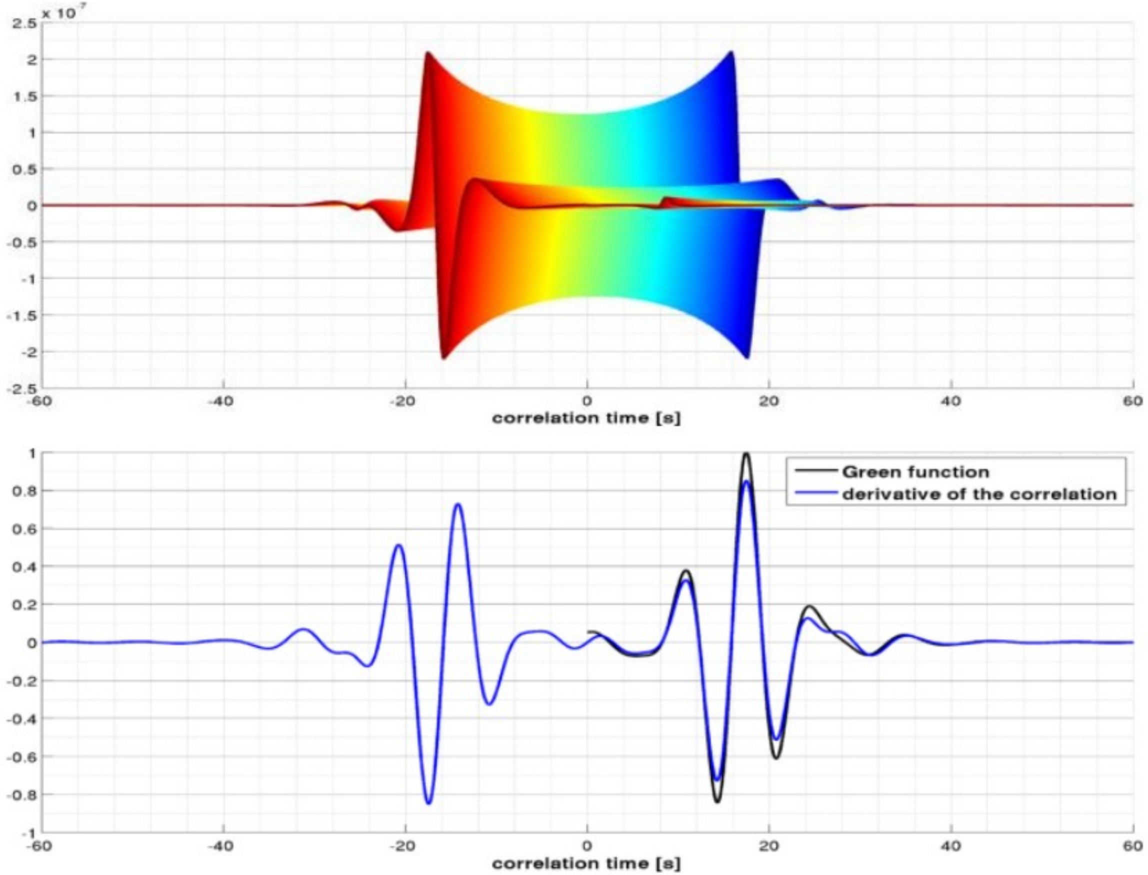


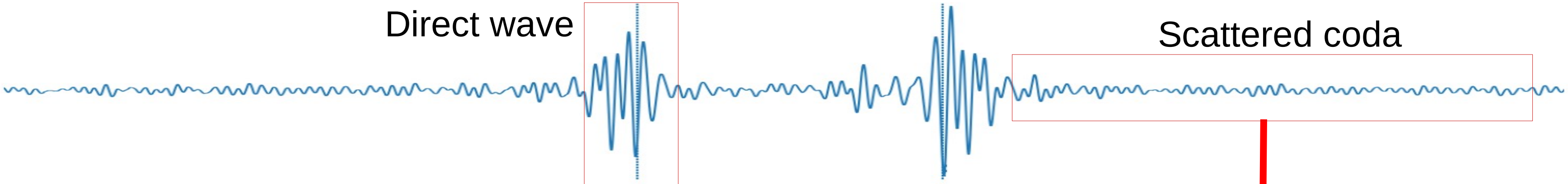
Retrieving the Green's function



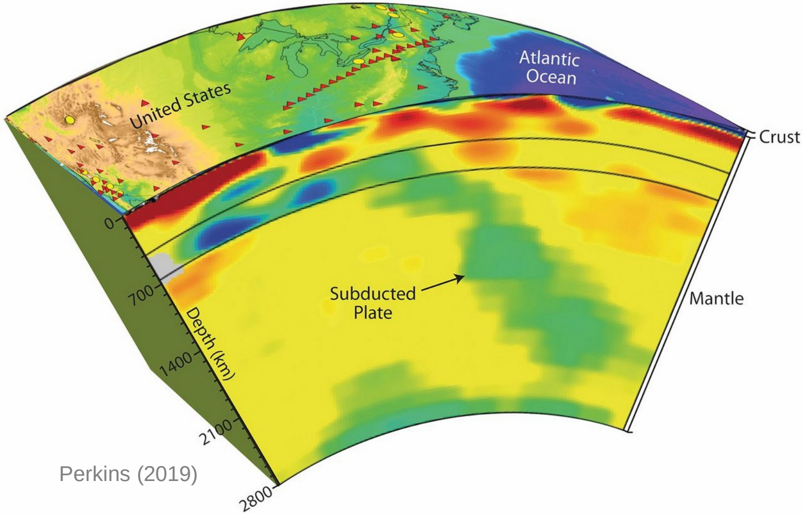
Why do we want the Green's function?

Direct wave

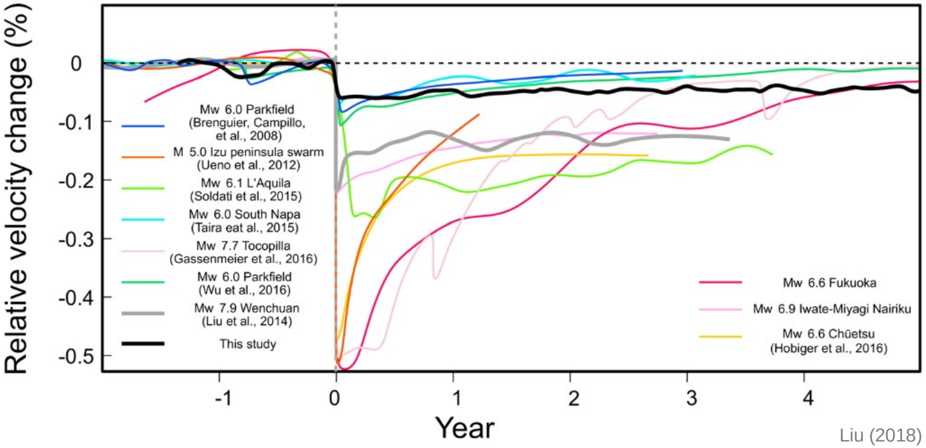
Scattered coda



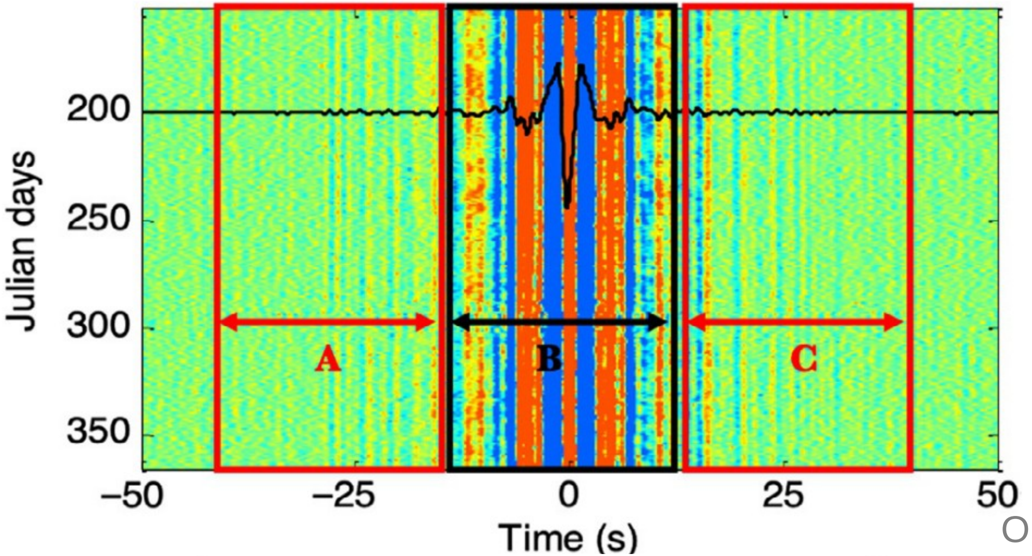
Imaging



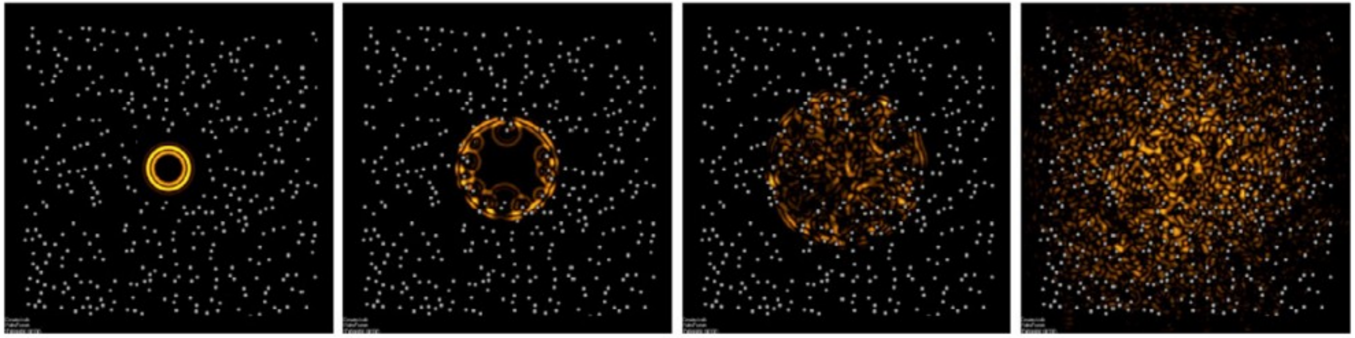
Time-lapse monitoring



Why use coda waves?



Obermann and Hillers (2019)



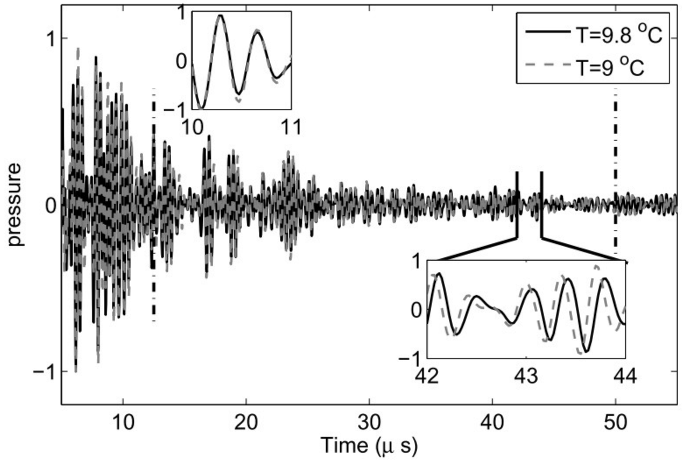
Retrieving the Green’s function

Stability of Monitoring Weak Changes in Multiply Scattering Media with Ambient Noise Correlation: Laboratory Experiments.

Céline Hadziioannou, Eric Larose, Olivier Coutant, Philippe Roux and Michel Campillo
Laboratoire de Géophysique Interne et Tectonophysique, CNRS & Université J. Fourier, BP53, 38041 Grenoble, France. Email: eric.larose@ujf-grenoble.fr

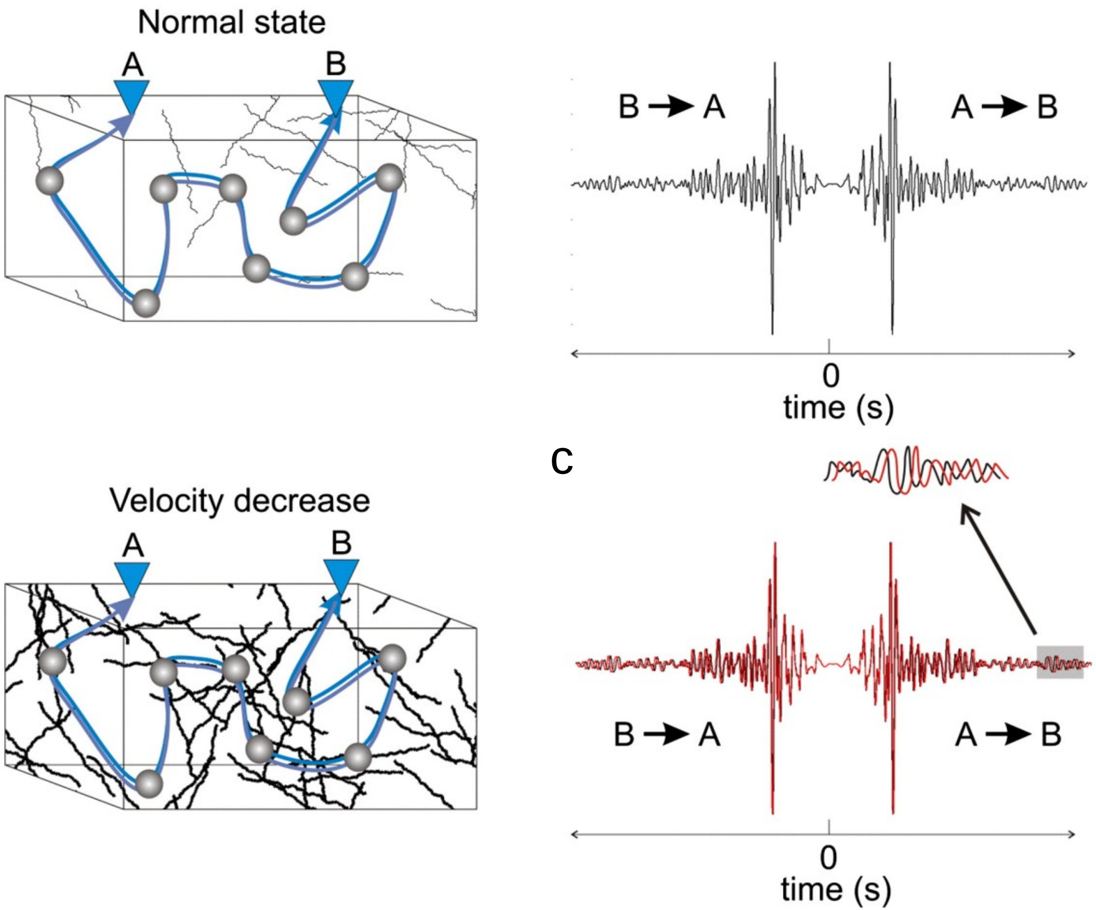
(Dated: August 9, 2018)

Previous studies have shown that small changes can be monitored in a scattering medium by observing phase shifts in the coda. Passive monitoring of weak changes through ambient noise correlation has already been applied to seismology, acoustics and engineering. Usually, this is done under the assumption that a properly reconstructed Green function as well as stable background noise sources are necessary. In order to further develop this monitoring technique, a laboratory experiment was performed in the 2.5MHz range in a gel with scattering inclusions, comparing an active (pulse-echo) form of monitoring to a passive (correlation) one. Present results show that temperature changes in the medium can be observed even if the Green function (GF) of the medium is not reconstructed. Moreover, this article establishes that the GF reconstruction in the correlations is not a necessary condition: the only condition to monitoring with correlation (passive experiment) is the relative stability of the background noise structure.



Hadziioannou et. al., (2009)

How do we measure velocity changes?



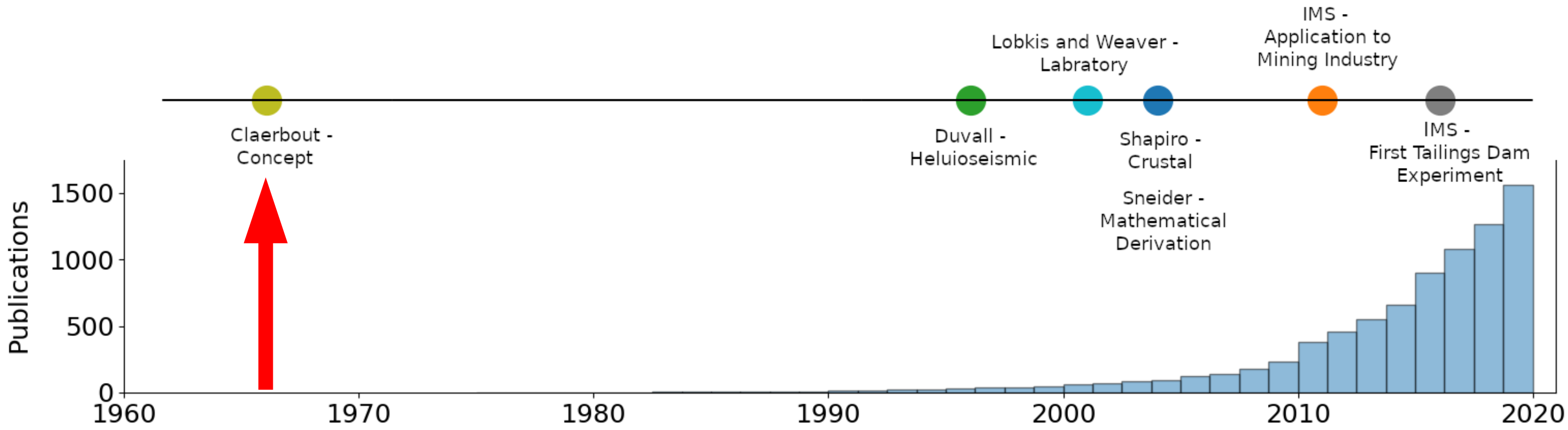
Brenguier et. al., (2016)

History of Seismic Interferometry

SYNTHESIS OF A LAYERED MEDIUM FROM ITS ACOUSTIC TRANSMISSION RESPONSE†

JON F. CLAERBOUT*

A direct (noniterative) method is presented to determine an acoustic layered medium from the seismogram due to a time-limited plane wave incident from the lower halfspace. It is shown that one side of the autocorrelation of the seismogram due to an impulsive source at depth is the seismogram due to an impulsive source on the surface. This transforms the problem to the acoustic reflections problem as solved by Kunetz. Both the deep source time function and the layering can be determined from a surface seismogram.



History of Seismic Interferometry

Downflows Under Sunspots Detected by Helioseismic Tomography

T.L. Duvall Jr.[†], S. D'Silva[*], S.M. Jefferies[‡], J.W. Harvey [*], & J. Schou[§]

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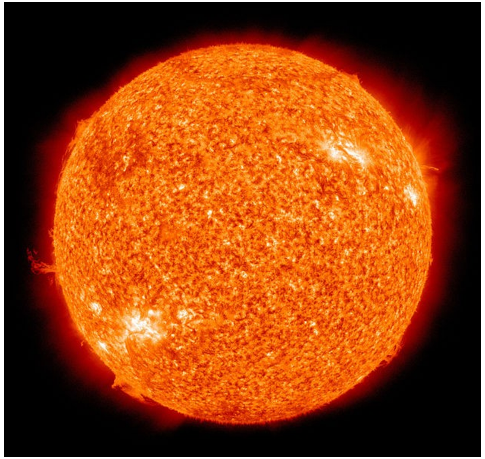
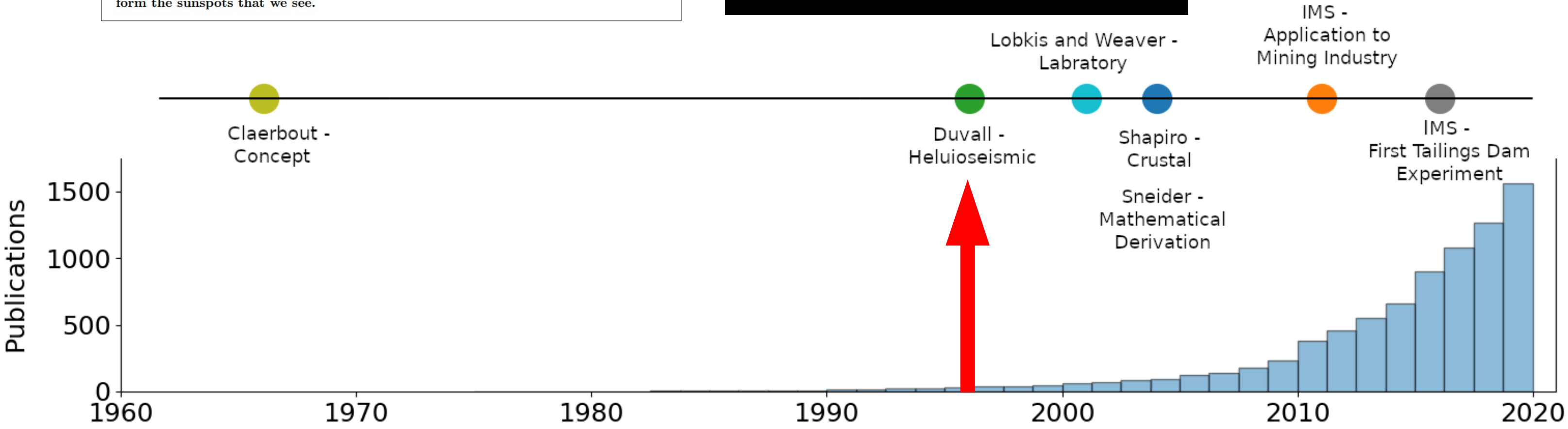
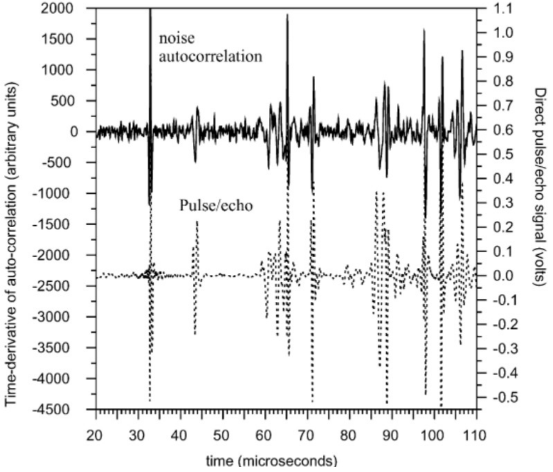
§ Stanford University, HEPL, Stanford, CA 94305-4085 USA

How sunspots form and are maintained is one of the oldest questions in astrophysics. Using the first resolved helioseismic maps of acoustic wave travel-time we have detected evidence of strong downflows beneath sunspots and plages. These observations support Parker's model[1] for the formation and structure of sunspots. This model proposes that small vertical magnetic flux tubes develop downflows around them when they emerge from the deep interior of the sun where they are generated. These downflows are then able to herd a large number of small flux tubes together in a cluster to form a sunspot, which behaves as a single flux bundle as long as the inflow associated with the downflows binds them together. We estimate the flows to persist to a depth of roughly 2000 km below the solar surface with a velocity of approximately 2 km/s. The data suggest that the vertical magnetic field in the sunspot can only be a coherent flux bundle to a depth of around 600 km. Below this point however, it is possible that the downflows loosely hold a collection of small flux tubes together to form the sunspots that we see.



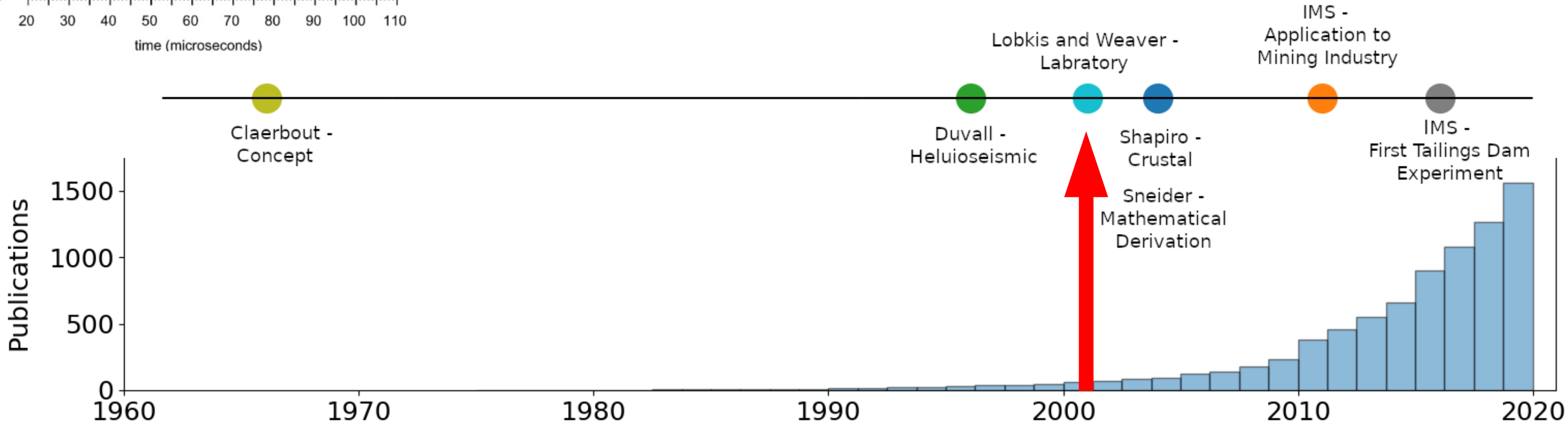


History of Seismic Interferometry

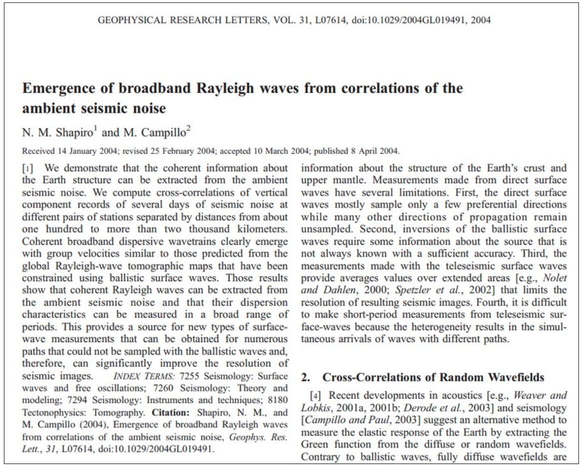


On the emergence of the Green's function in the correlations of a diffuse field: pulse-echo using thermal phonons

Richard Weaver *, Oleg Lobkis



History of Seismic Interferometry



GEOPHYSICAL RESEARCH LETTERS, VOL. 31, L07614, doi:10.1029/2004GL019491, 2004

Emergence of broadband Rayleigh waves from correlations of the ambient seismic noise

N. M. Shapiro[1] and M. Campillo[2]

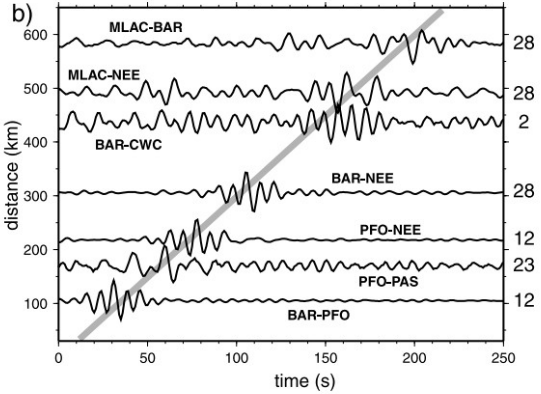
Received 14 January 2004; revised 25 February 2004; accepted 10 March 2004; published 8 April 2004.

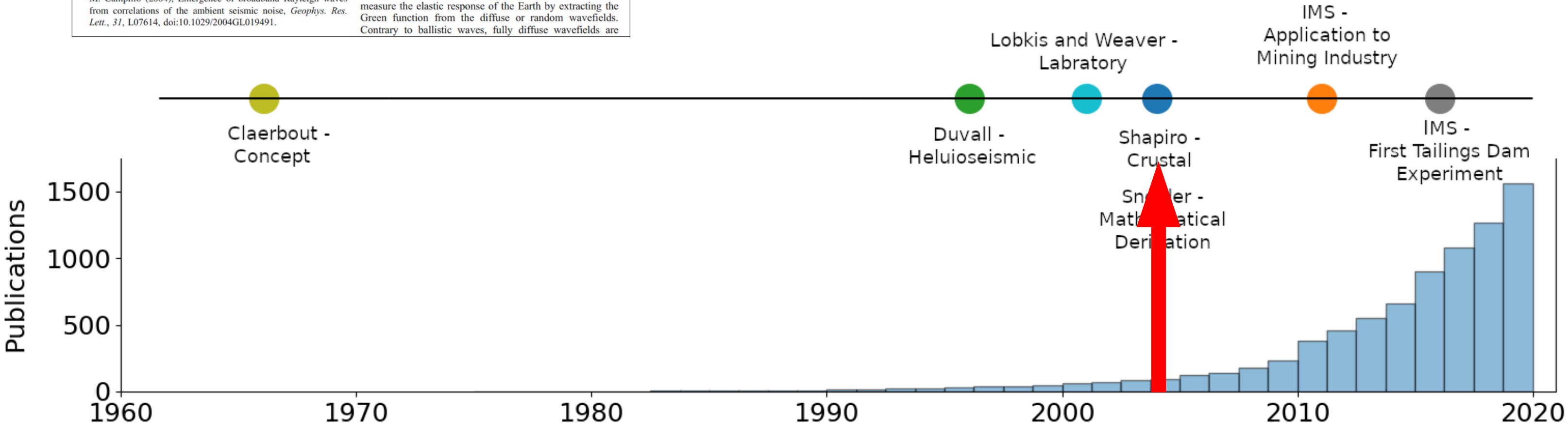
[1] We demonstrate that the coherent information about the Earth structure can be extracted from the ambient seismic noise. We compute cross-correlations of vertical component records of several days of seismic noise at different pairs of stations separated by distances from about one hundred to more than two thousand kilometers. Coherent broadband dispersive wavetrains clearly emerge with group velocities similar to those predicted from the global Rayleigh-wave tomographic maps that have been constrained using ballistic surface waves. Those results show that coherent Rayleigh waves can be extracted from the ambient seismic noise and that their dispersion characteristics can be measured in a broad range of periods. This provides a source for new types of surface-wave measurements that can be obtained for numerous paths that could not be sampled with the ballistic waves and, therefore, can significantly improve the resolution of seismic images. *INDEX TERMS:* 7255 Seismology: Surface waves and free oscillations; 7260 Seismology: Theory and modeling; 7294 Seismology: Instruments and techniques; 8180 Tectonophysics: Tomography. **Citation:** Shapiro, N. M., and M. Campillo (2004), Emergence of broadband Rayleigh waves from correlations of the ambient seismic noise, *Geophys. Res. Lett.*, *31*, L07614, doi:10.1029/2004GL019491.

information about the structure of the Earth's crust and upper mantle. Measurements made from direct surface waves have several limitations. First, the direct surface waves mostly sample only a few preferential directions while many other directions of propagation remain unsampled. Second, inversions of the ballistic surface waves require some information about the source that is not always known with a sufficient accuracy. Third, the measurements made with the teleseismic surface waves provide averages values over extended areas [e.g., *Nolet and Dahlen*, 2000; *Spetzler et al.*, 2002] that limits the resolution of resulting seismic images. Fourth, it is difficult to make short-period measurements from teleseismic surface-waves because the heterogeneity results in the simultaneous arrivals of waves with different paths.

2. Cross-Correlations of Random Wavefields

[4] Recent developments in acoustics [e.g., *Weaver and Lobkis*, 2001a, 2001b; *Derode et al.*, 2003] and seismology [*Campillo and Paul*, 2003] suggest an alternative method to measure the elastic response of the Earth by extracting the Green function from the diffuse or random wavefields. Contrary to ballistic waves, fully diffuse wavefields are





History of Seismic Interferometry

PHYSICAL REVIEW E **69**, 046610 (2004)

Extracting the Green's function from the correlation of coda waves: A derivation based on stationary phase

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Center for Wave Phenomena and Department of Geophysics, Colorado School of Mines, Golden, Colorado 80401-1887, USA

(Received 30 May 2003; revised manuscript received 2 December 2003; published 29 April 2004)

The Green's function of waves that propagate between two receivers can be found by cross-correlating multiply scattered waves recorded at these receivers. This technique obviates the need for a source at one of these locations, and is therefore called "passive imaging." This principle has been explained by assuming that the normal modes of the system are uncorrelated and that all carry the same amount of energy (equipartitioning). Here I present an alternative derivation of passive imaging of the ballistic wave that is not based on normal modes. The derivation is valid for scalar waves in three dimensions, and for elastic surface waves. Passive imaging of the ballistic wave is based on the destructive interference of waves radiated from scatterers away from the receiver line, and the constructive interference of waves radiated from secondary sources near the receiver line. The derivation presented here shows that the global requirement of the equipartitioning of normal modes can be relaxed to the local requirement that the scattered waves propagate on average isotropically near the receivers.

DOI: 10.1103/PhysRevE.69.046610 PACS number(s): 43.20.+g, 91.30.−f, 42.30.−d

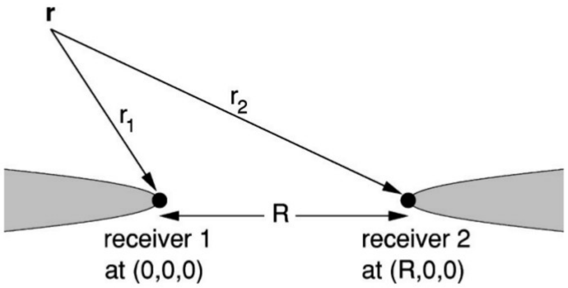
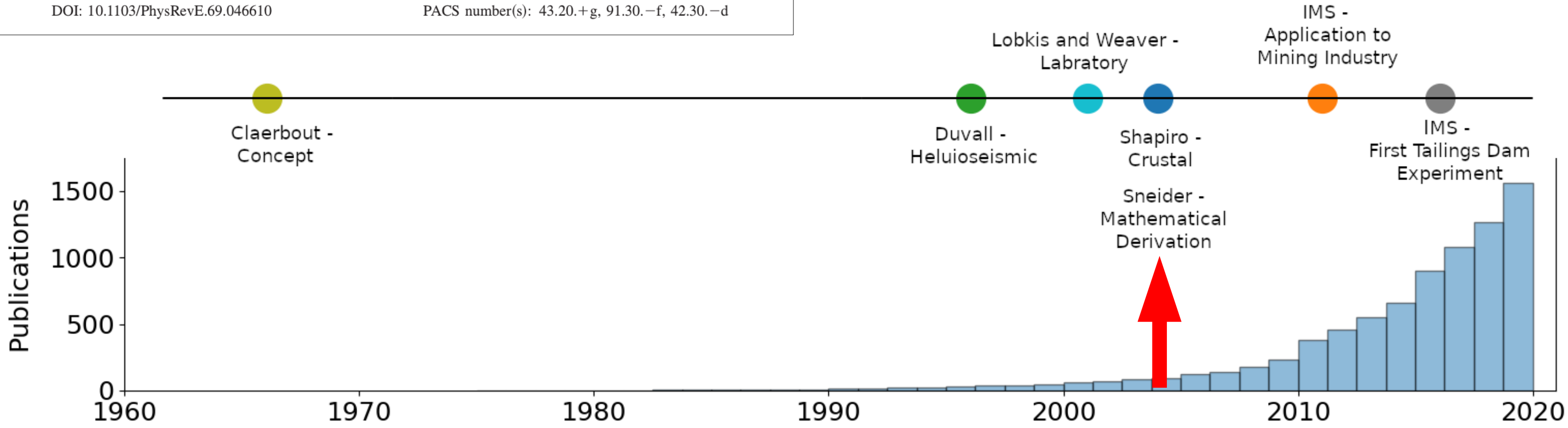
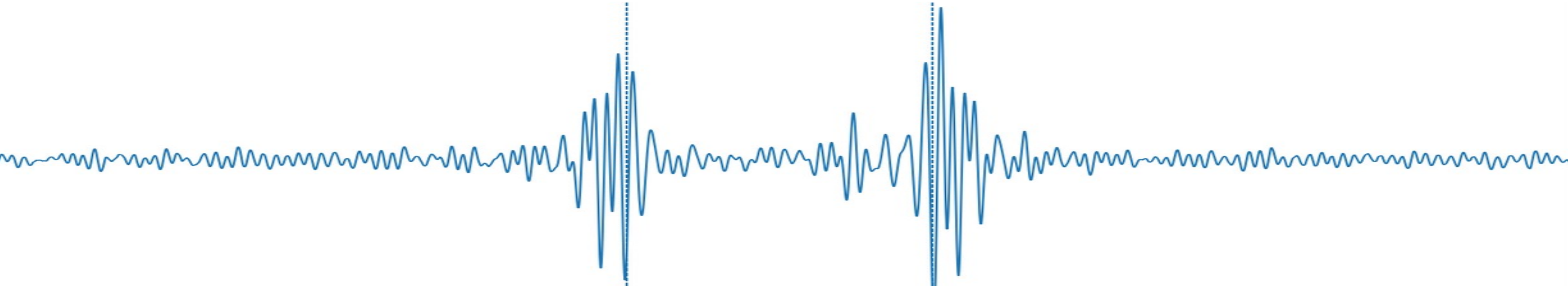


FIG. 2. Definition of the geometric variables for the waves that travel from a scatterer at location **r** to two receivers. The region of constructive interference is indicated by the shaded regions.



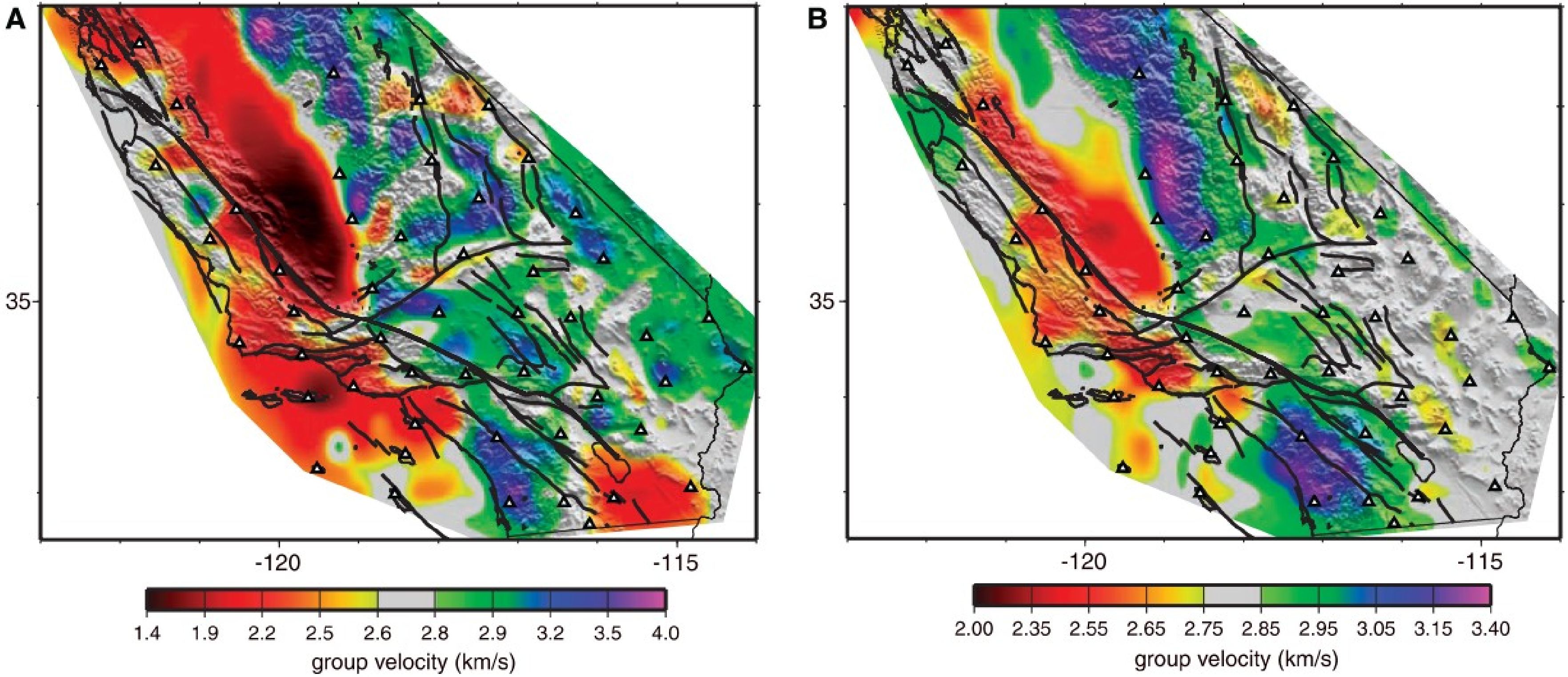
Applications of seismic interferometry

- ✔ **Image** the upper crustal structure of the earth e.g. Shapiro et al., (2005)
- ✔ **Monitor** seismic response to earthquake e.g. Brenguier et al., (2008)
- ✔ **Monitor** volcanoes e.g. Brenguier et al., (2008), Olivier et al., (2020)
- ✔ **Monitor** landslide failure e.g. Mainsant et al., (2012)
- ✔ **Monitor** earthen embankment e.g. Planès et al., (2016)
- ✔ **Monitor** tailings dam e.g. Olivier et al., (2017)
- ✔ **Image** tailings dam e.g. Olivier et al., (2018)



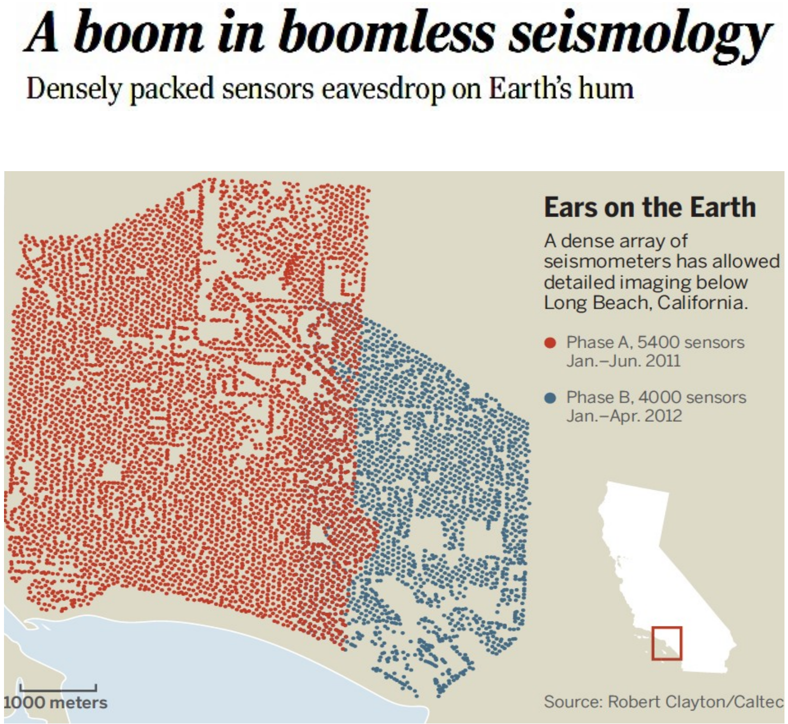
Imaging the Earth’s crust

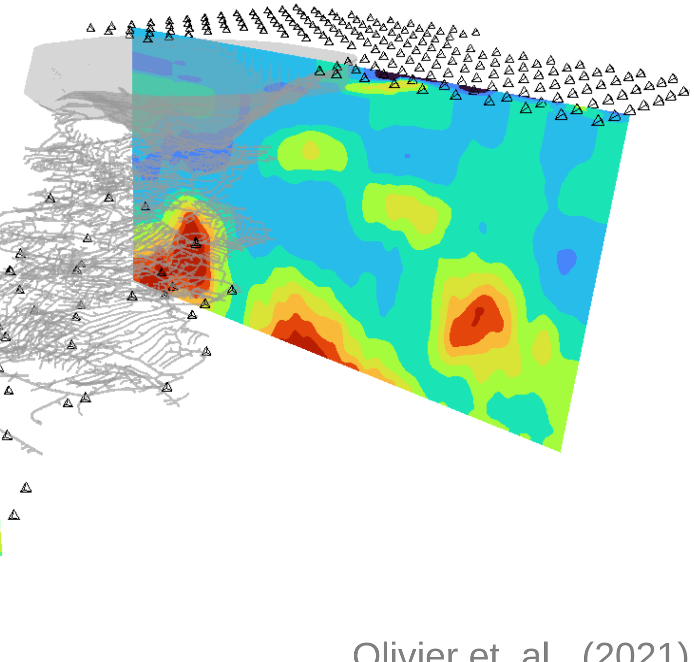
“High-Resolution Surface-Wave Tomography from Ambient Seismic Noise”



Shapiro et. al., (2005)

Imaging for resource exploration





Olivier et. al., (2021)

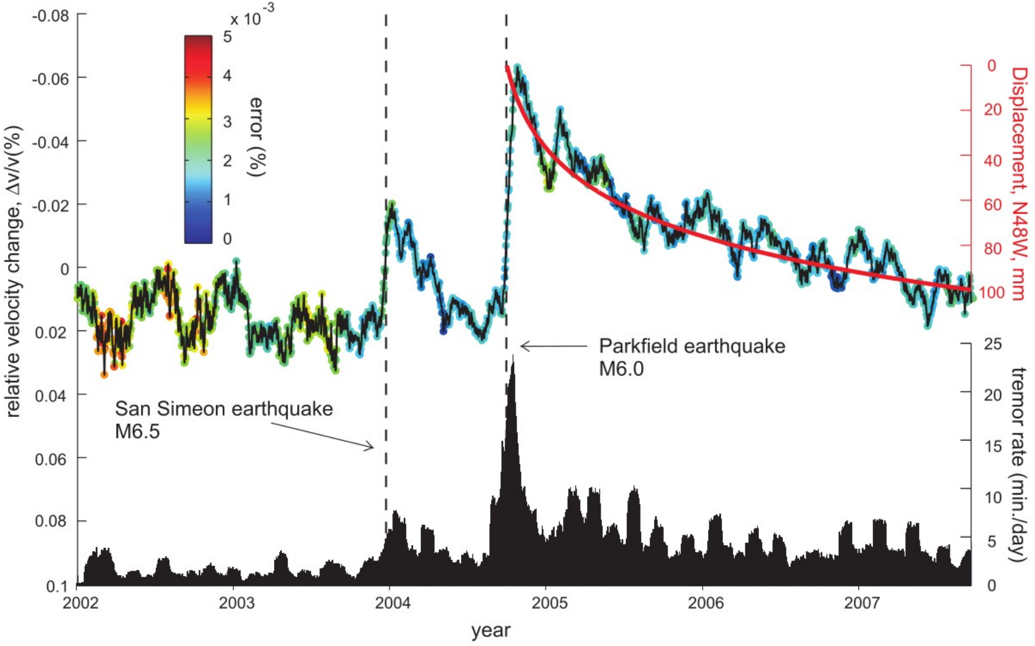
Earthquake Monitoring

REPORT

Postseismic Relaxation Along the San Andreas Fault at Parkfield from Continuous Seismological Observations

F. Brenguier[1,2,*], M. Campillo[2], C. Hadziioannou[2], N. M. Shapiro[1], R. M. Nadeau[3], E. Larose[2]
+ See all authors and affiliations

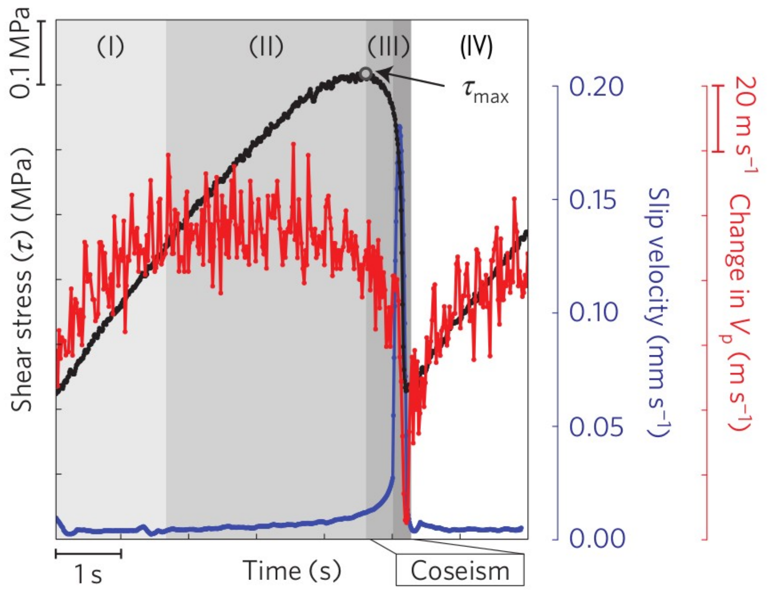
Science 12 Sep 2008:
Vol. 321, Issue 5895, pp. 1478-1481



nature geoscience
LETTERS
PUBLISHED ONLINE: 8 AUGUST 2016 | DOI: 10.1038/NGEO2775

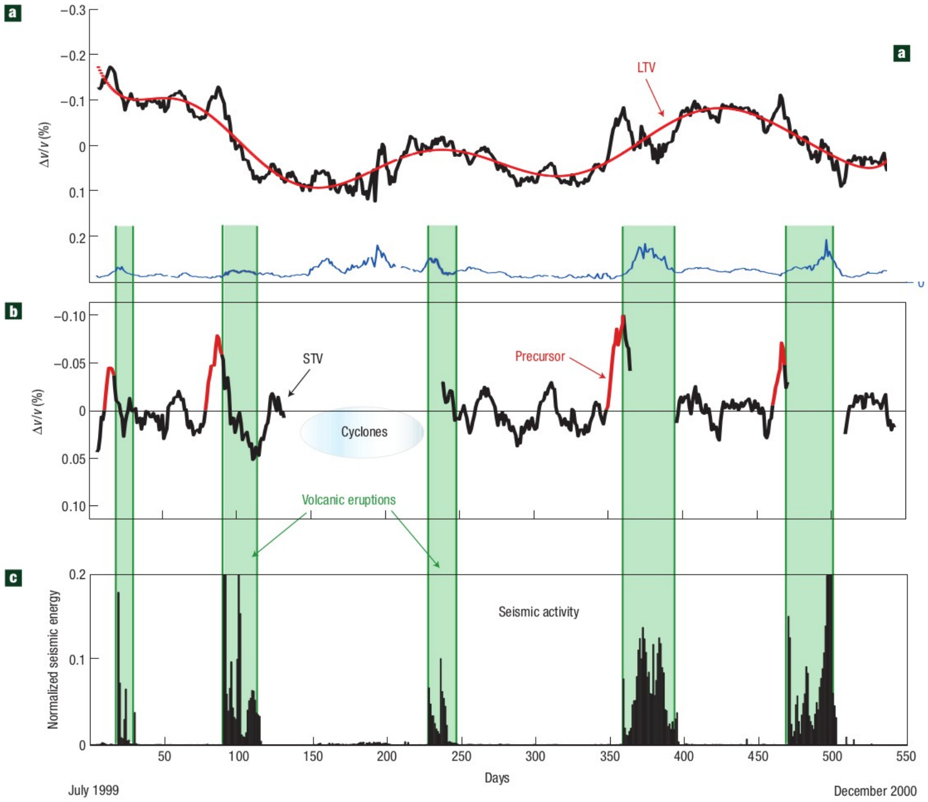
Precursory changes in seismic velocity for the spectrum of earthquake failure modes

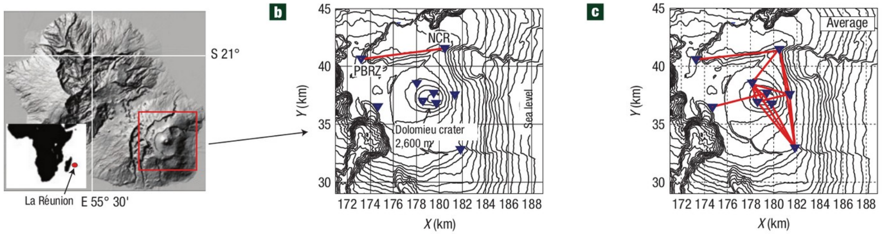
M. M. Scuderi[1,2*], C. Marone[3], E. Tinti[2], G. Di Stefano[2] and C. Collettini[1,2]



Volcano Monitoring

"Towards forecasting volcanic eruptions using seismic noise"

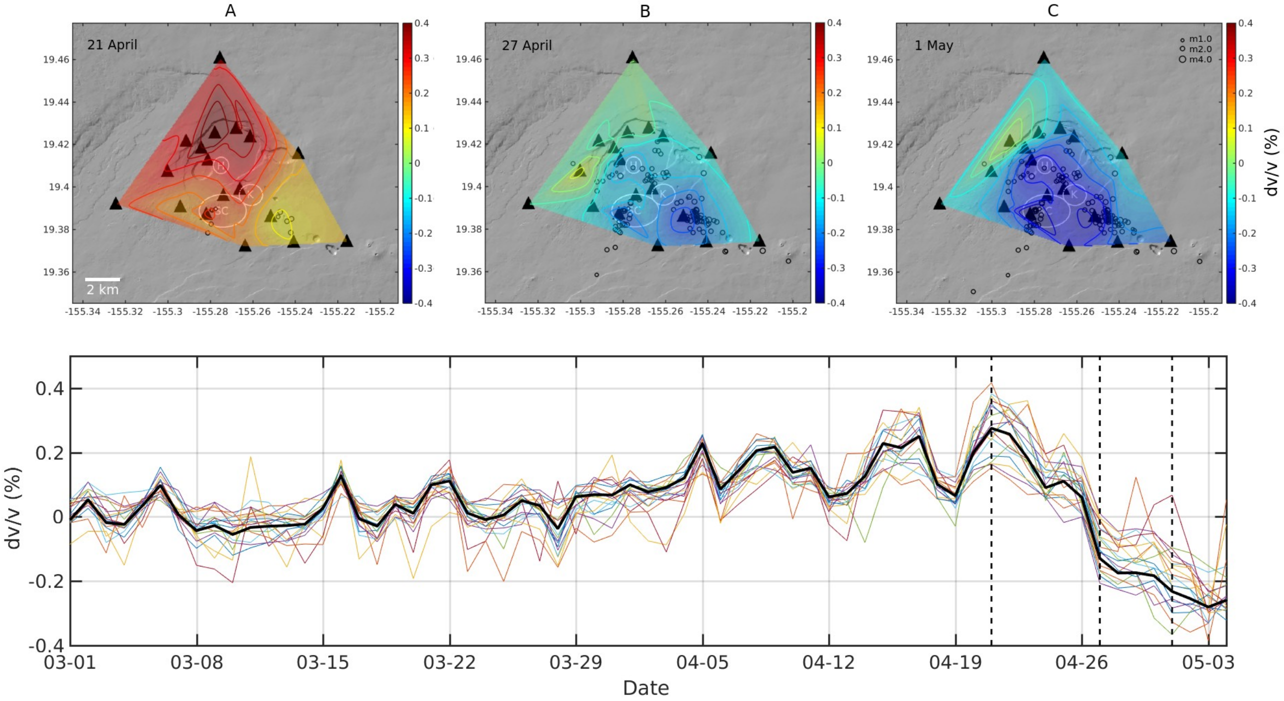




Brenguier et. al., (2008)

Volcano Monitoring

“the **velocity decrease prior to eruption** is likely due to accumulating damage induced by the pressure exerted by the magma reservoir on the edifice”



Geophysical Research Letters

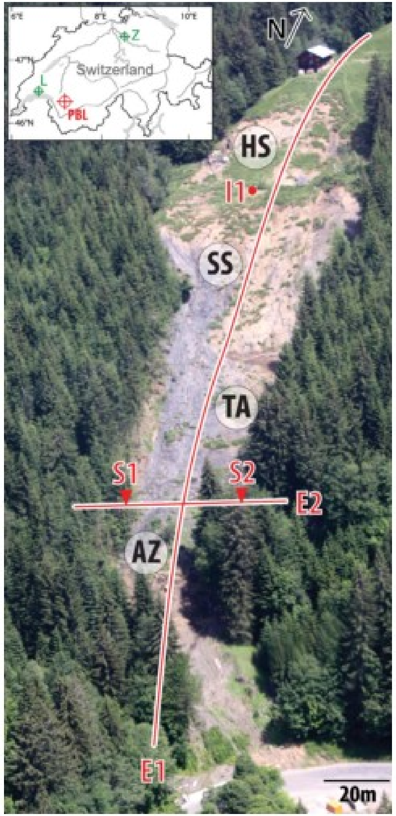
Research Letter

Decrease in Seismic Velocity Observed Prior to the 2018 Eruption of Kīlauea Volcano With Ambient Seismic Noise Interferometry

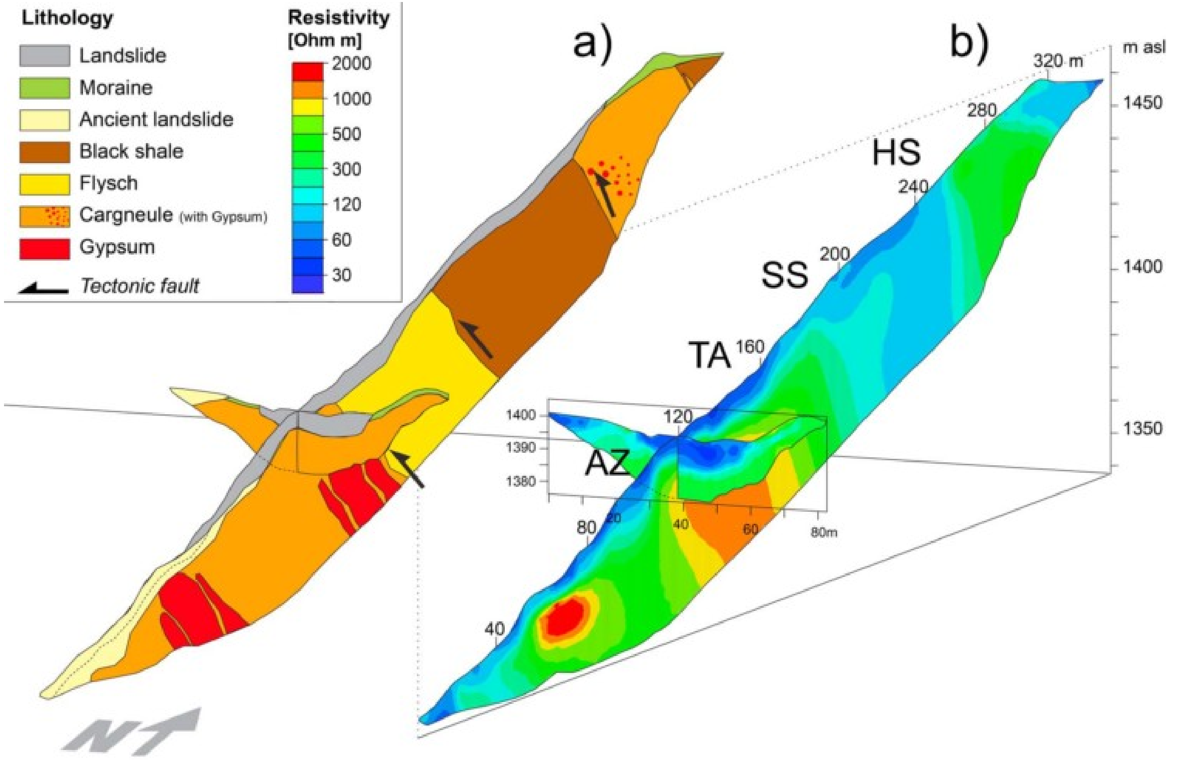
G. Olivier, F. Brenguier, R. Carey, P. Okubo, C. Donaldson

Landslide Study

"Ambient seismic noise monitoring of a clay landslide: Toward failure prediction"



Aerial photo of the Pont Bourquin landslide in Switzerland [9]

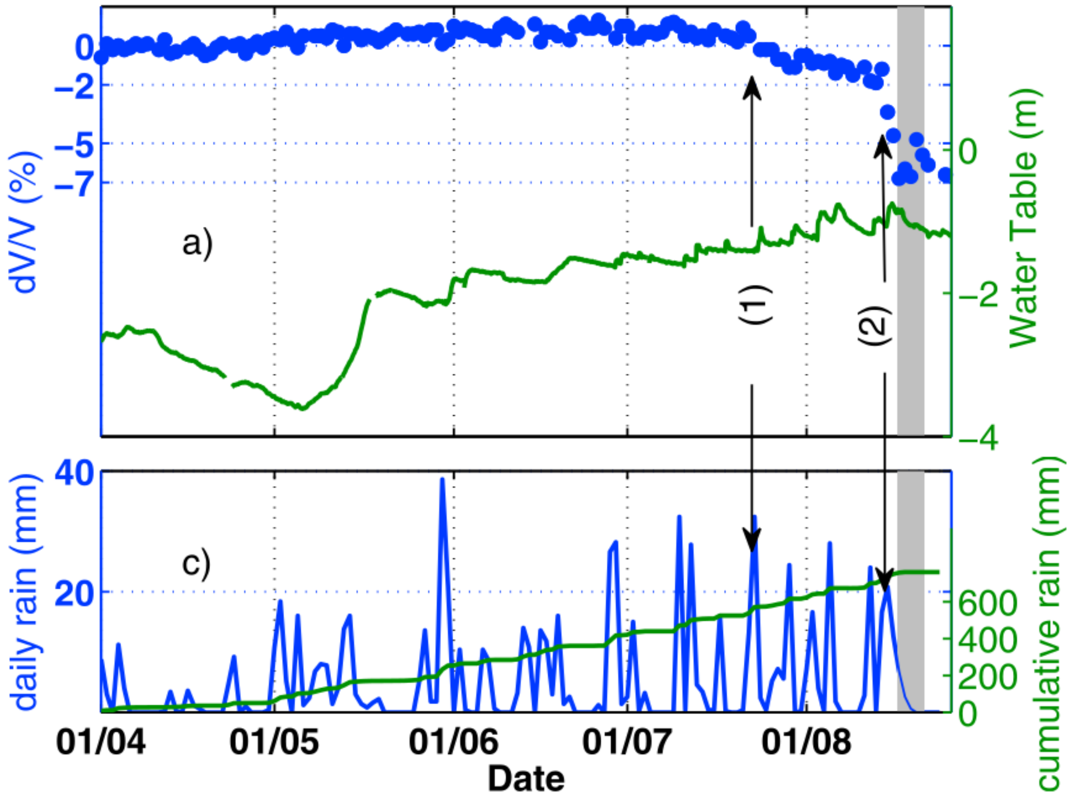


North-south and east-west (a) geological cross section and (b) electrical resistivity tomography profiles

Mainsant et. al., (2012)

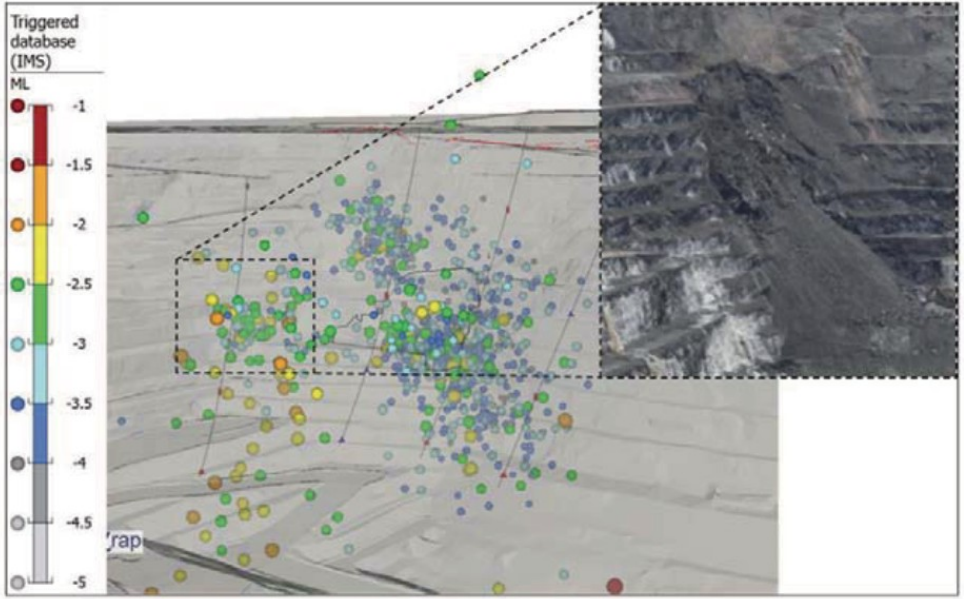
Landslide Study

"Ambient seismic noise monitoring of a clay landslide: Toward failure prediction"



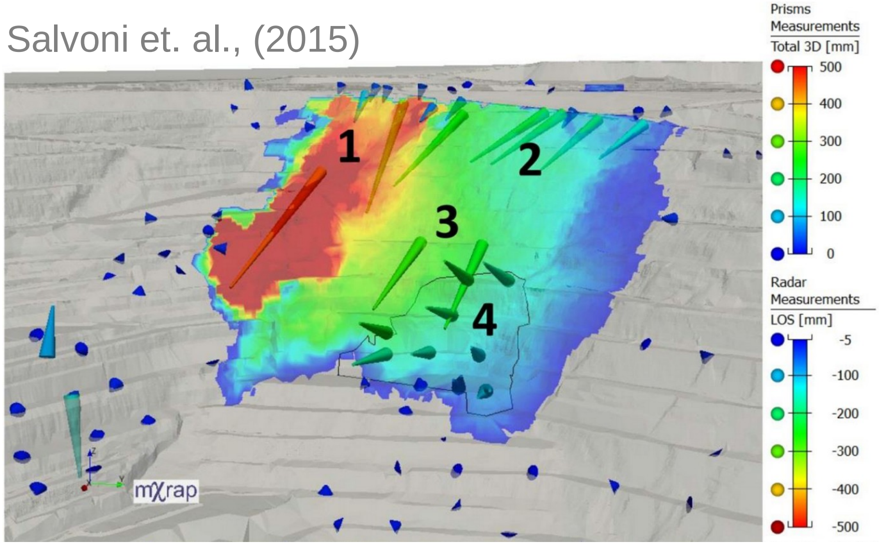
Mainsant et. al., (2012)

Open Pit Slope Monitoring

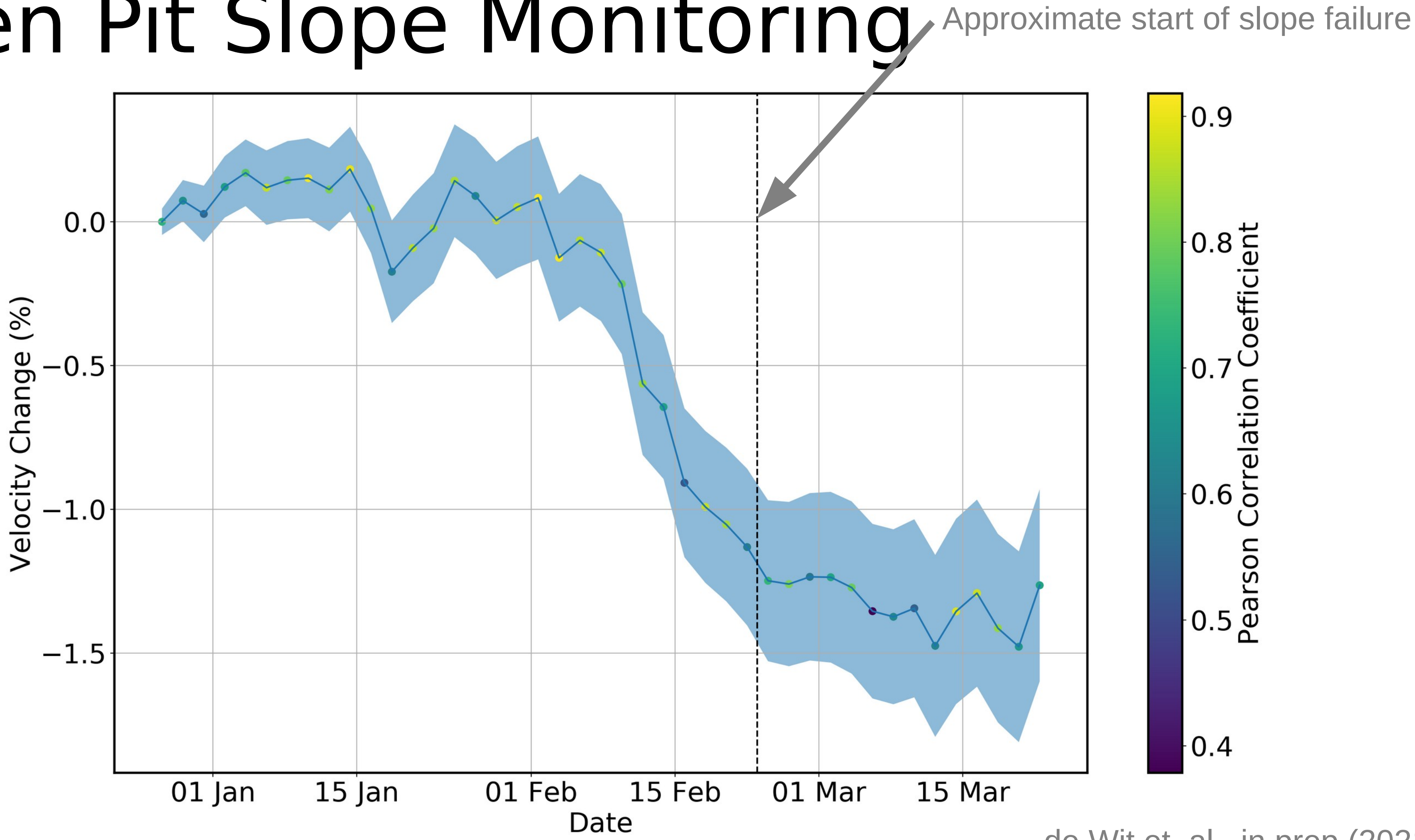


Luo et. al., (2018)

Salvoni et. al., (2015)



Open Pit Slope Monitoring



de Wit et. al., in prep (2021)

Monitoring Earthen Dams

Planès, T. *et al*. (2016). *Géotechnique* **66**, No. 4, 301–312 [http://dx.doi.org/10.1680/jgeot.14.P.268]

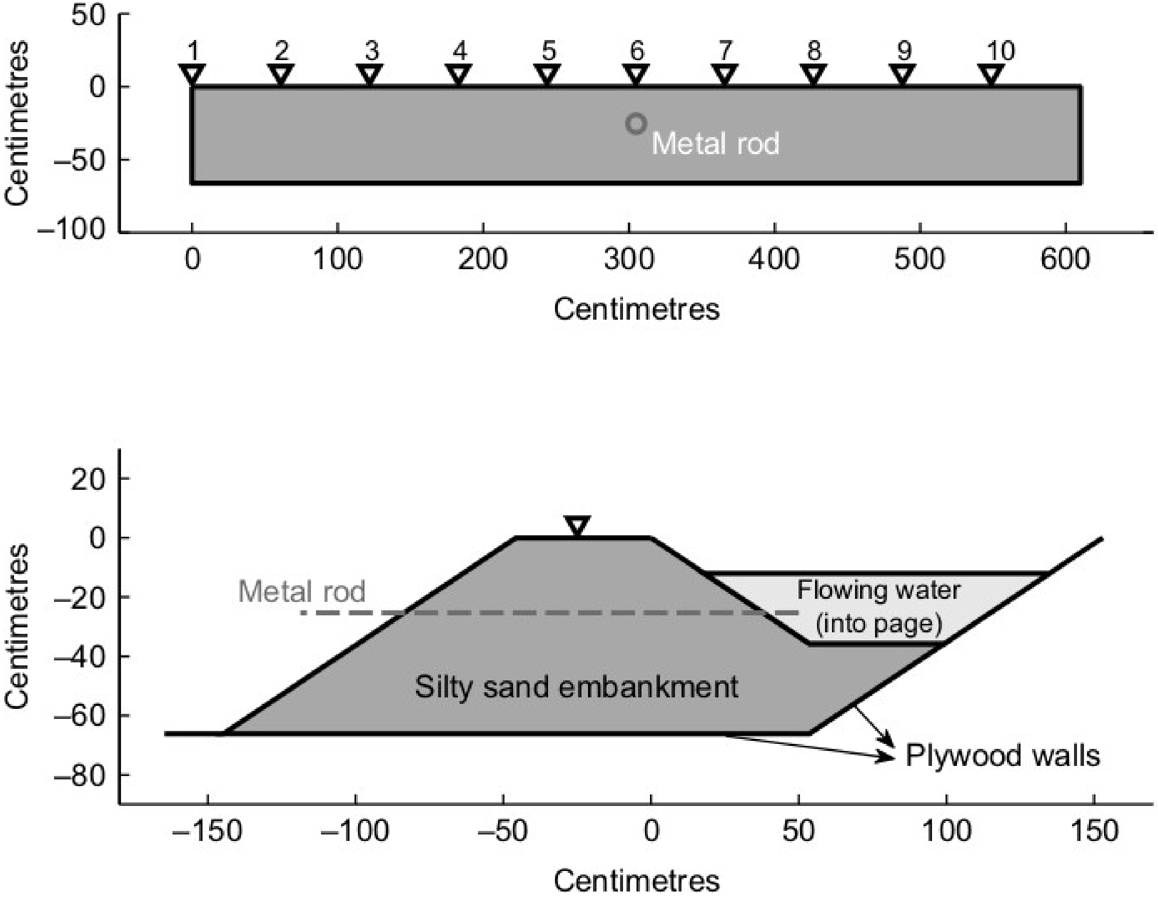
Time-lapse monitoring of internal erosion in earthen dams and levees using ambient seismic noise

T. PLANÈS*, M. A. MOONEY*, J. B. R. RITTGERS†, M. L. PAREKH*, M. BEHM† and R. SNIEDER†

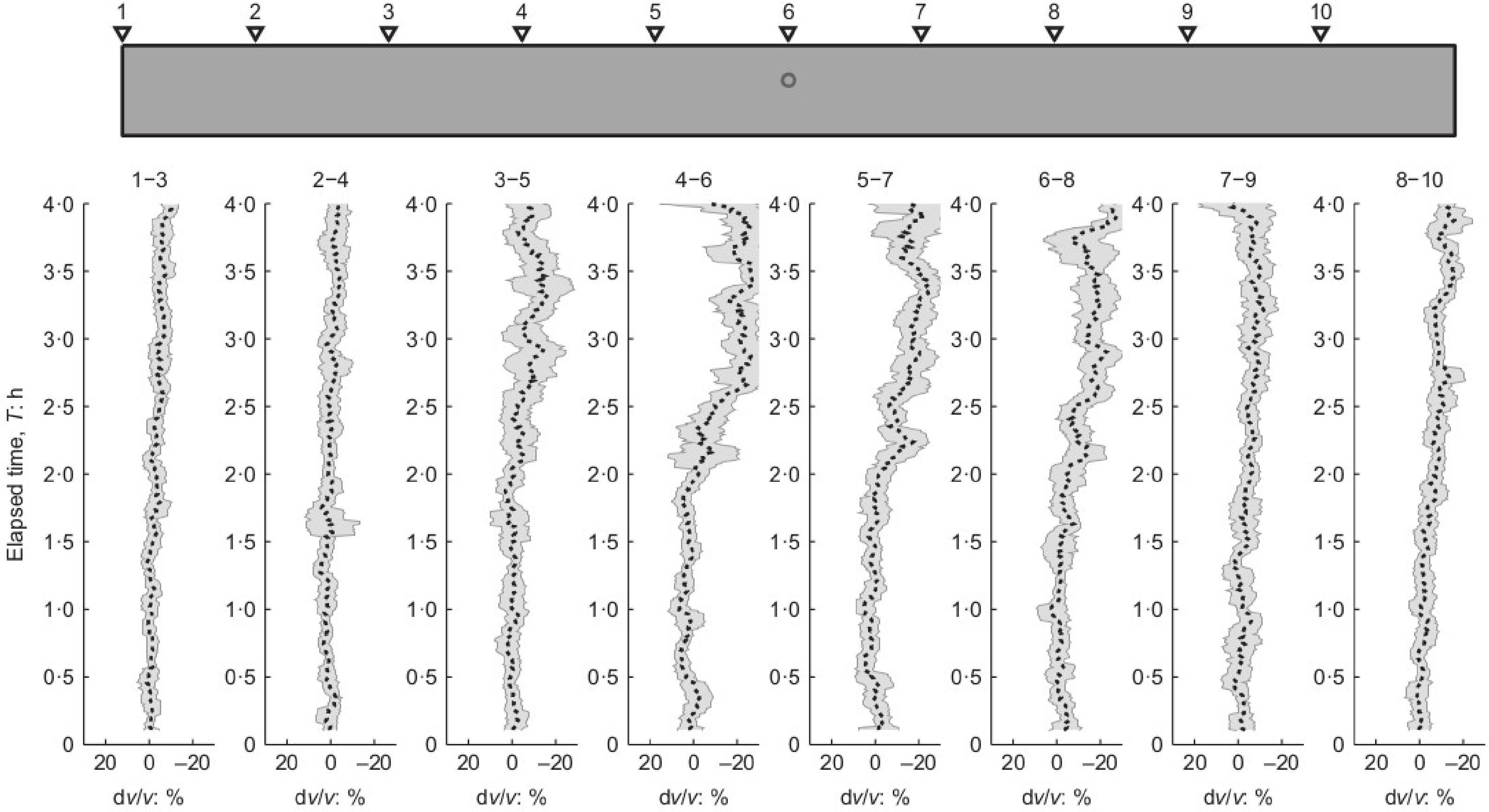
Earthen dams and levees are prone to progressive failure through internal erosion of their structure. Internal erosion is often invisible to current methods of inspection until it manifests itself at the exterior surface. This study focuses on the novel use of passive seismic interferometry to monitor temporal changes in earthen embankments caused by internal erosion. This technique uses the ambient seismic noise – i.e. ambient vibrations – propagating through the structure. Laboratory-scale and field-scale embankment failure experiments are monitored. Seismic impulse responses are reconstructed from the ambient noise and temporal variations in seismic wave velocities are observed throughout each test. The application of seismic interferometry on a canal embankment tested to failure by internal erosion revealed up to 20% reductions in surface wave velocity as internal erosion progressed. The monitoring of a field embankment loaded to partial failure revealed a 30% reduction in averaged surface wave velocity. Some local velocity variations showed good agreement with local pore water pressure responses.

KEYWORDS: dams; embankments; erosion; geophysics; monitoring

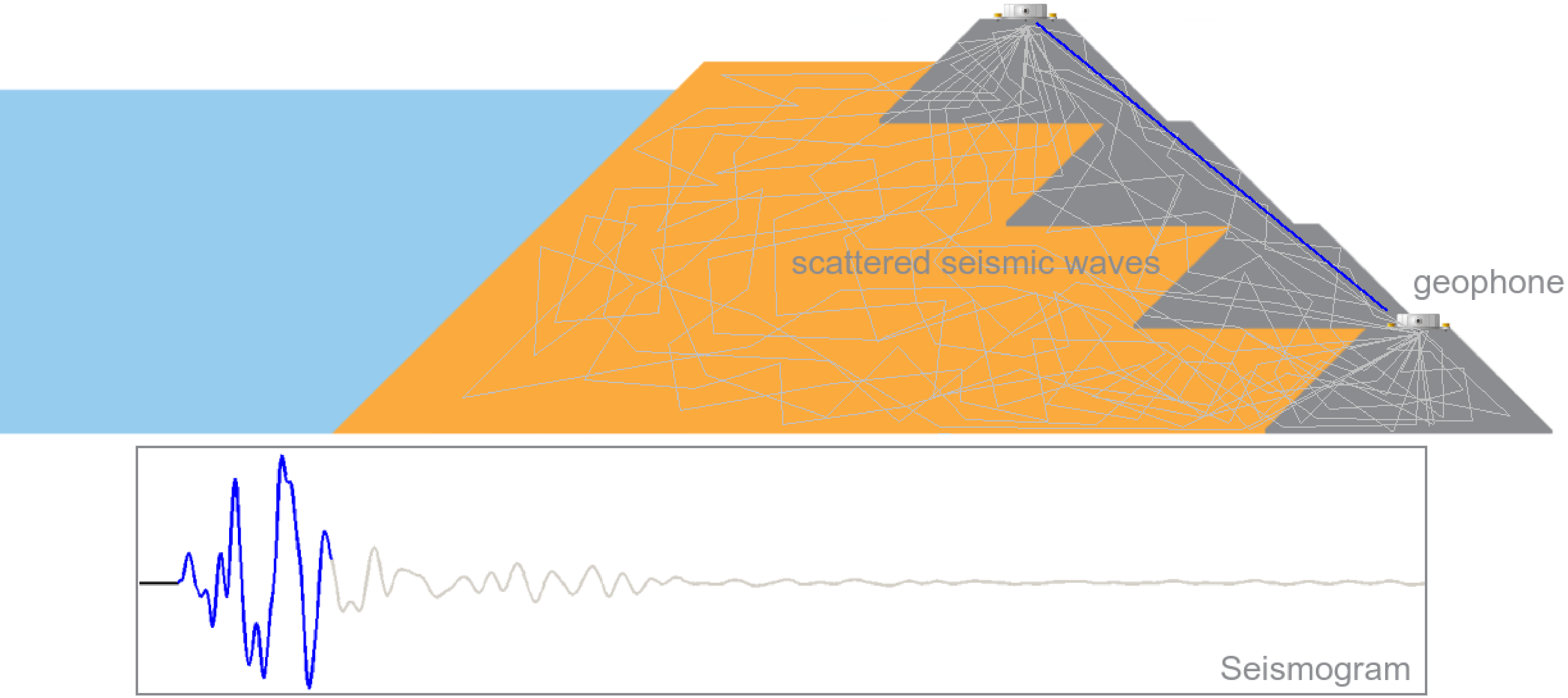
Monitoring Earthen Dams



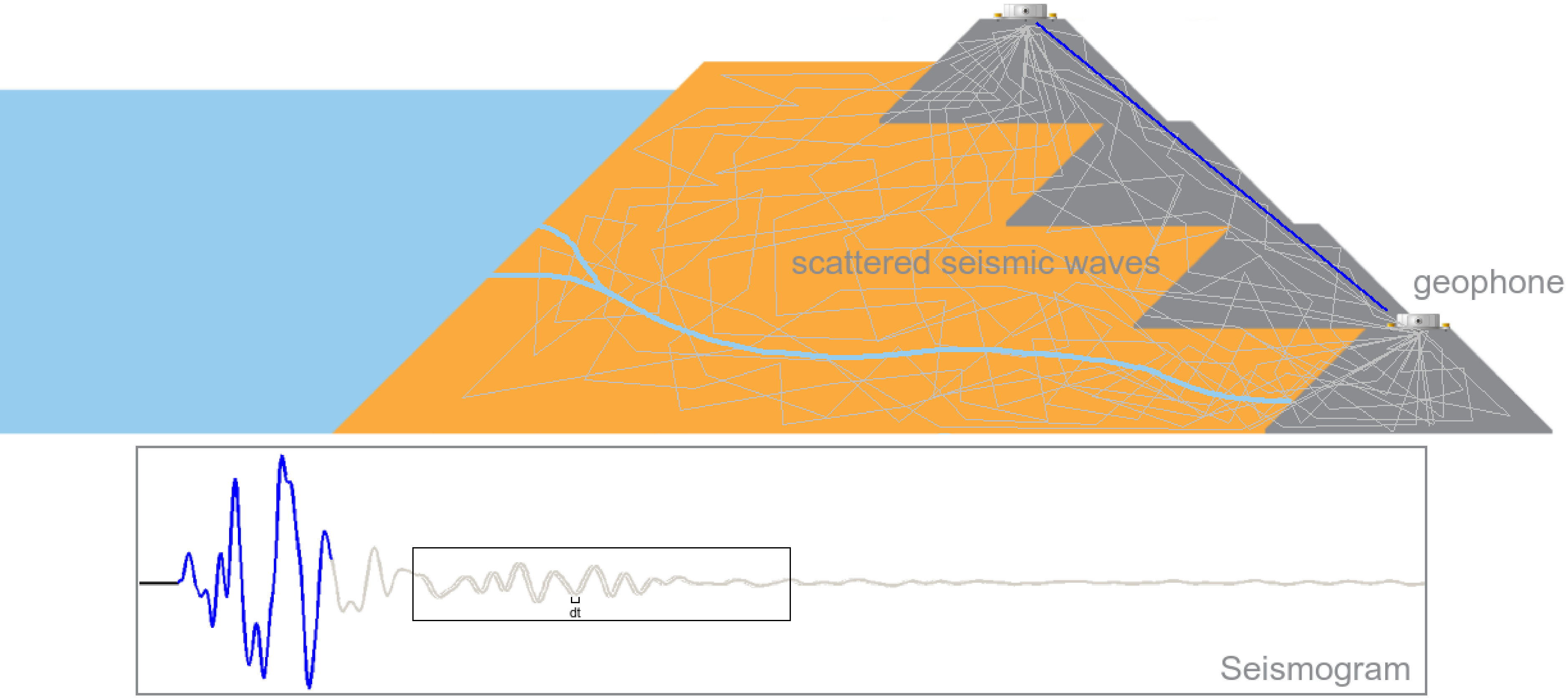
Monitoring Earthen Dams



How does it work in a dam?

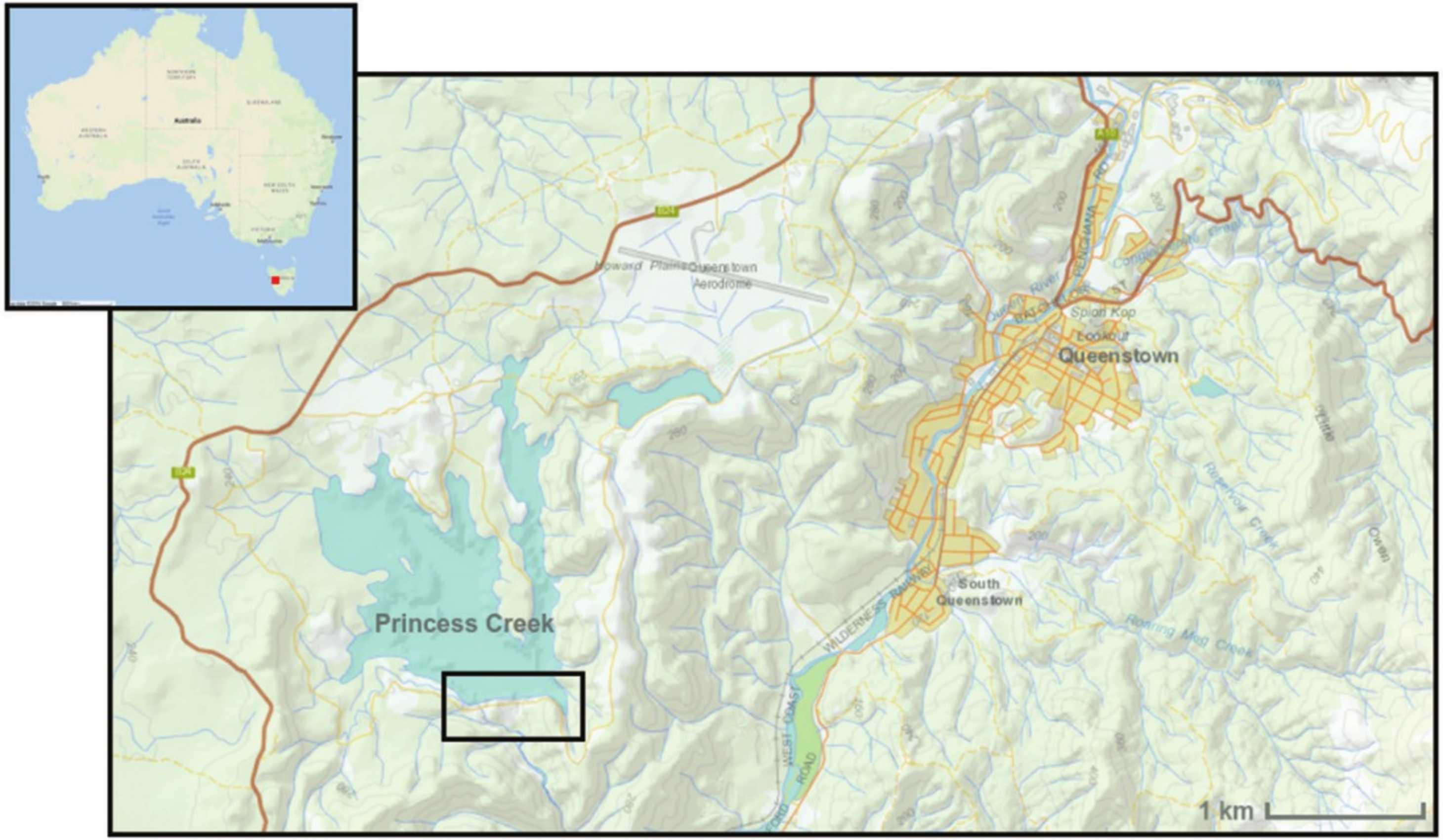


How does it work in a dam?



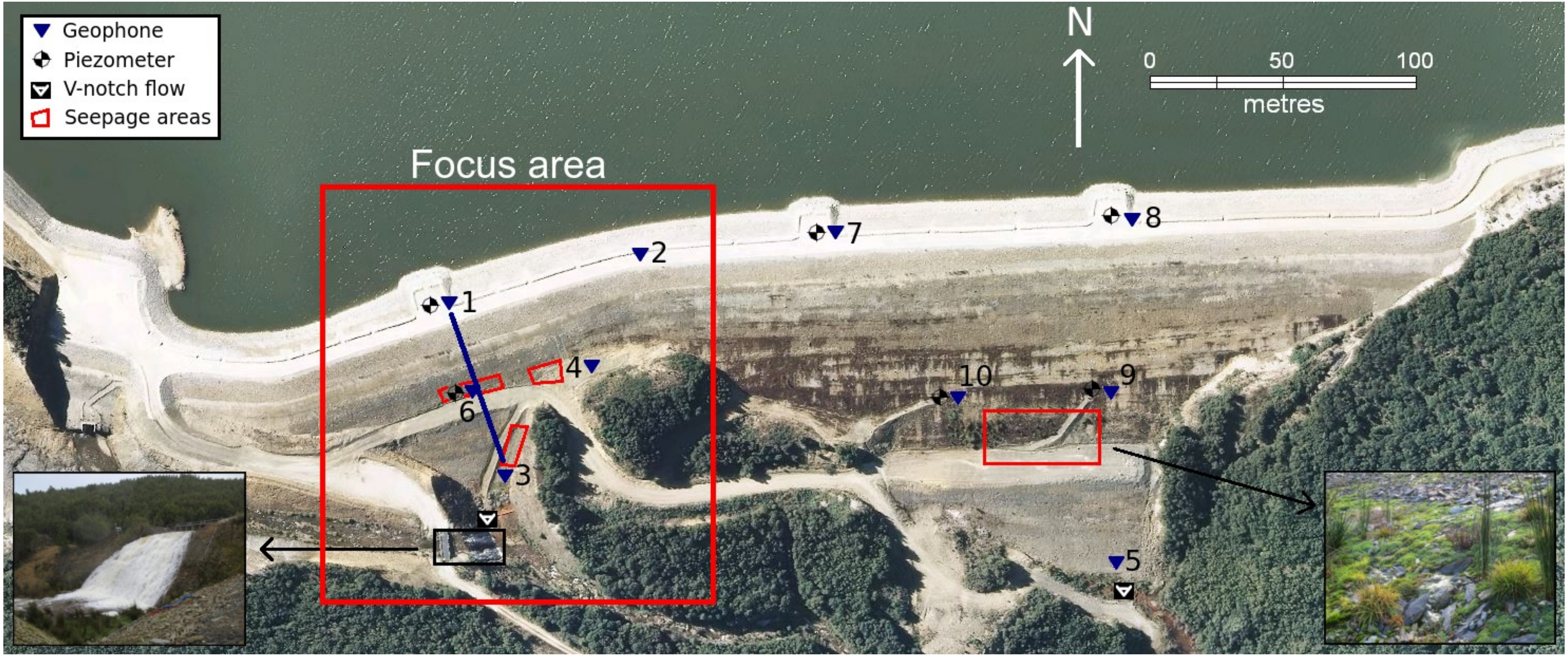
Experiment at Princes Creek, Australia

Experiment at Princes Creek, Australia

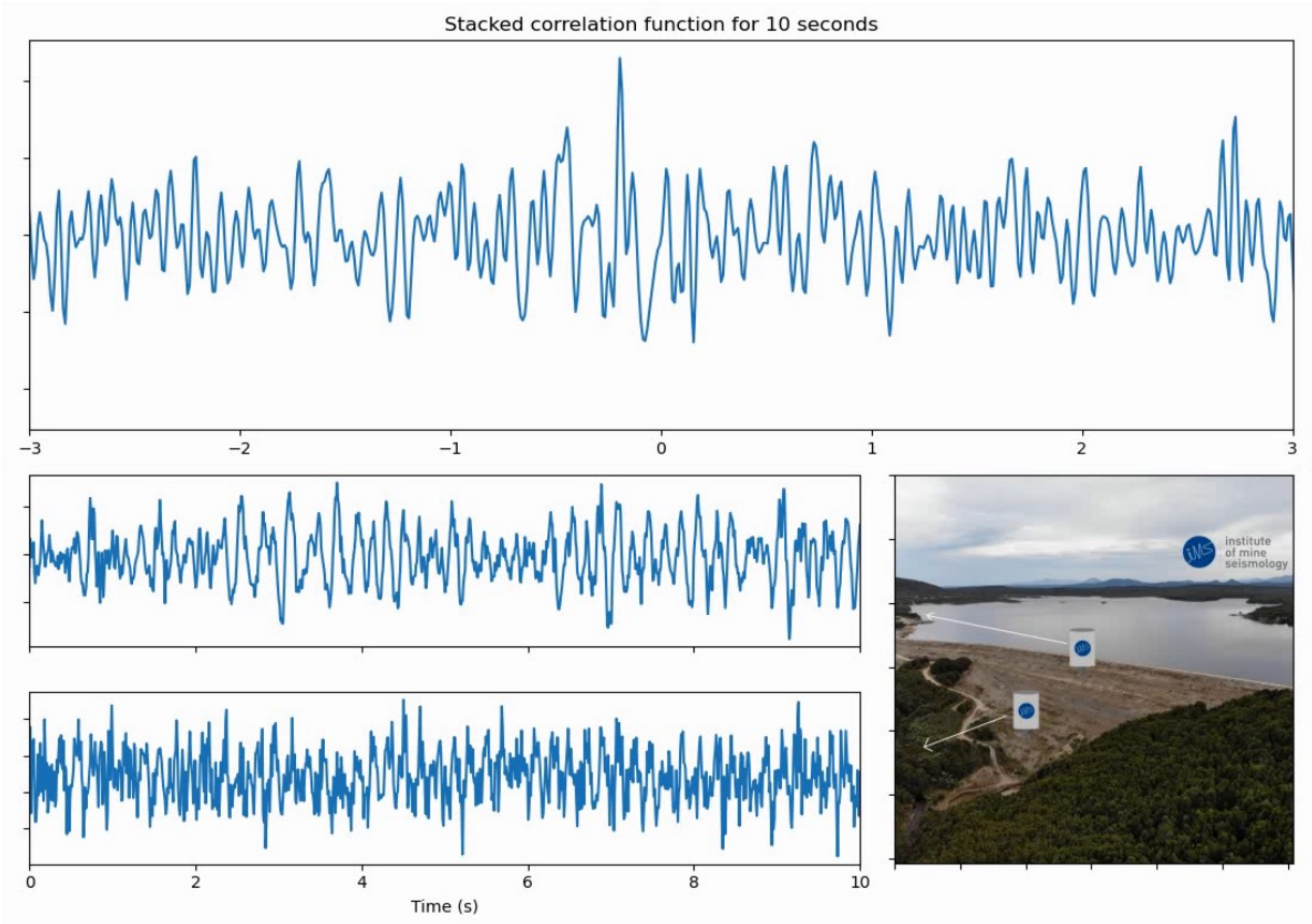


Olivier et. al., (2017)

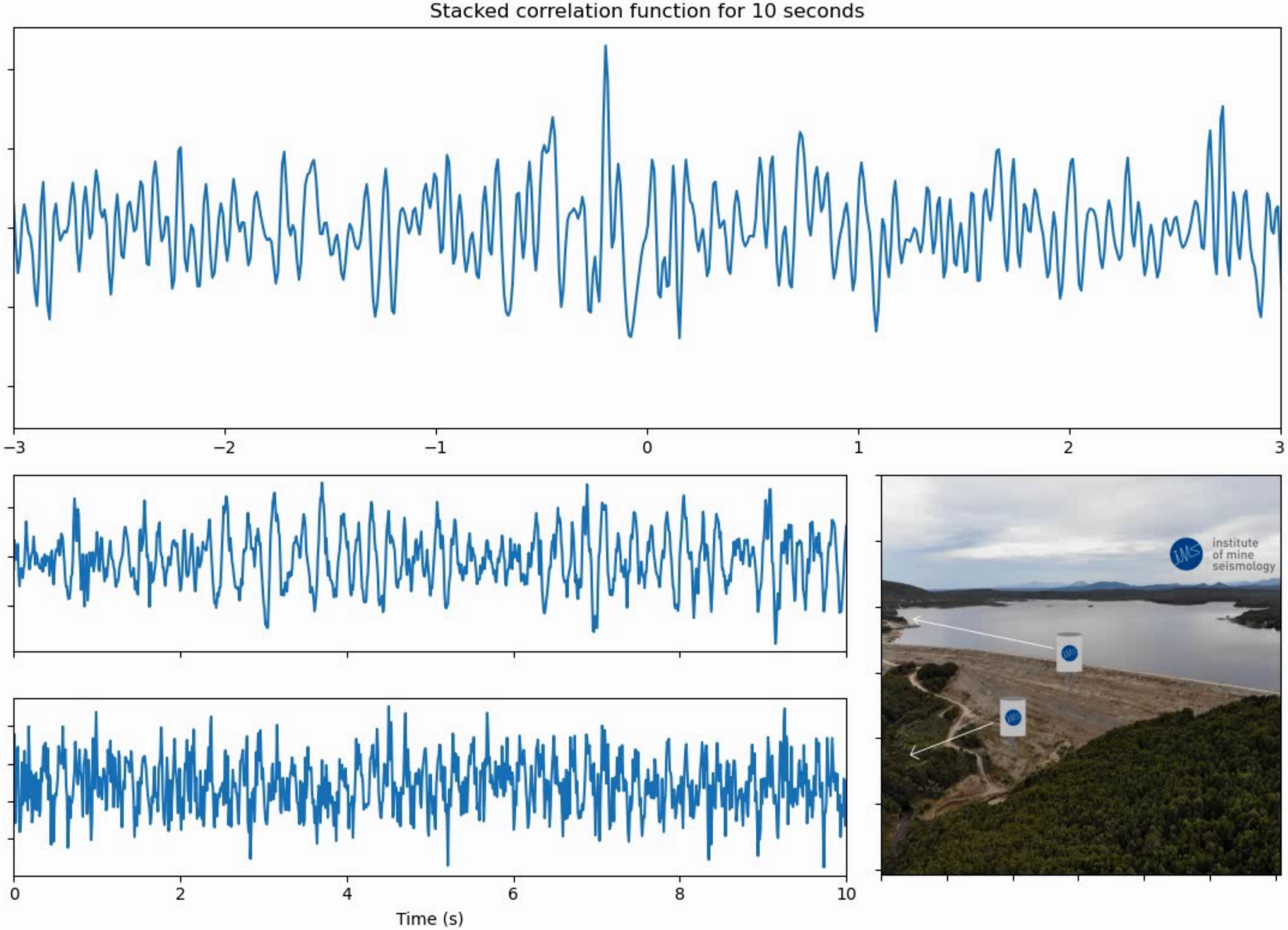
Experiment at Princes Creek, Australia



Olivier et. al., (2017)



After only a few minutes of noise correlations we can make stable measurements of changes in seismic velocity



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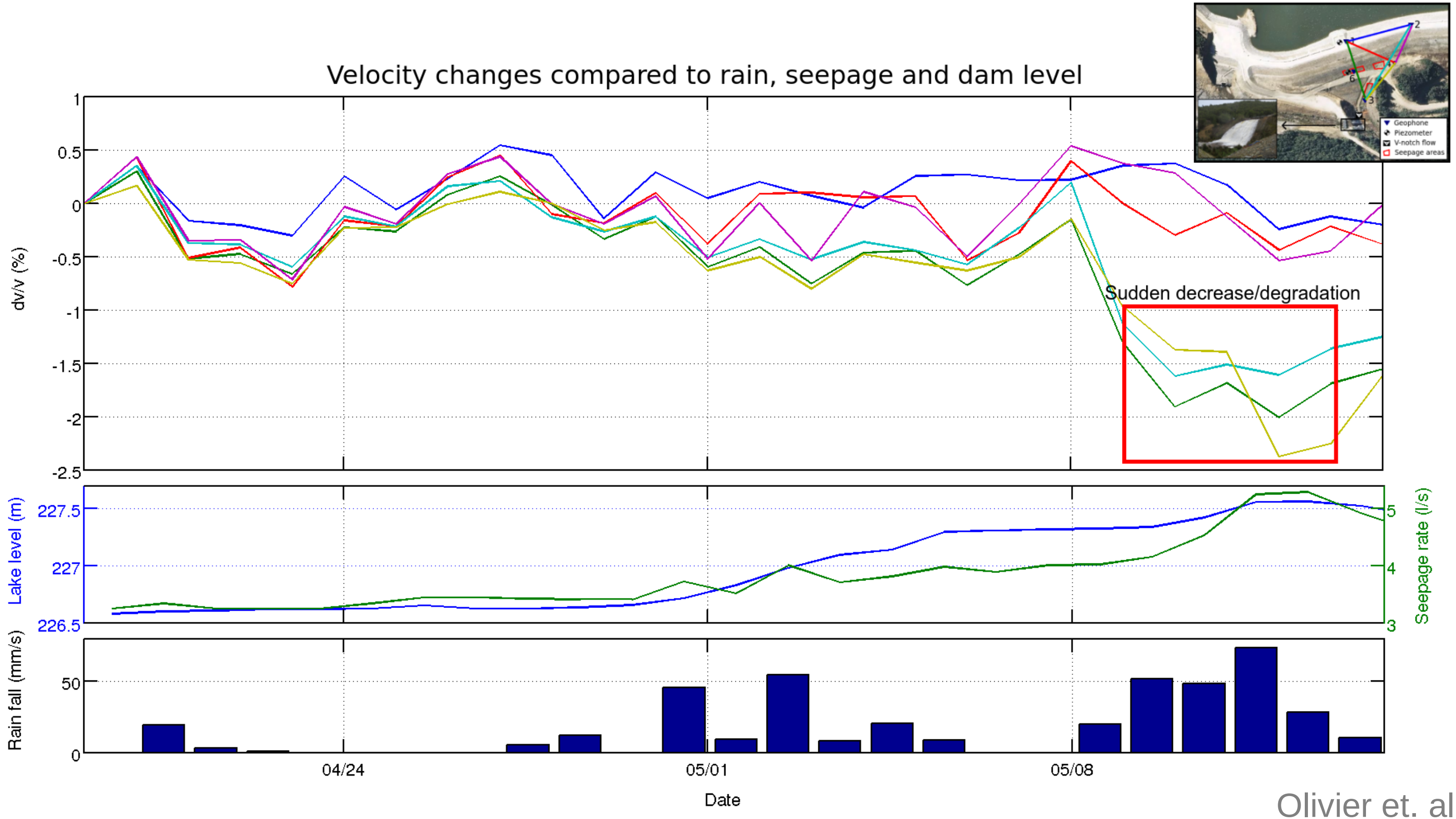
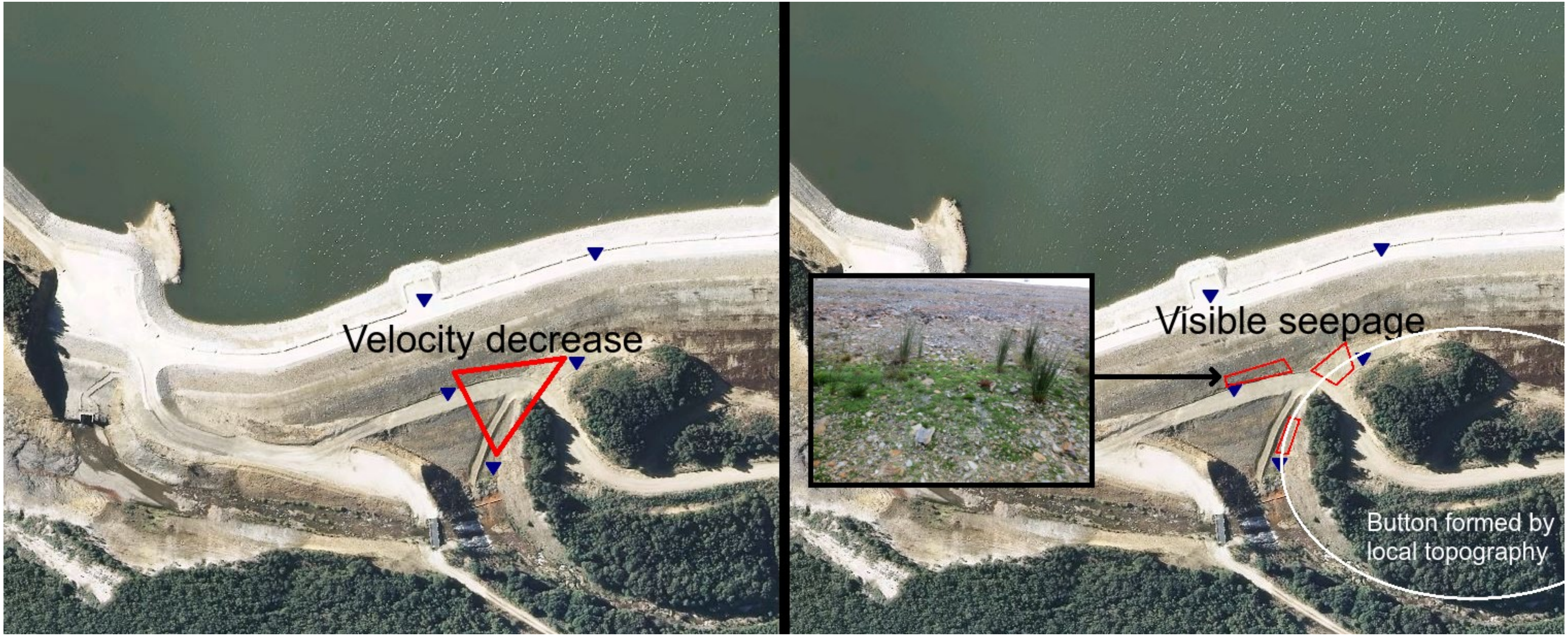
Experiment at Princes Creek, Australia



Olivier et. al., (2017)

Experiment at Princes Creek, Australia



Olivier et. al., (2017)

Experiment at Princes Creek, Australia

Monitoring the stability of tailings dam walls with ambient seismic noise

Gerrit Olivier[1], Florent Brenguier[2], Tjaart de Wit[1], and Richard Lynch[1]

Abstract

Tailings dams are massive structures designed to contain the waste slurry remaining after processing ore at open pit and underground mines. These structures fail far more regularly than normal water-storage dams. In recent years, catastrophic tailings dam failures have occurred, causing significant damage to the environment and even loss of life. To mitigate these catastrophic events in the future, there is an urgent need to develop cost-effective methods to monitor the structural stability of these constructions over time. The lack of current cost-effective monitoring methods prompted us to investigate whether ambient seismic noise can be used to detect internal changes in a tailings dam wall during a period of heavy rainfall. We recorded three weeks of continuous seismic data with 10 short-period geophones at a tailings dam in Tasmania, Australia. Seismic interferometry was used on ambient noise to create virtual seismic sources. With these virtual source signals, small changes in seismic velocity were measured daily and compared to rainfall, seepage flow rates, and fluid pore pressure. The observed velocity changes were driven by fluid saturation, ground water level, increased loading from increased dam water level, and a sudden increase in fluid pore pressure in a section of the dam wall. The results suggest that this relatively inexpensive method can be used to monitor and locate small changes in the interior of the tailings dam wall, providing a valuable tool to remotely monitor the structural stability of tailings dam walls over time.

Massive dams, massive risks

Tailings dams are some of the largest man-made structures on Earth and also among the most technically challenging areas for geotechnical engineers to maintain and monitor. Over the last few decades, many tailings dam failures have occurred, and it is estimated that approximately two to five major failures occur per year (Davies, 2002). The failure rate of these structures is more than 100 times higher than normal water-storage dams (Azam and Li, 2010). This is due to the relatively loose regulations surrounding these structures in developing countries and due to the cost-saving methods that are used when these structures are designed. The most common tailings dam design is called the upstream method. In this method, the tailings next to the dam wall are allowed to dry, and these solidified tailings are then used as the foundation for subsequent raises (or lifts) to accommodate more tailings. This method is attractive from an economic standpoint as it requires the least amount of earth moving to increase the dam capacity. However, walls built using this method are also the most likely to fail (Breitenbach, 2010). This wall-design method is particularly susceptible to soil liquefaction due to shaking from earthquakes, mine blasts, or other vibrations (Fell et al., 1992; Martin and McRoberts, 1999). Consequently, this design method is banned in some earthquake-prone countries such as Chile and Peru (Breitenbach, 2010).

In November 2015, the Fundão tailings dam wall in Brazil suddenly failed. This incident is considered to be one of the largest environmental disasters in recent years (de Oliveira Neves et al., 2016). Recent results indicate that the failure of the dam wall may have been triggered by a sequence of small magnitude earthquakes (Agurto-Detzel et al., 2016). This could suggest that the dam wall was in an already-weakened state at this time, as the largest seismic event in this sequence had a relatively small moment magnitude of $M_w = 2.0$. The possibility that such a small seismic sequence could trigger such a catastrophic disaster is concerning for numerous other tailings dams around the world and emphasizes the need to monitor the structural stability of the walls over time in order to be aware of degradation and weakening and to investigate the mechanisms of failure.

In Australia, there are regulations in place to ensure that many tailings dams are equipped with monitoring equipment to help understand the long-term response of the internal wall structure to the rising tailings level and weathering. Additionally, the short-term response of the wall to external factors like heavy rainfall or earthquakes is of interest since it is known that these factors can contribute to failures (Azam and Li, 2010). Current monitoring methods appear to mostly address the long-term behavior of the wall. Methods to monitor the short-term behavior of the wall to external factors include ground-based radar. These methods are employed only when a specific concern is raised, in large part due to the significant costs involved in installing and operating these methods.

Borehole piezometers are used to monitor the pore pressures and groundwater level inside the dam walls, since gradual increases in these parameters can cause static liquefaction (Eckersley, 1990; Martin and McRoberts, 1999). In some cases, radars and/or high-resolution cameras are used to monitor small deformations of the dam walls. Unfortunately, these methods measure surface perturbations and are not capable of detecting internal changes in the walls. Crucially, the delays between the time that surface perturbations become detectable and the time of failure are often not sufficient for early warning (Fell et al., 2003). Other failure mechanisms, like internal erosion (or piping failure), are monitored with flow meters that measure the cumulative seepage at the toe of the embankment, but these also do not give much advance warning. Another concern with current monitoring technology is the poor performance during heavy rainfall. Small deformations on the dam wall become very difficult to detect because of the fluid on the surface of the wall. Similarly, seepage flow rates are hard to interpret during heavy

[1]Institute of Mine Seismology, Hobart, Tasmania, Australia.
[2]Institut des Sciences de la Terre, Université Grenoble Alpes, Grenoble, France.

http://dx.doi.org/10.1190/tle36040072.1.

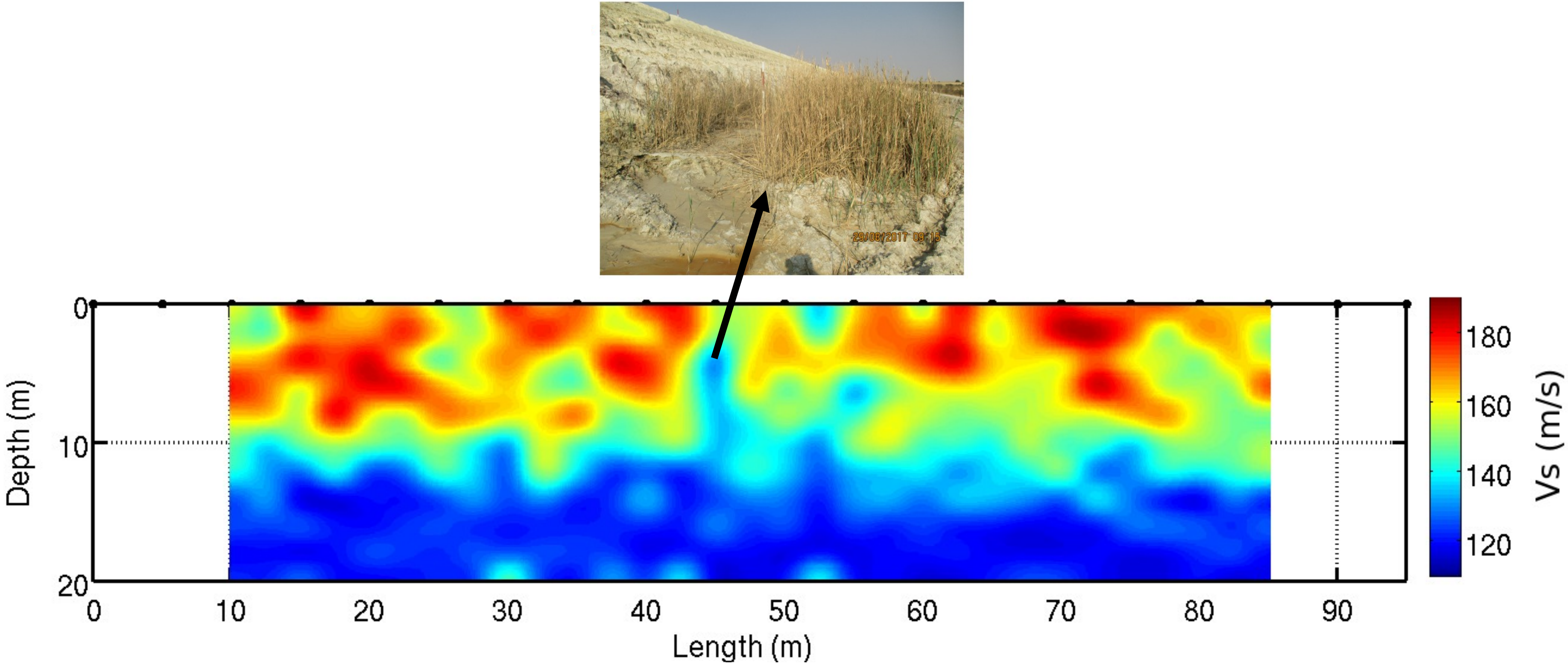
See paper for more details:

Olivier, G., Brenguier, F., de Wit, T., & Lynch, R. (2017). Monitoring the stability of tailings dam walls with ambient seismic noise. The Leading Edge, 36(4), 350a1-350a6. https://doi.org/10.1190/tle36040350a1.1

Imaging Experiment, Welkom, South Africa

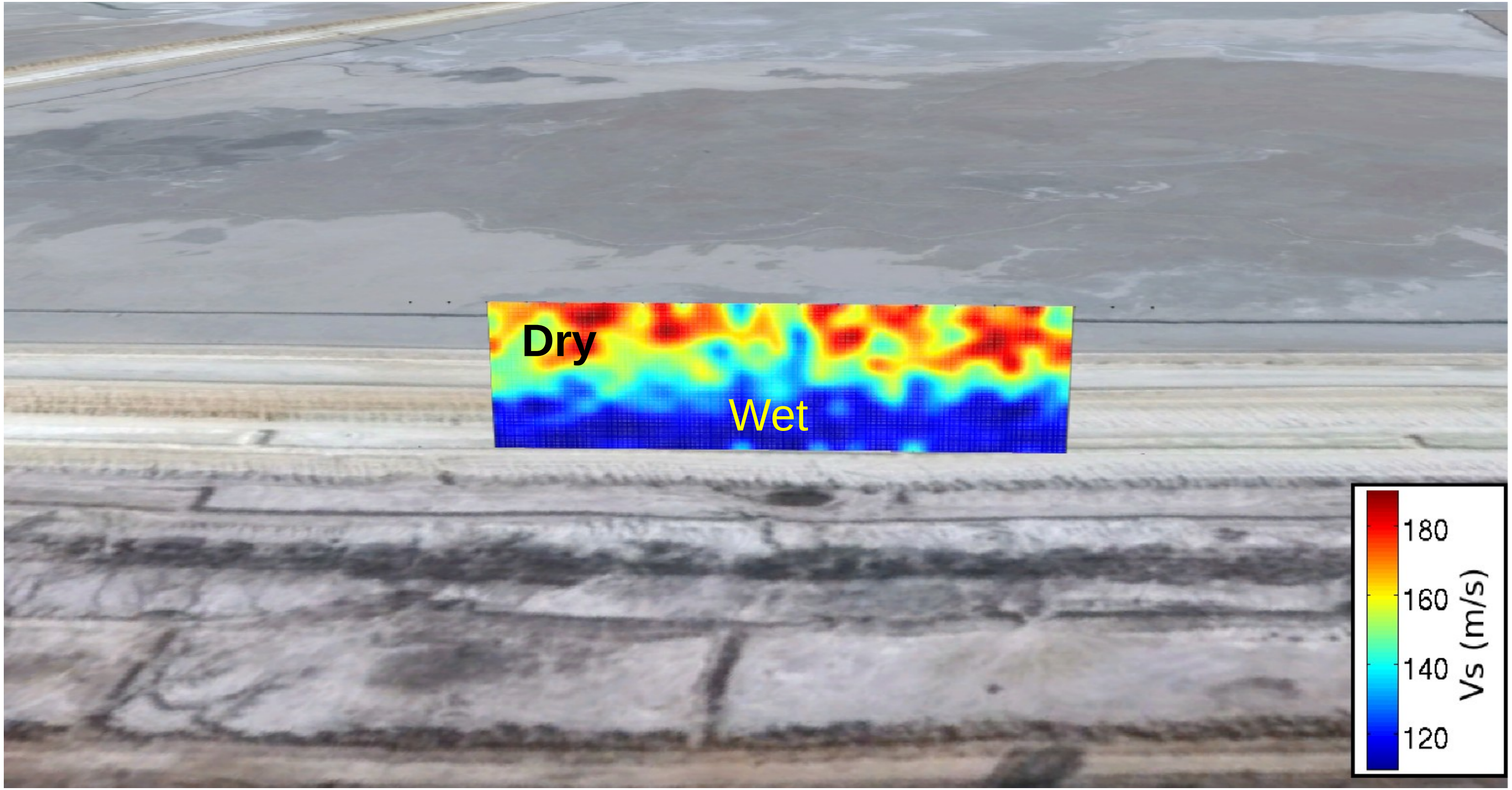
Olivier et. al., (2018)

Imaging Experiment, Welkom, South Africa



Olivier et. al., (2018)

Imaging Experiment, Welkom, South Africa



Olivier et. al., (2017)

Current Monitoring

We currently monitor 17 tailings dams in Brazil in real time for Vale and Mosaic with our local partner, Tetra Tech.

Further tailings dams are to be commissioned in Australia, Mexico and USA (Freeport McMoRan) in the next few months.

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Invited review

Landslide monitoring using seismic ambient noise correlation: challenges and applications

Mathieu Le Breton [a,b,*], Noélie Bontemps [a], Antoine Guillemot [a], Laurent Baillet [a], Éric Larose [a]

[a] Univ. Grenoble Alpes, CNRS, Univ. Savoie Mont-Blanc, IRD, IFSTTAR, ISTerre, 38000 Grenoble, France
[b] Géolithe & Géolithe Innov, 38920 Crolles, France

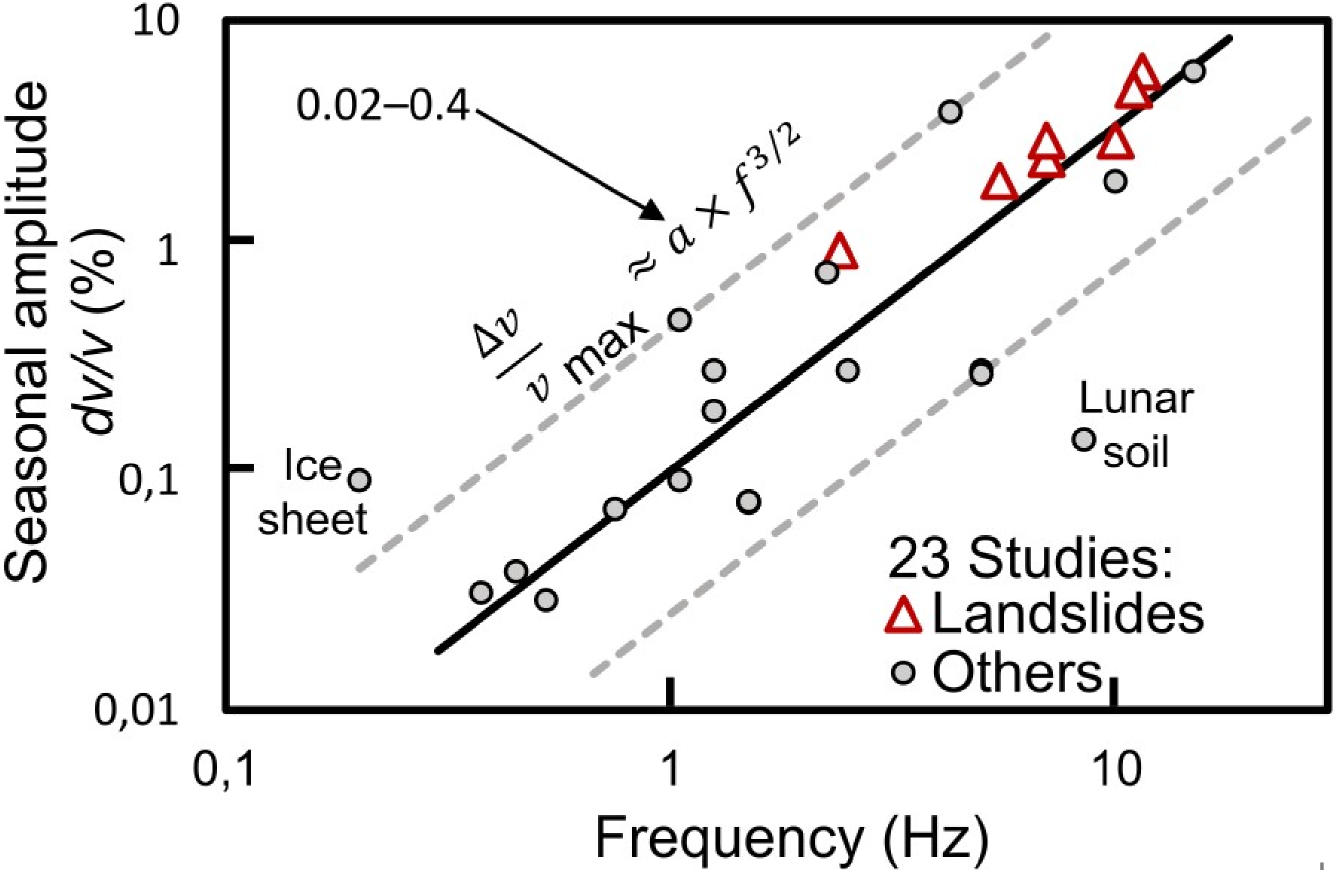
ARTICLE INFO

Keywords:
Early warning system
Ambient noise interferometry
Cross-correlations
Landslide monitoring
Environmental seismology
Seismic ambient noise

ABSTRACT

Monitoring landslides is essential to understand their dynamics and to reduce the risk of human losses by raising warnings before a failure. A decade ago, a decrease of apparent seismic velocity was detected several days before the failure of a clayey landslide, that was monitored with the ambient noise correlation method. It revealed its potential to detect precursor signals before a landslide failure, which could improve early warning systems. To date, nine landslides have been monitored with this method, and its ability to reveal precursors before failure seems confirmed on clayey landslides. However three challenges remain for operational early-warning applications: to detect velocity changes both rapidly and with confidence, to account for seasonal and daily environmental influences, and to check for potential instabilities in measurements. The ability to detect a precursory velocity change requires to adapt the processing workflow to each landslide: the key factors are the filtering frequency, the correlation time window, and the choice of temporal resolution. Other optional processing steps are described, to better measure rapid velocity changes, improve signal-to-noise ratio, or estimate the measurement uncertainty. The velocity also fluctuates seasonally, by 1 to 6% on the reviewed landslide studies, due to environmental influences. This review reveals a linear trend between the amplitude of seasonal fluctuations and the filtering frequency over the 0.1–20 Hz range, encompassing both landslide and non-landslide studies. The environmental velocity fluctuations are caused mostly by groundwater levels and soil freezing/thawing, but could also be affected by snow height, air temperature and tide depending on the site. Daily fluctuations should also occur on landslides, and can be an issue when seeking to obtain a sub-daily resolution useful for early-warning systems. Finally, spurious fluctuations of apparent velocity—unrelated to the material dynamics—should be verified for. They can be caused by changes in noise sources (location or spectral content), in site response (change of scatterers, attenuation, or resonance frequency due to geometrical factors), or in inter-sensor distance. As a perspective, the observation of seismic velocity changes could contribute in assessing a landslide stability across time, both during the different creeping stages occurring before a potential failure, and during its reconsolidation after a failure.

Velocity Change Thresholds



Le Breton et. al., (2021)

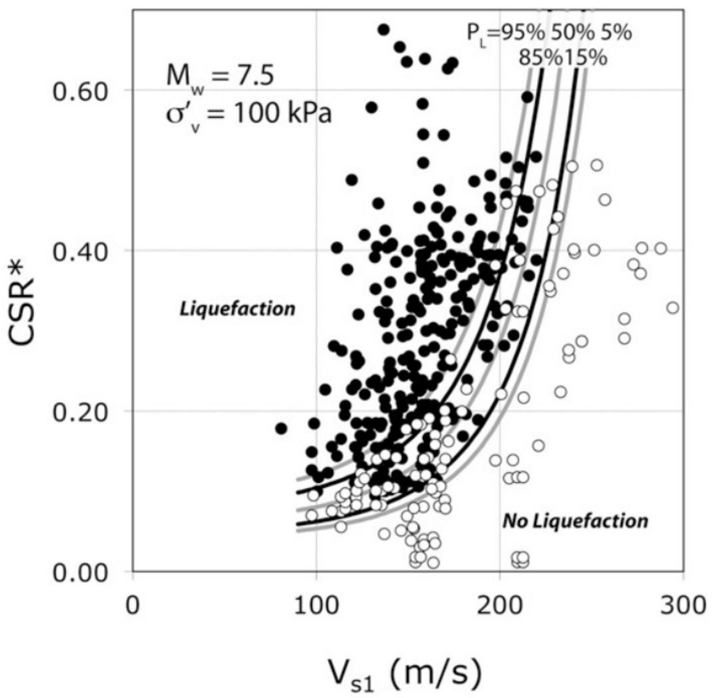
Velocity Change Thresholds

Shear-Wave Velocity–Based Probabilistic and Deterministic Assessment of Seismic Soil Liquefaction Potential

R. Kayen, M.ASCE[1]; R. E. S. Moss, M.ASCE[2]; E. M. Thompson, A.M.ASCE[3]; R. B. Seed, M.ASCE[4]; K. O. Cetin, M.ASCE[5]; A. Der Kiureghian, M.ASCE[6]; Y. Tanaka[7]; and K. Tokimatsu, M.ASCE[8]

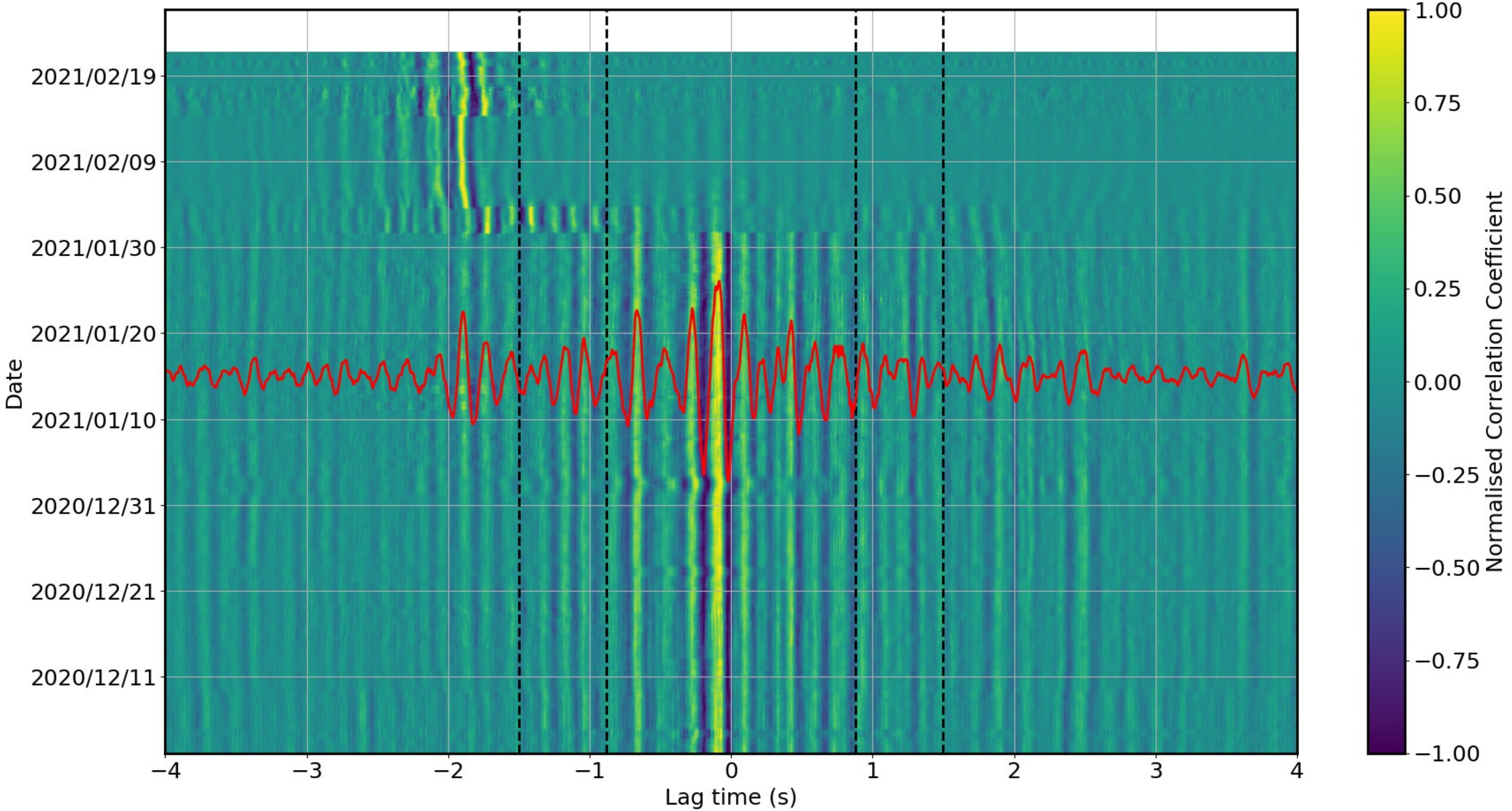
$$P_L = \Phi\left\{ \frac{\left[(0.0073 \cdot V_{s1.})^{2.8011} - 1.946 \cdot \ln(\mathrm{CSR}) - 2.6168 \cdot \ln(M_w) - 0.0099 \cdot \ln(\sigma'_{vo}) + 0.0028 \cdot (\mathrm{FC})\right]}{0.4809} \right\}$$

$$FS_{\mathrm{liq}} = \frac{\mathrm{CRR}_{P_L(15\%)}}{\mathrm{CSR}}$$

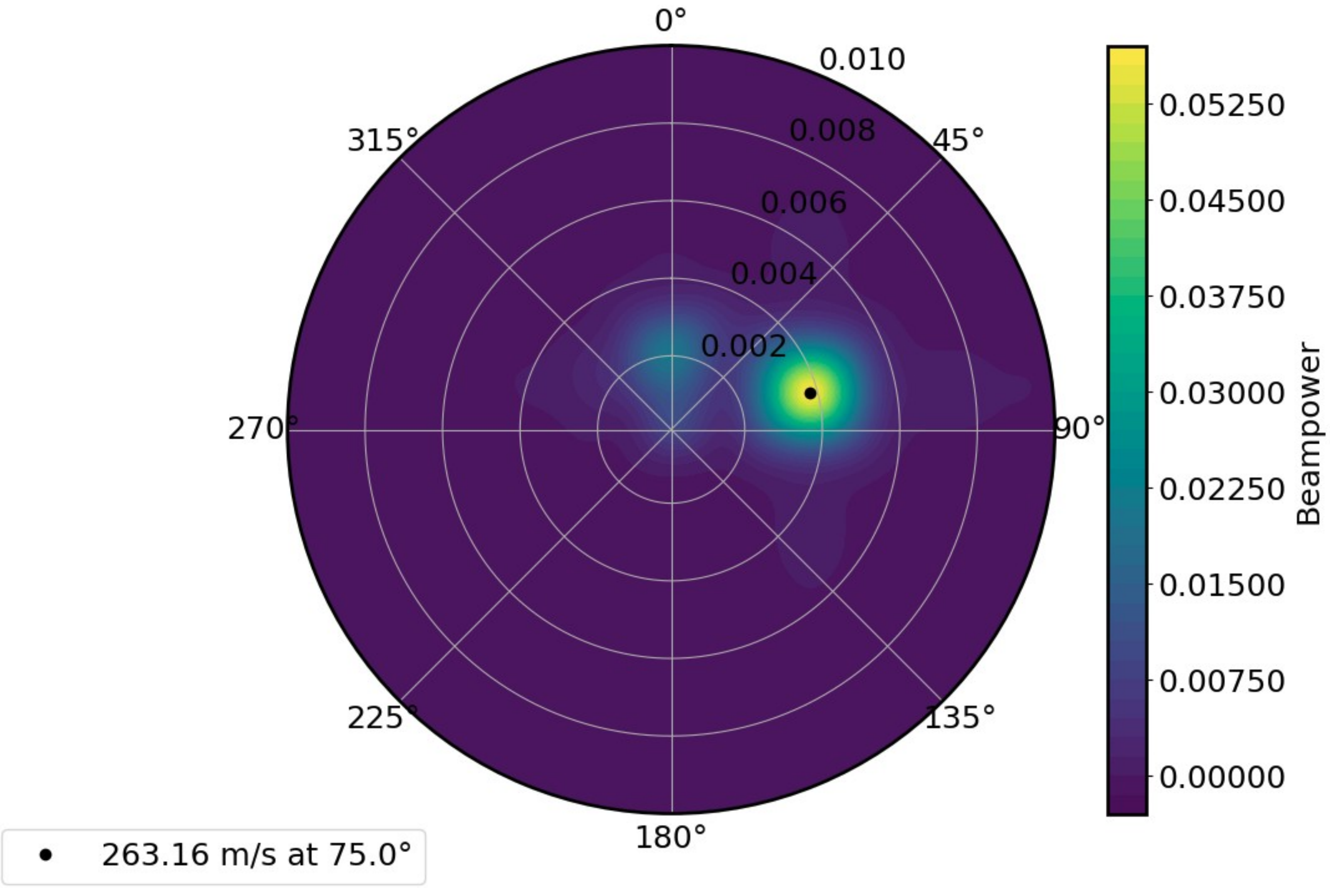


Kayen et. al., (2013)

Changes in Noise Conditions



Changes in Noise Conditions



Depth of Measurements

3.2. Investigation depth

The diffuse propagation between two sensors, represented by the CCF, involves body and surface waves. These waves, that mutually convert due to heterogeneities beneath the free surface (Shapiro et al., 2000; Larose et al., 2005; Margerin et al., 2009), exhibit very different sensitivity depths (Obermann et al., 2013b). This section investigates the contributions of body and surface waves to the apparent dv/v, depending on the depth and properties of the medium.

The surface waves considered in the literature and in this review are mostly Rayleigh waves, because vertical sensors are generally used. In a multilayer terrain, the phase velocity of these waves depends on their frequency—they are dispersive. The investigation depth z_{max} of Rayleigh waves—which is generally shallower than body waves—is approximately one third of the maximum wavelength (e.g., Park et al., 1999). The maximum wavelength depends on the phase velocity at the lowest

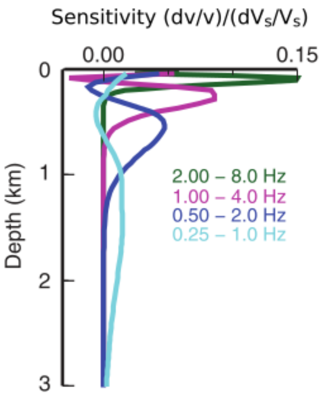
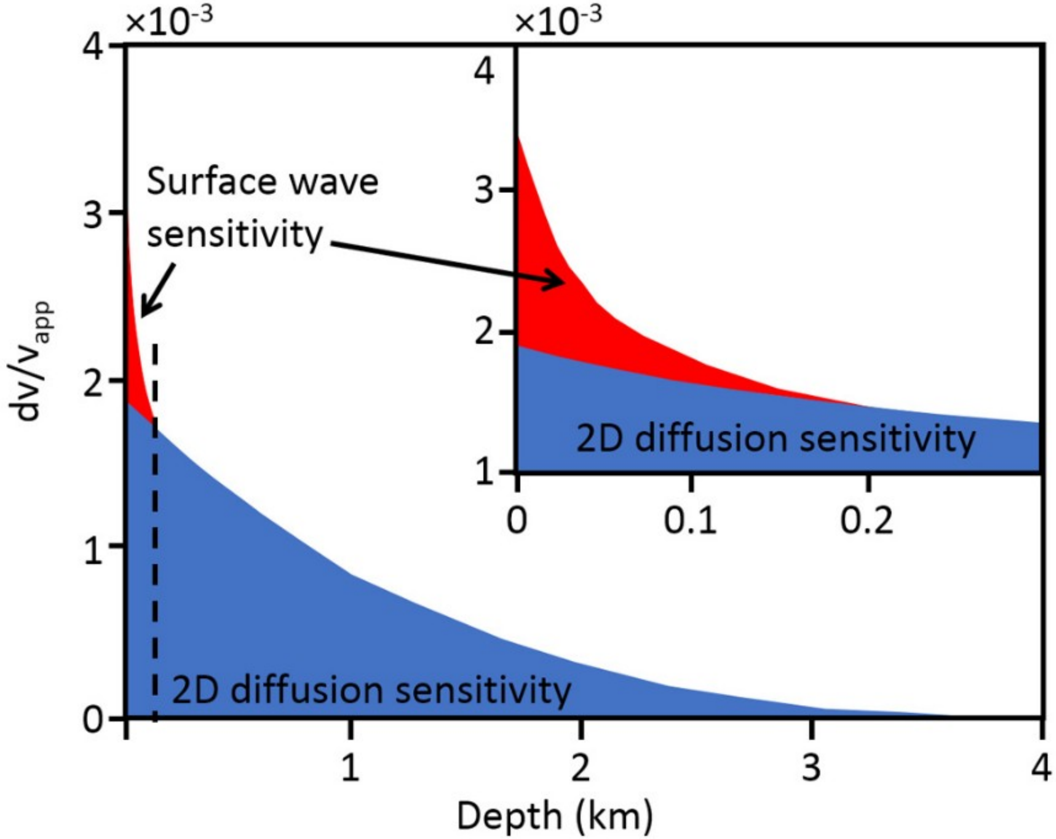


Fig. 5. Example showing the sensitivity of the Rayleigh phase velocity to shear velocity perturbation dV_s over a thin layer, for various frequency ranges, computed for the Deep Heat Mining Project in Basel, Switzerland. Adapted from (Hillers et al., 2015a, b).

Le Breton et. al., (2021)



Obermann et. al., (2013)

Conclusions

Seismic interferometry is a cost effective method to monitor internal changes in tailings dams in real-time to provide early warning of potential failures.

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