Modelling flint acoustics for detection of submerged Stone Age sites

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Outline

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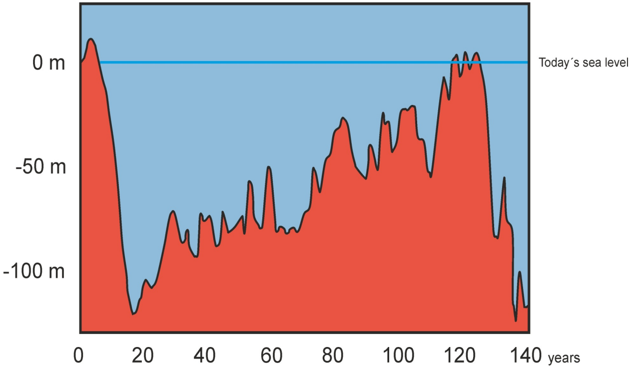
1. Submerged cultural heritage and environment
2. Acoustic methods for submerged Stone Age sites detection
3. Basis for the development of a new acoustic method
4. Finite-element time-domain modelling
5. Conclusion and discussion

Submerged cultural heritage and environment

Today, the oceans to a higher and higher degree become part of the industrial zone – with consequences for the submerged environment, cultural heritage, and the environmental information linked to the cultural heritage sites.

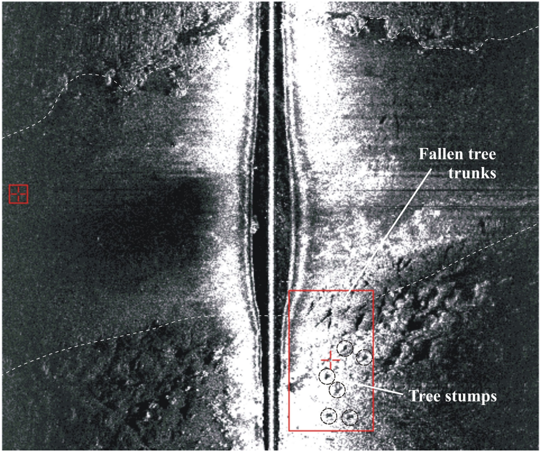
Submerged cultural heritage and environment

The average sea level 140000 years back. A large number of Stone Age sites will be found close to the earlier sea shores.



Submerged cultural heritage and environment

Side scan of sea floor with 7000 years old tree stumps and fallen tree trunks about 5 m deep from the submerged cultural landscapes in Denmark.

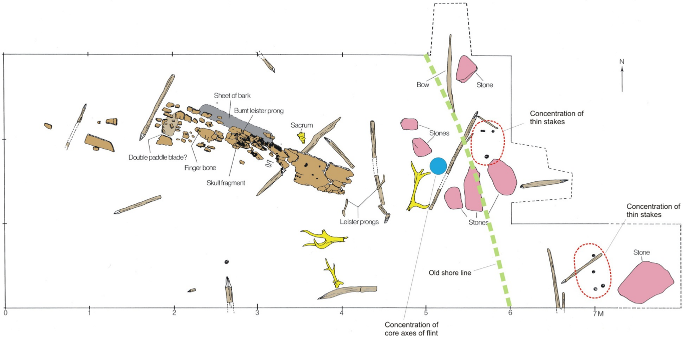


Some archaeological sites around Denmark

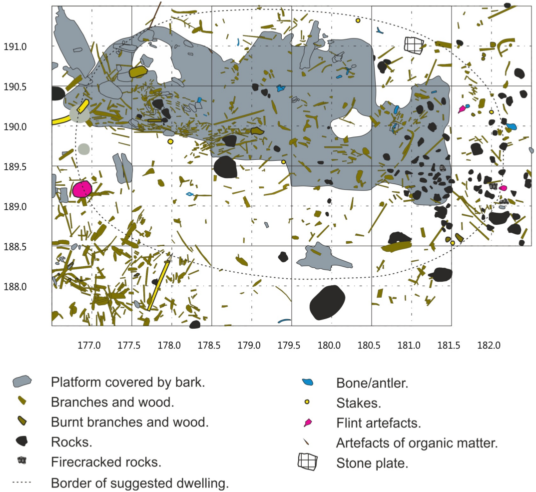
Picture from the 1930s of dredger crew having problems with roots from the submerged Stone Age forests.

Submerged cultural heritage and environment

7000 years old grave excavated 4.5 m deep at the extensive submerged Stone Age settlement Møllegabet, Denmark.

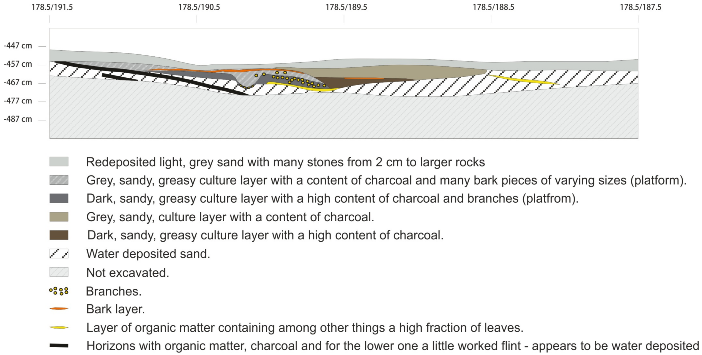


Submerged cultural heritage and environment



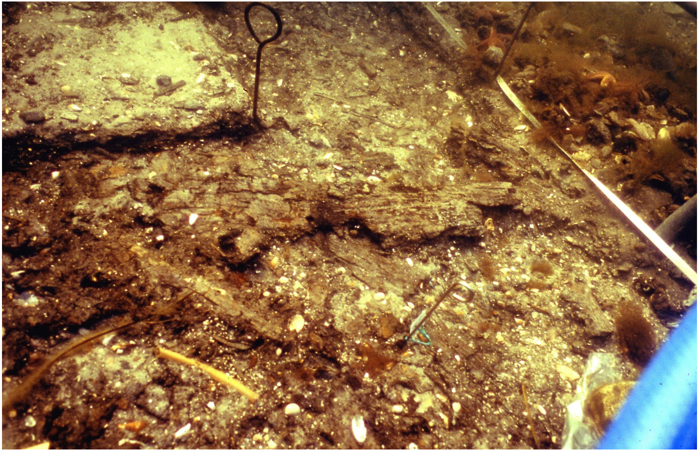
An excavated 7000 years old Stone Age dwelling, 4.5 m deep from the large submerged Stone Age site Møllegabet.

Submerged cultural heritage and environment



Section through the excavated dwelling-pit from Møllegabet with bark-covered platform etc.

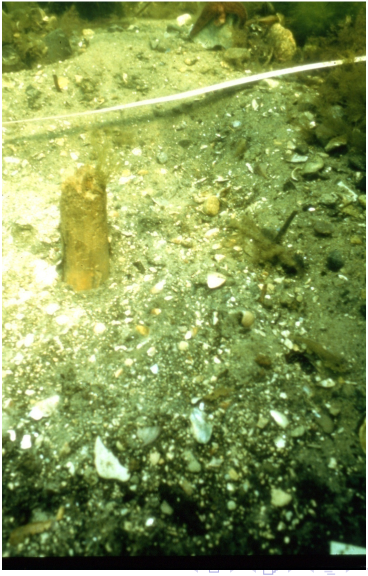
Submerged cultural heritage and environment



The preserved bark layer found on the platform of the excavated dwelling at Møllegabet.

Submerged cultural heritage and environment

The remains of a wall stake of the dwelling still standing at its periphery.



Submerged cultural heritage and environment

DNA remains are preserved well under cold and saline conditions – from blood, other body liquors, fat, etc. The DNA particles simply bond to the sediment particles.

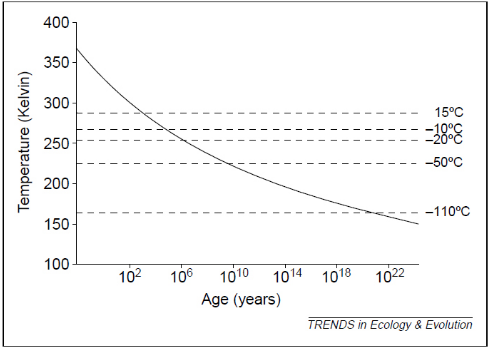


Figure 2. Long-term survival of 100 bp of DNA as a function of temperature. The calculations are based upon a genome size of 3.0×10^6 bp, the Arrhenius equation and depurination kinetics of Lindahl and Nyberg [39] (i.e. a depurination rate of 4×10^{-9} sites sec^{-1} at 70 °C, pH 7.4, and a constant activation energy of 31 kcal mol^{-1}). We have simplified calculations assuming damage is distributed equally over the genome at all purine sites.

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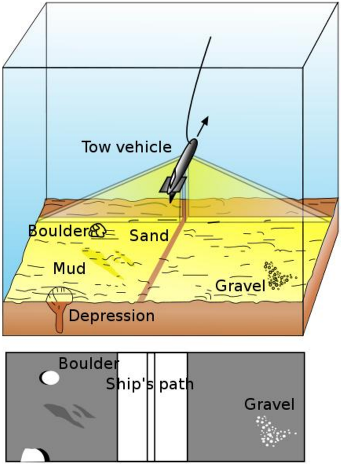
- Because the prehistoric hunters gathered useful species from the environment in their settlements & the conditions of preservation seems good in the saline and relatively cold sea floor sediments, the submerged Stone Age sites seem to represent a submerged archive of earlier environmental systems and dynamics.
- Therefore it is important to develop methods for mapping and managing this submerged cultural-environmental resource.

Outline

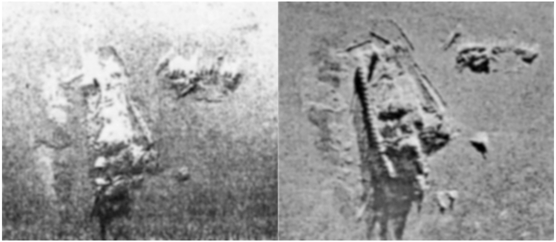
Existing acoustic methods

- Side scanners



Existing acoustic methods

- Side scanners
- Side scan of wreck (left) with post-processed improved image (right)



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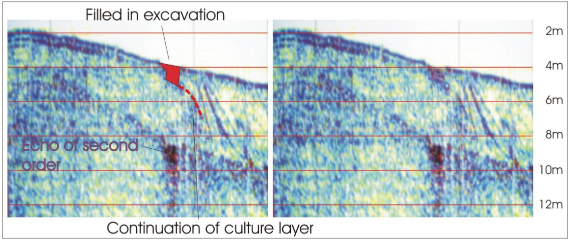
- Chirp-systems
- Chirp profile through the excavated submerged Blak II Stone Age site



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Basis for the development of new acoustic method

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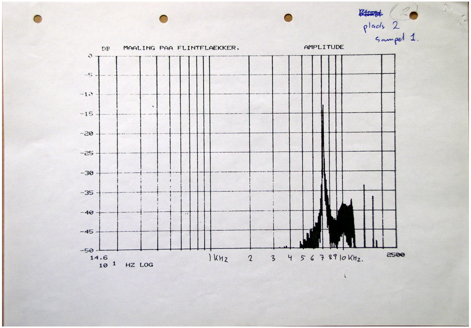

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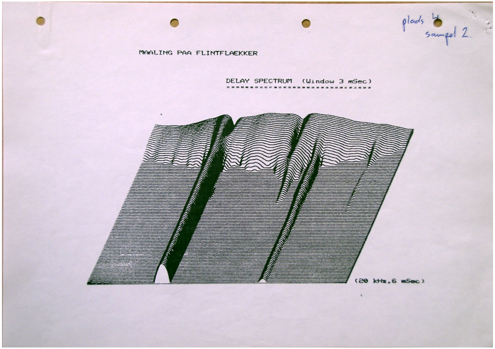

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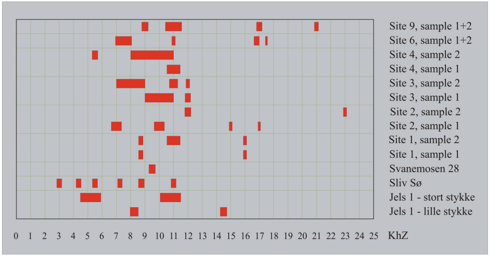
- Resonance spectrum of one flint piece measured by Rasmussen
- Time-delays of resonance signals
- Peaks of all tested flint blades and flakes resonance spectra



Use resonance for flint detection for ideal condition

The feasibility of using flint resonance for underwater Stone Age sites detection was considered with a simple acoustic model [Ren, *et al*], and

1. approximates a flint blade or flake as a thin plate with thickness h, width w and length l. For a flint that satisfies $l \gg w \gg h$, its resonance frequency can be written as:

$$f = \frac{m}{2l}\sqrt{\frac{E}{\rho}},$$

where E and ρ are the Young's modulus and density of the flint material, respectively, and $m = 1, 2, 3$, etc.

2. uses Wavelet transform and frequency domain wavelet transform to extract resonance features;

3. discriminates flint pieces from other scattering objects with the extracted resonance feature.

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- In a complex, three-dimensional, range-dependent, layered, heterogeneous medium with fluid (acoustic) and sediment (elastic) layers

Outline

Time-domain modelling of acoustic wave propagation

The elasto-acoustic, linearized wave equation is used to model the acoustic wave propagation problem:

$$\rho \mathbf{u}_{tt} - (\lambda + 2\mu)\nabla\nabla \cdot \mathbf{u} - \mu\Delta\mathbf{u} = f,$$

where $\mathbf{u} = (u_1, u_2, u_3)$ is the displacement in the x-, y- and z-direction, λ and μ are the Lamé coefficients, ρ is the medium density and f is an initial impulse that represents the acoustic source.

$$c_p^2 = \frac{\lambda + 2\mu}{\rho} \qquad \text{and} \qquad c_s^2 = \frac{\mu}{\rho},$$

where c_p is the pressure wave speed and c_s is the shear wave speed. An acoustic layer is obtained in the model by simply setting $\mu = 0$ locally.

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- Love, Stoneley and Raleigh waves along the interfaces

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- a zero pressure condition on the sea surface
- continuity conditions on the normal components of u and the stresses between layers
- absorbing condition on bottom layer and on lateral boundaries
- hydrophones are "simulated" by simply recording the solution at given points

Time-domain modelling of acoustic wave propagation

The flint detection problem here is formulated as

1. a source-detection problem that considers an individual flint, or a group of closely-spaced flints as a source of diffracted waves;

2. detect the rapid changes in the compressional and shear speed profiles: the outstanding characteristics of flints and other buried objects;

3. analyze the frequency content of the measured signals and identify the resonances of individual flints (typically between 10 kHz and 20 kHz) as measured in laboratory conditions.

The first two inverse problems can be formulated and solved by using an adjoint approach. [Hermand *et al*, 2006].

Direct modelling: finite element approach

Use a Spectral Galerkin Method (SEM) [Komatitsch, *et al* 2008], which has the advantages of:

- Greater accuracy and ability to deal effectively with smaller spatial scales with high degree (9th order) polynomial spatial approximation

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- Hexahedral elements that produce a diagonal mass matrix and thus significantly reduce the simulation cpu times needed for time-domain simulations
- Extremely efficient numerical model for acoustic-seismic wave propagation

Adapting the SEM

Interface with CAD software to treat variable sound speed profiles, highly accurate, 3D flint geometries, especially in advanced meshing, which:

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- respects all geometrical and property discontinuities
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- guarantees a consistent numerical resolution throughout the modelled region

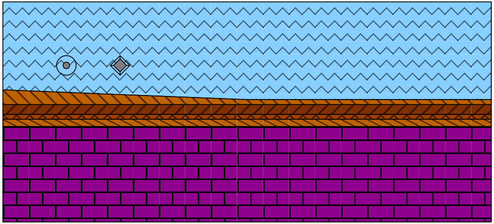
Geometry for 2D simulation

Realistic, 2D environment with 6 layers:

Sea water

Sand, Mud, Cultural layer, Sand

Moraine substrate

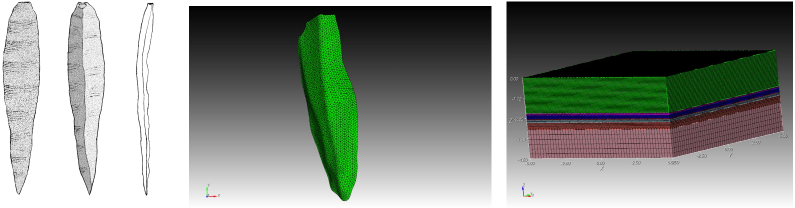


Source
is placed at the position of $x_s = 1.5$ m, $z_s = -1.5$ m

Horizontal array of 10 hydrophones (the rightmost one is shown)

$H_1, \ldots, H_{10}$, are placed at depth $z = -1.5$ m, and at positions from $x = 1.6$ m to $x = 2.6$ m with 10-cm intervals.

Advanced 3D meshing



(a) (b) (c)

(a) Flint flake geometry, (b) Mesh of flint and flake and (c) Mesh for the coastal environment.

Physical parameter values

Acoustic properties of typical flint material

Density	2300 kg/m^3
Compression speed	8433 m/s
Shear speed	5843 kg/m^3
Young's module	185 GPa
Poisson's Ratio	0.27

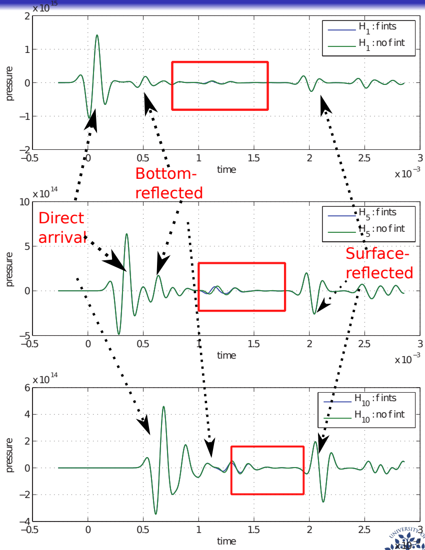
Bottom layer properties and the cultural layer that contains flint blades and flakes

Layer	Thickness (cm)	ρ (kg/m^3)	c_p(m/s)	c_s(m/s)	α_p(dB/λ)	α_s(dB/λ)
seawater	0 – 500 (200)	1000	1500	–	–	–
sand	10 – 25 (10)	1900	1650	110	0.8	–
mud	20 – 30 (20)	1500	1500	50	0.2	–
cultural	5 – 10 (5)	1500	1500	50	0.2	–
sand	15 – 50 (15)	1900	1650	110	0.8	–
substrate (moraine)	semi–∞	2100	1950	600	0.4	1.0

Results for individually spaced flints

Three flint pieces have lengths of $l_1 = 10$ cm, $l_2 = 12$ cm and $l_3 = 8$ cm and are centered at $x_1 = 1.55$ m, $x_2 = 1.8$ m and $x_3 = 2.1$ m. Their thickness is taken as 5 mm.

- Received time signal for hydrophone 1 (top), 5 (middle) and 10 (bottom) with arbitrary source frequency of 4.5 kHz



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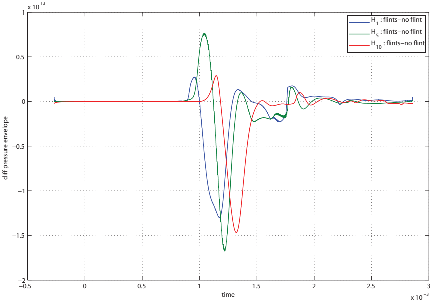
- Differences of the results of flints and no-flint envelopes



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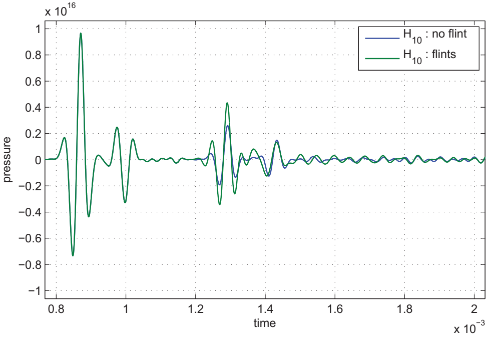
- Received time signal for hydrophone 1 (top), 5 (middle) and 10 (bottom) with arbitrary source frequency of 4.5 kHz
- Differences of the results of flints and no-flint envelopes
- Source frequency near flint resonance of 14.0 kHz for $l_1 = 10$ cm as calculated by $f = \frac{m}{2l}\sqrt{\frac{E}{\rho}}$



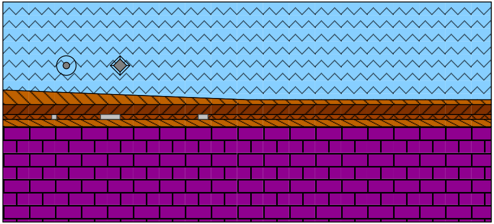
Geometry for 2D simulation for flint clusters

Three flint clusters are modeled by a simplified, rectangular geometry, have horizontal extensions of $l_1 = 10$ cm, $l_2 = 53$ cm and $l_3 = 21$ cm and are centered at positions $x_1 = 1.1$ m, $x_2 = 2.4$ m and $x_3 = 4.3$ m are placed in the cultural layer. Their thickness is 5 cm.

Sea water

Sand, Mud, Cultural layer, Sand

Moraine substrate

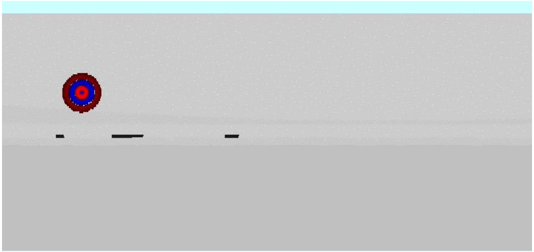


The geometry for source and receiver is the same with that flint blade simulation

Results for flint clusters

Animation of pressure sound propagation for source frequency of 5 kHz with 3 flint clusters embedded in the cultural layer:

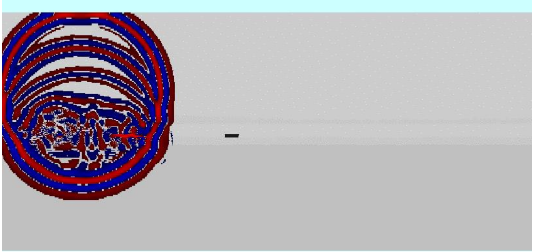
- t=0.0005 s



Results for flint clusters

Animation of pressure sound propagation for source frequency of 5 kHz with 3 flint clusters embedded in the cultural layer:

- t=0.0005 s
- t=0.0010 s



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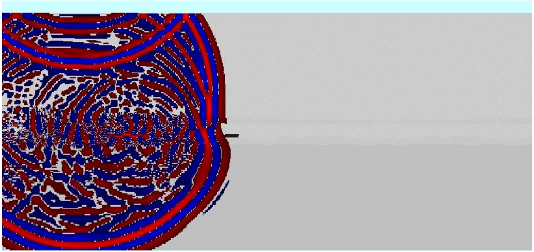

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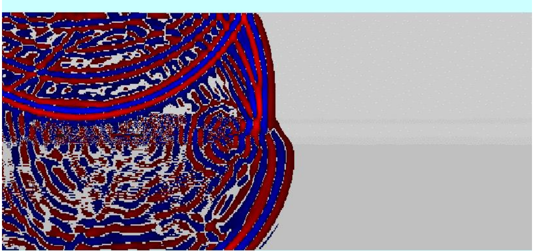

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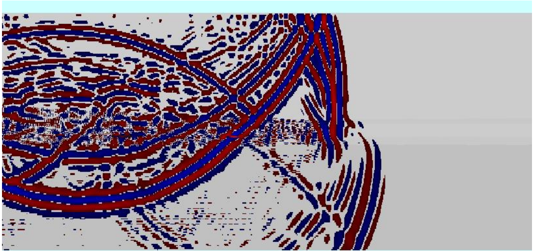

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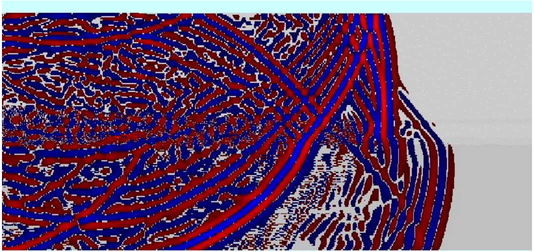
- t=0.00325 s



Results for flint clusters

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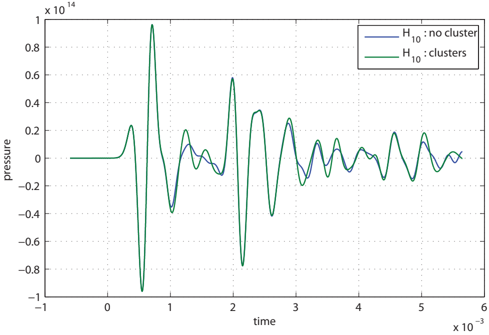
- Result for source frequency of 2 kHz for hydrophone 10



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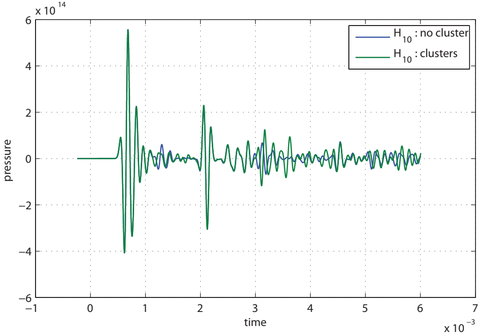
- Result for source frequency of 2 kHz for hydrophone 10
- Result for source frequency of 5 kHz for hydrophone 10



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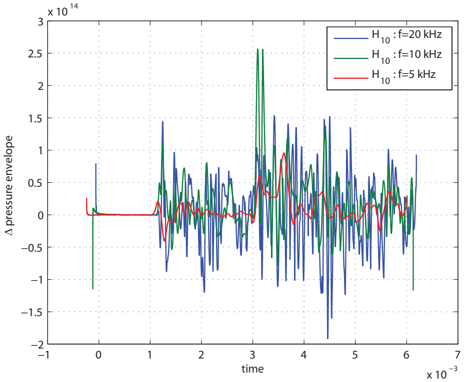
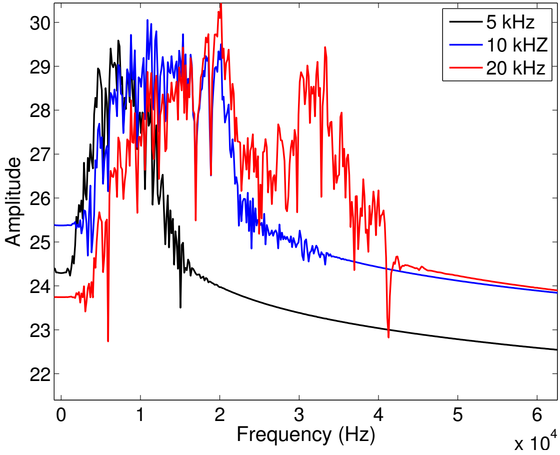
- Result for source frequency of 2 kHz for hydrophone 10
- Result for source frequency of 5 kHz for hydrophone 10
- Differences of the results of flint and no-flint clusters envelopes for hydrophone 10 and the source frequencies of 5, 10 and 20 kHz



Spectra of difference signals



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- 2D acoustic simulations show that the presence of individually-spaced flints or clusters embedded in the cultural layer is detectable;
- These promising numerical results are a first step toward solving the 3D inverse problem of flint detection and localization.

Thank you for your attention !