Accurate and Efficient Viscoelastic Finite-difference Modelling for Analysis of Seismic Wavefields Applied to On-Site Inspection

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Outline

key aspects of our FD modelling

set of structural models
for the vertical emplacement

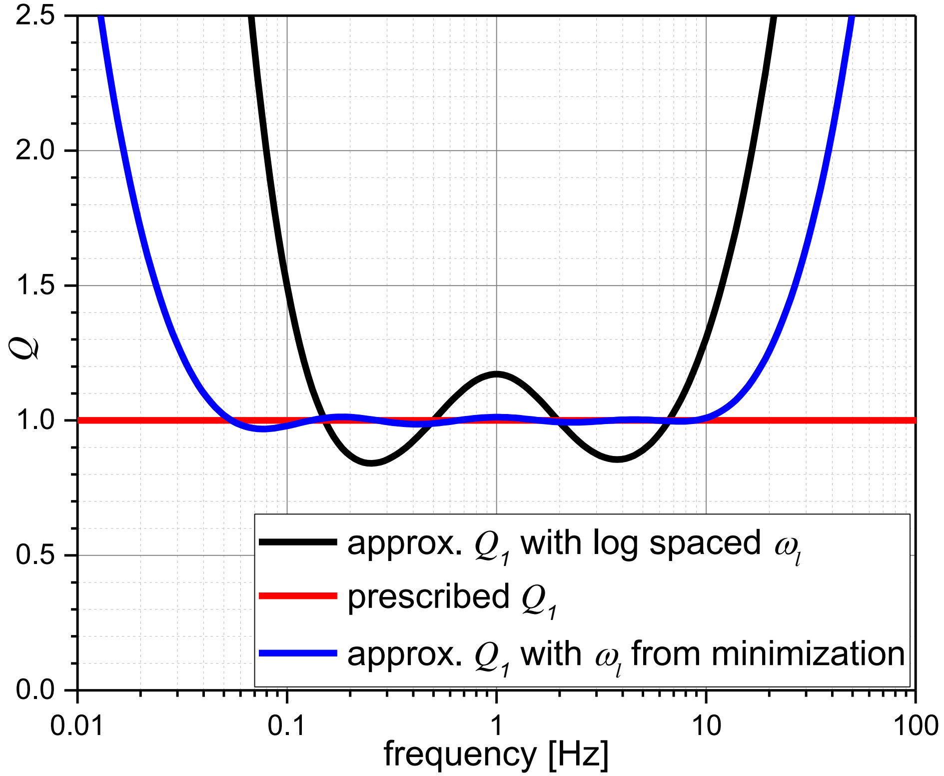
first simulations

key aspects of our FD modelling

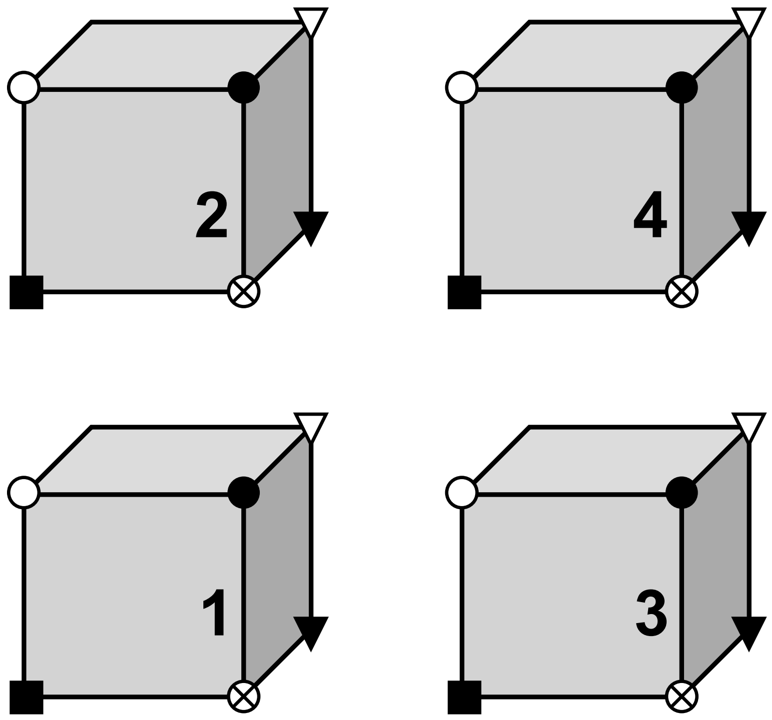
- realistic rheological model
  ~ GMB EK/GZB with material-independent memory variables
  and coarse graining

realistic rheological model

GMB EK/GZB with material-independent memory variables and coarse graining



4 relaxation frequencies



numbers
l = **1**,…,**4** indicate
l–th relaxation frequency

each grid cell contains
all anelastic coefficients

but

only **one** memory variable
for
each stress-tensor component

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  ~ TE (2,4) VS SG FDS in weakly heterogeneous media
  ~ TE-DRP (2,4) VS SG FDS in high-contrast media

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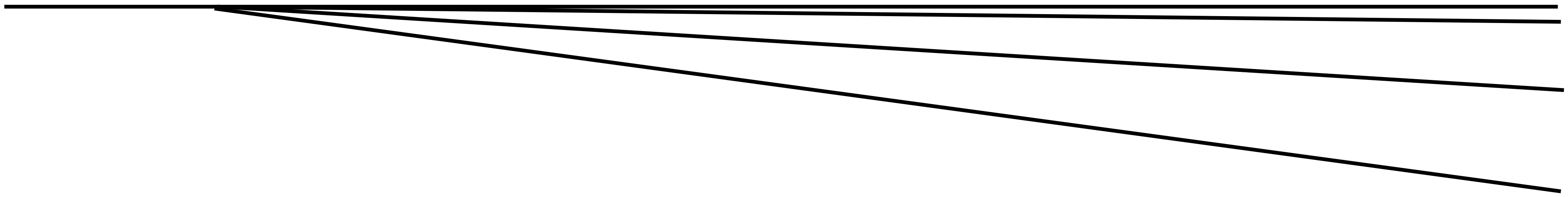
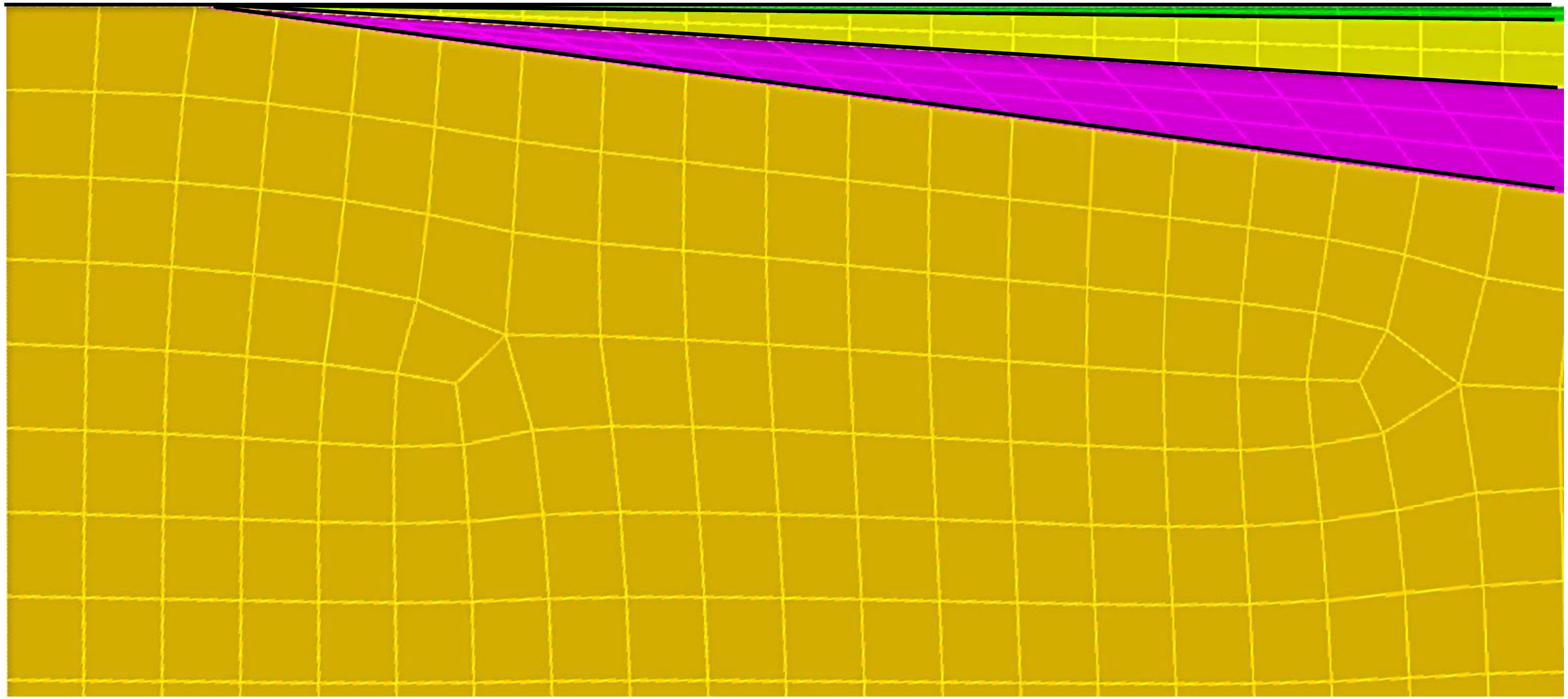
  ~ volume orthorhombic averaging

sufficiently accurate representation of the boundary conditions at a material interface



sufficiently accurate representation of the boundary conditions at a material interface



Florent De Martin EFISPEC3D available at http://efispec.free.fr

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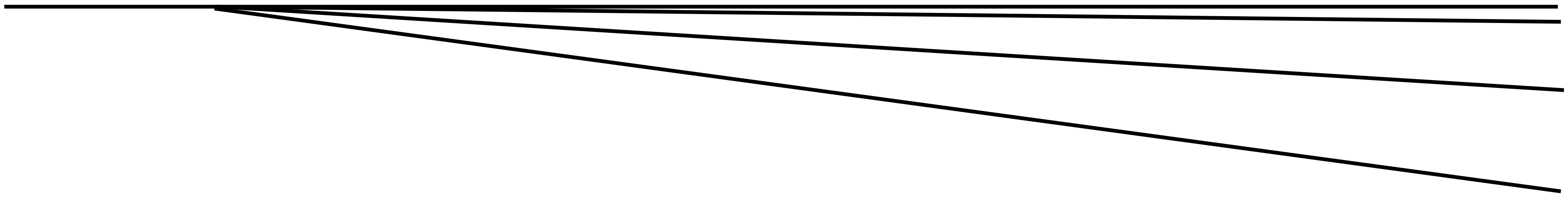

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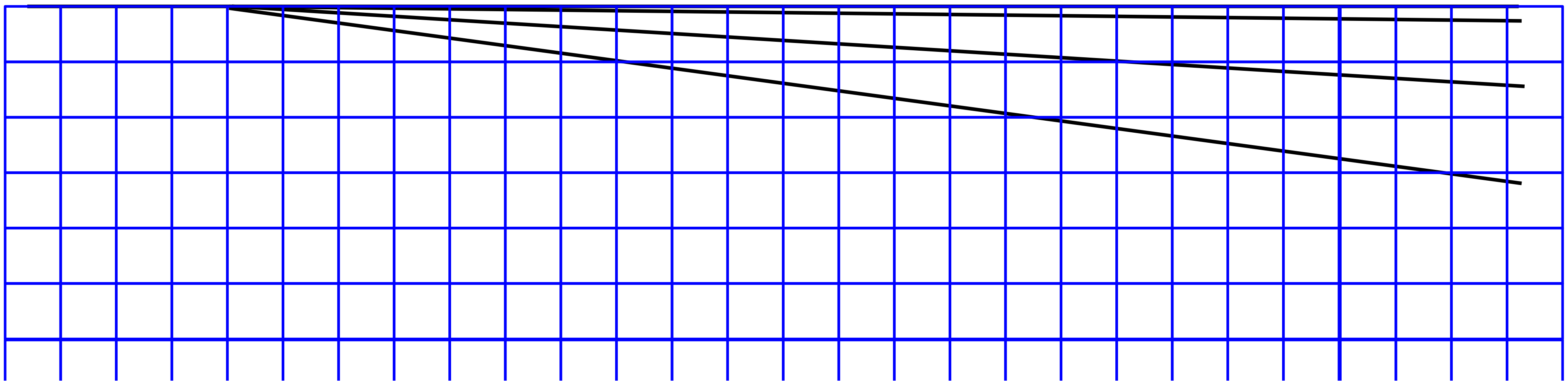

SPEM minimum node-to-node distance: 0.1 m
FDM grid spacing: 5.0 m

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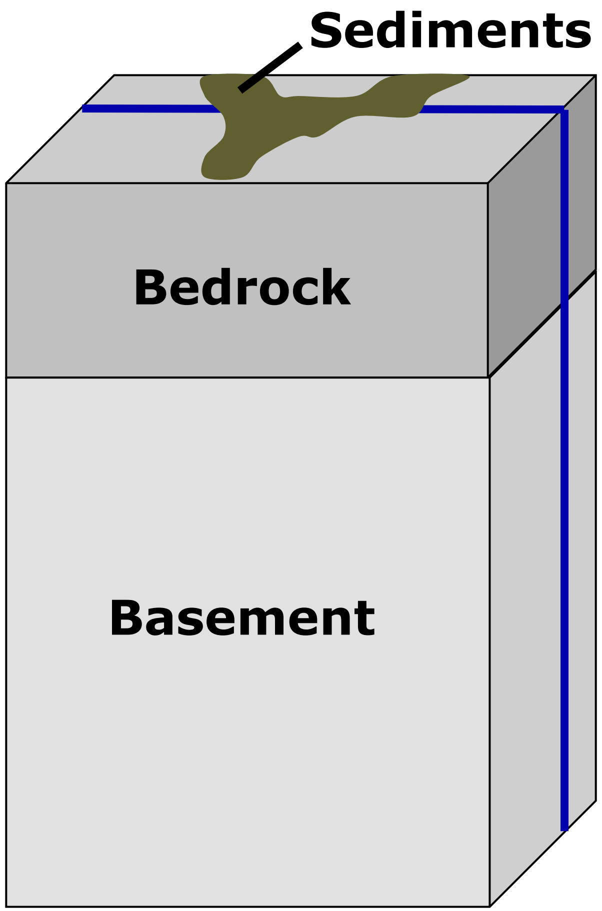
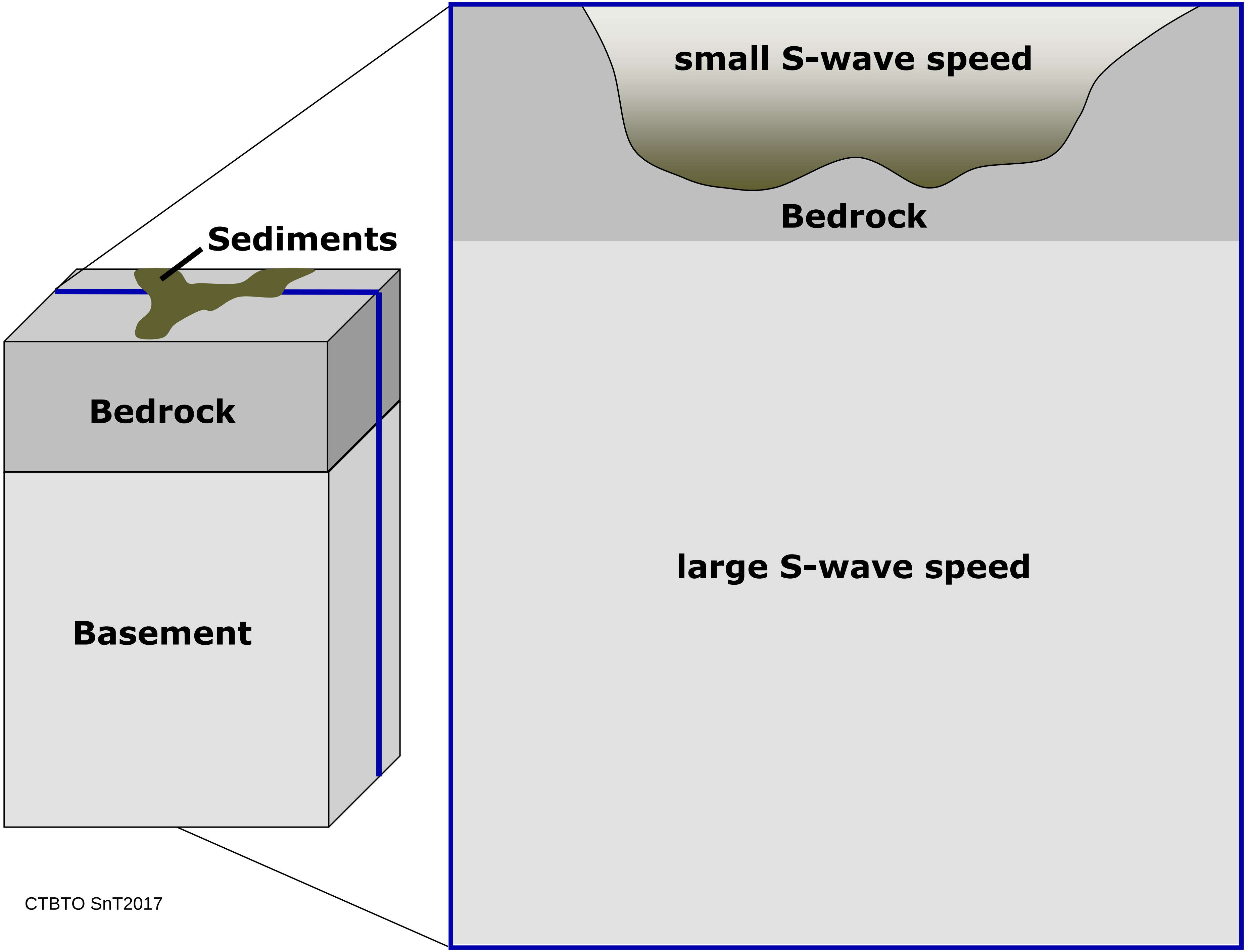
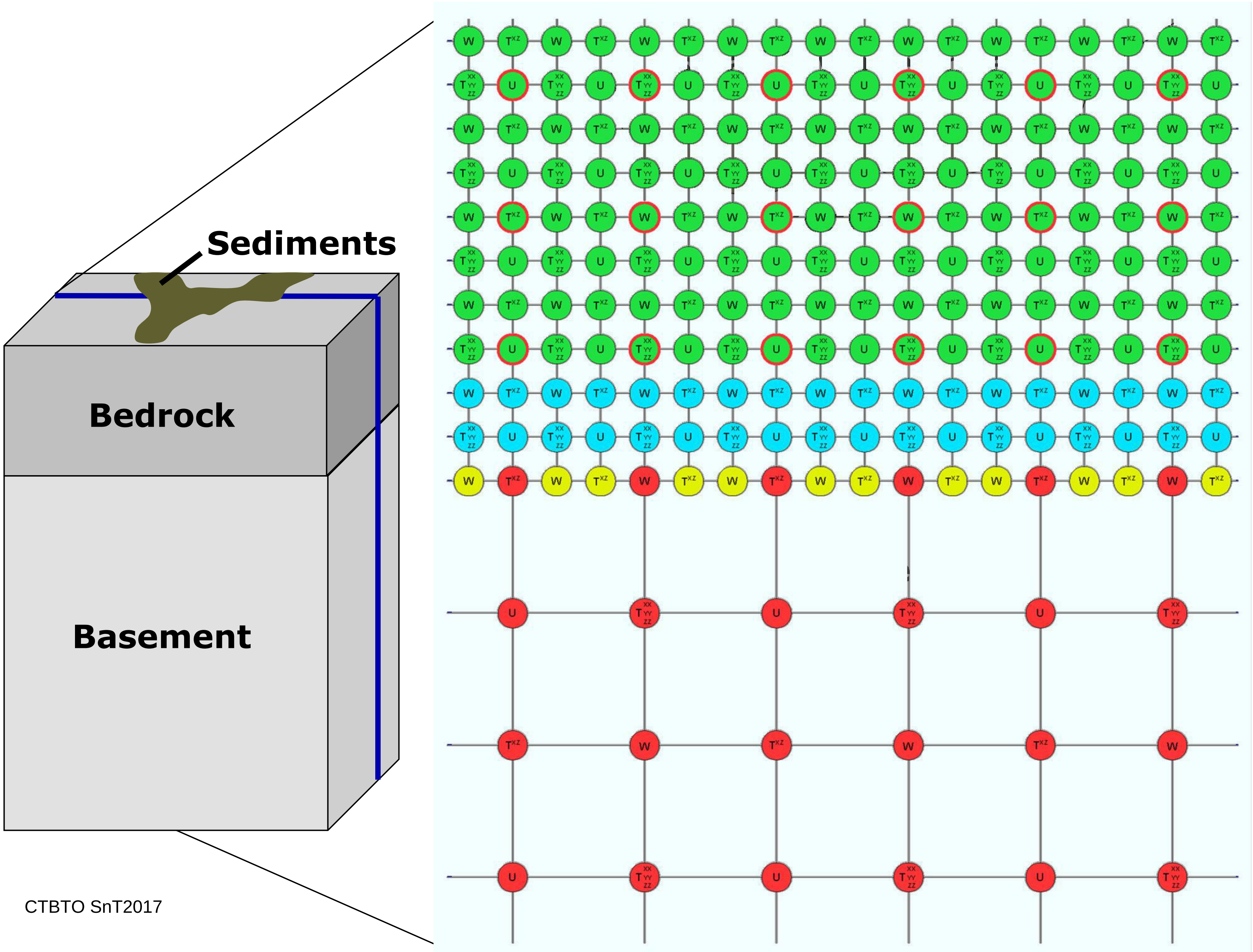
- efficient grid
  ~ arbitrary spatial discontinuous grid – stable algorithm

efficient grid

arbitrary spatial discontinuous grid




small S-wave speed
Sediments
Bedrock
Bedrock
Basement
large S-wave speed
CTBTO SnT2017



arbitrary-discontinuous staggered grid

$$\frac{h_{\mathrm{COARSE}}}{h_{\mathrm{FINE}}} = \text{odd number}$$

we numerically tested ratios up to 25

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- accurate and efficient non-reflecting grid boundaries
  ~ PML

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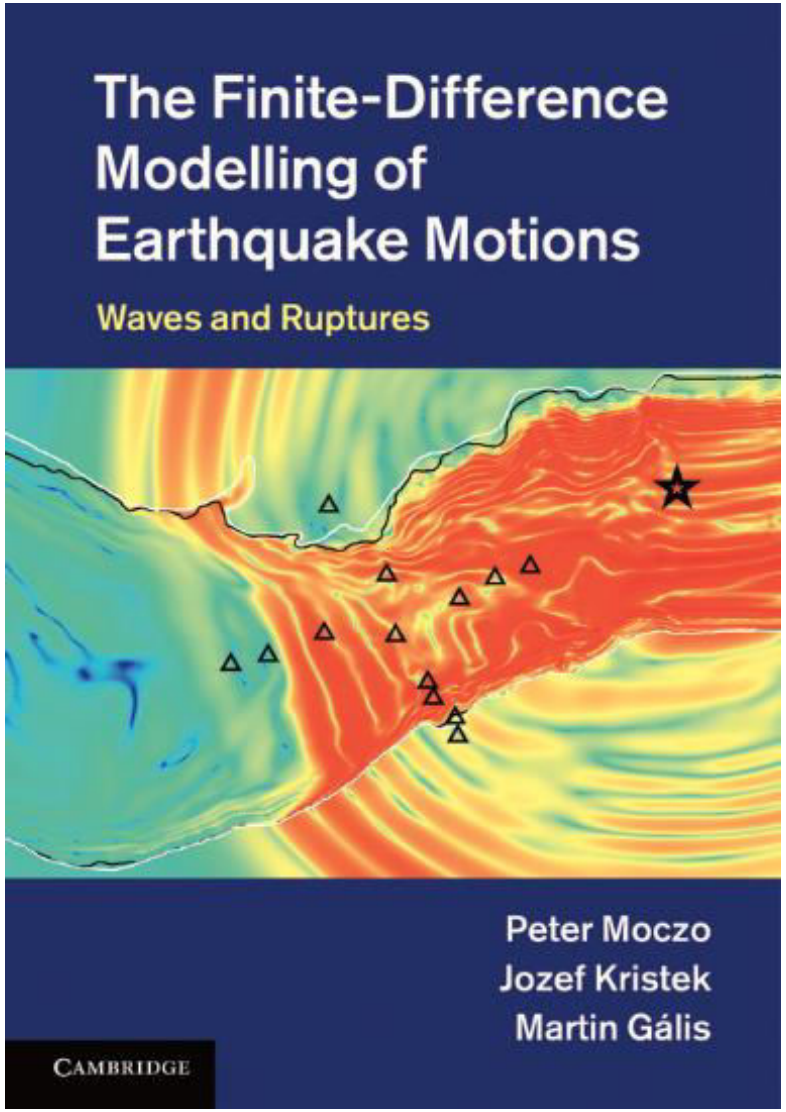
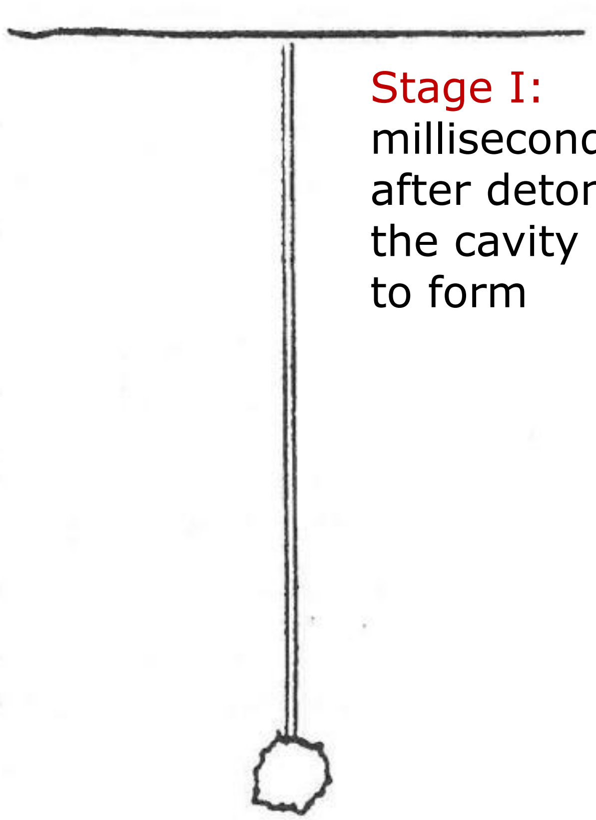


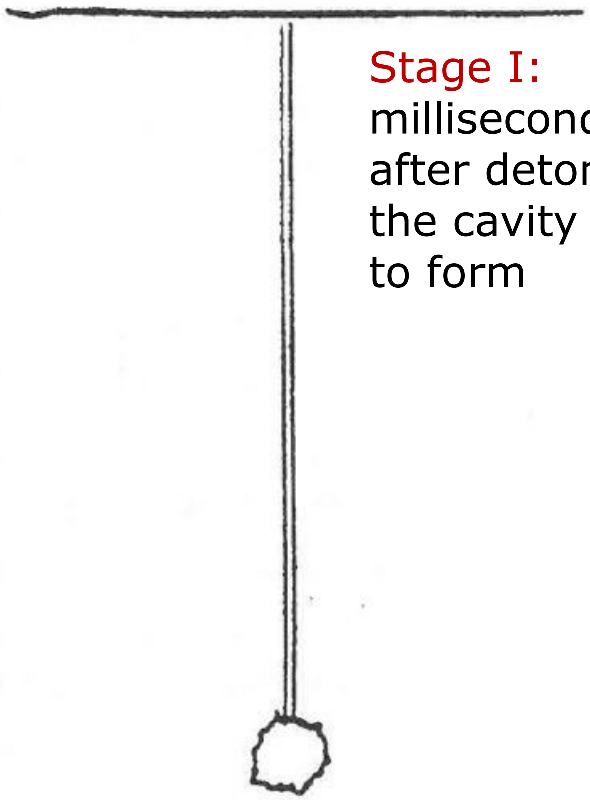
computer code available at
www.nuquake.eu/FDSim
www.cambridge.org/Moczo

properties of geological environment
after contained underground nuclear explosion



Stage I:
milliseconds
after detonation,
the cavity begins
to form

properties of geological environment after contained underground nuclear explosion



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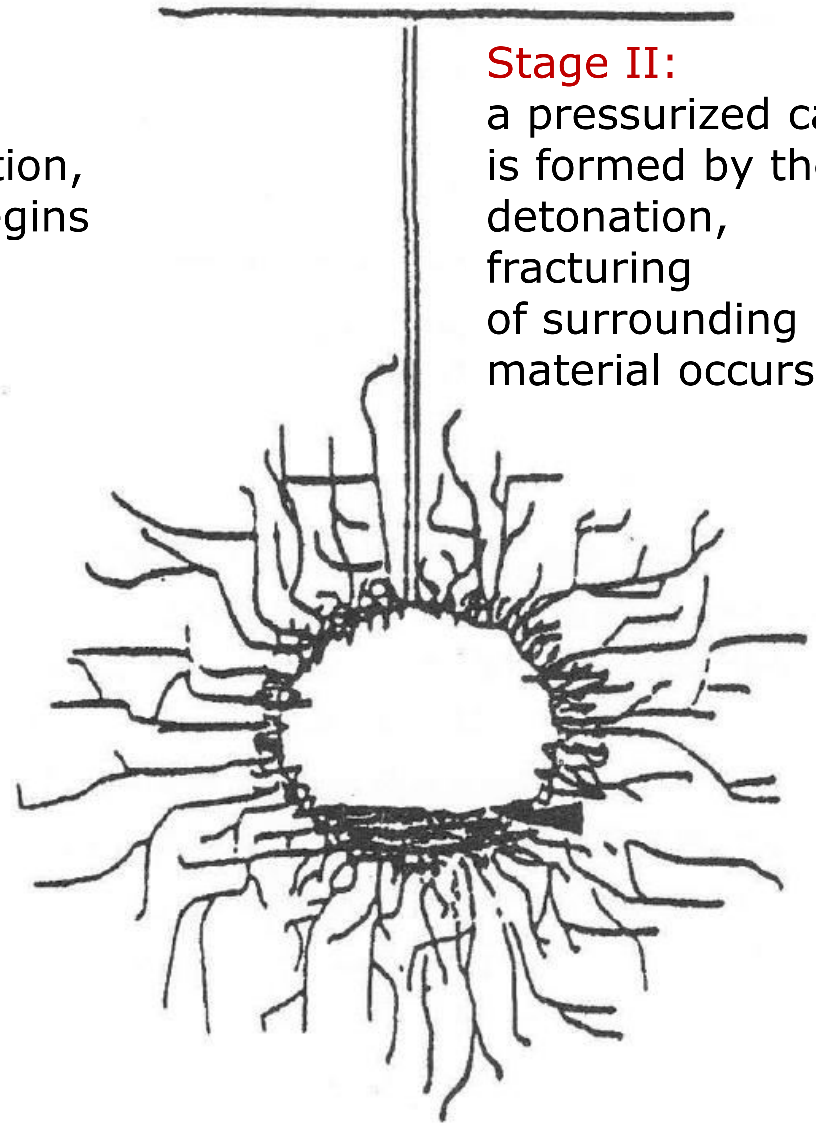
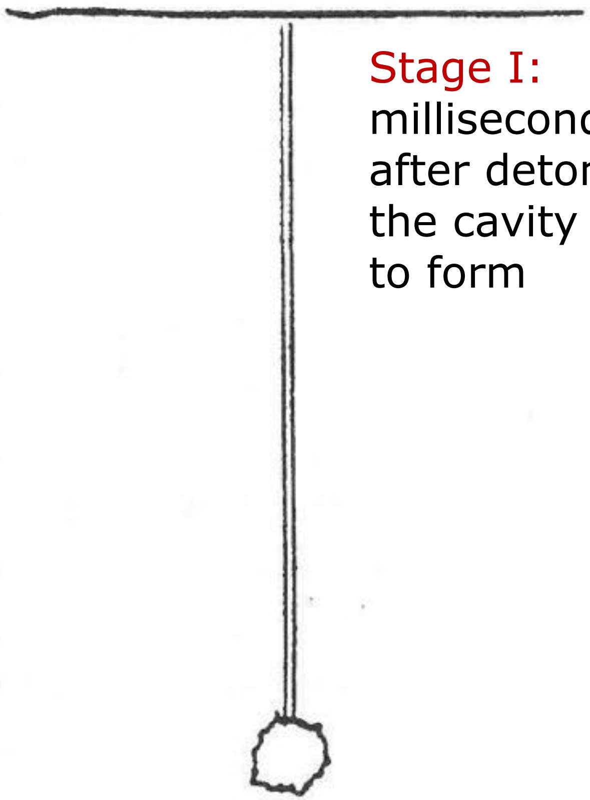


Stage II:
a pressurized cavity is formed by the detonation, fracturing of surrounding material occurs

properties of geological environment after contained underground nuclear explosion



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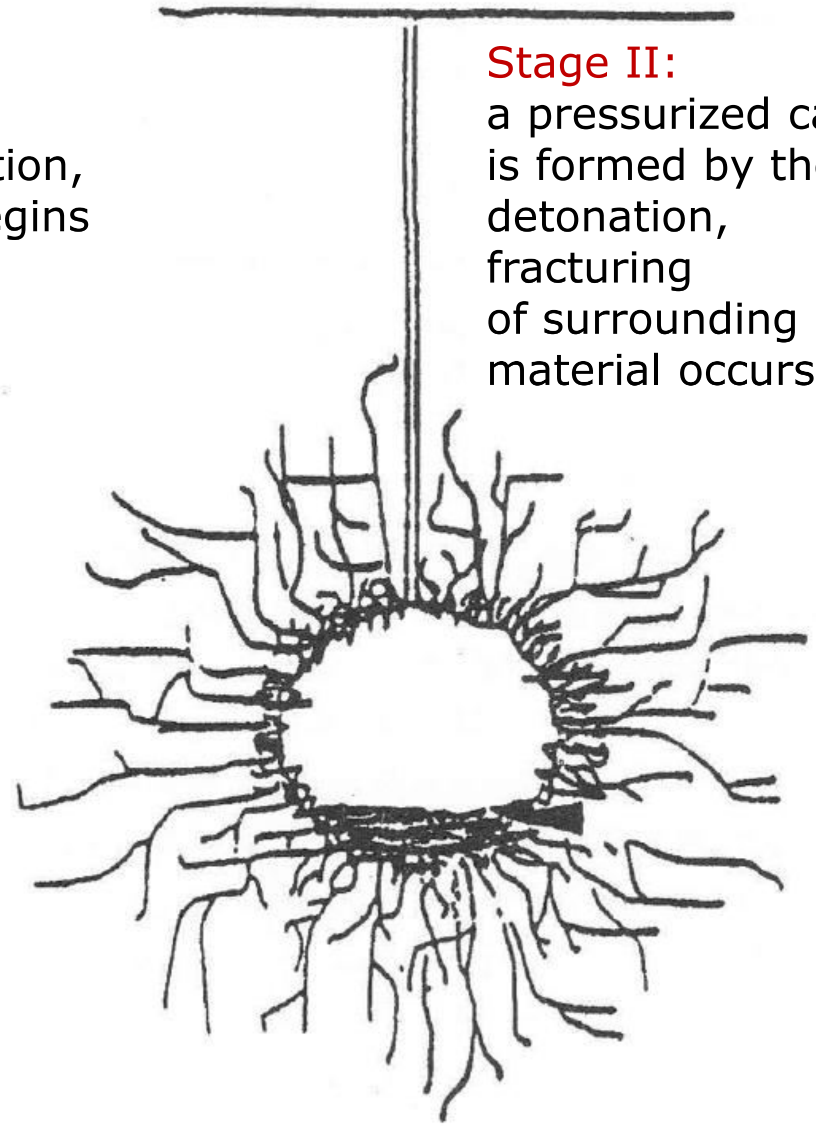

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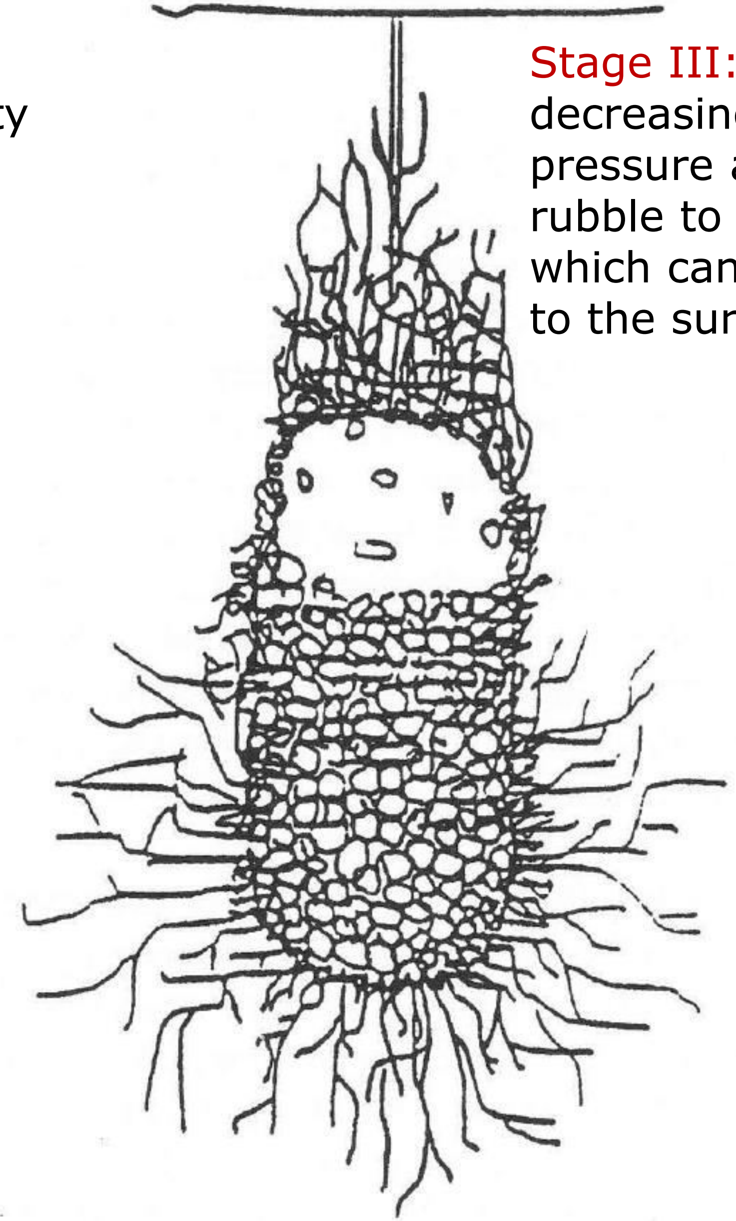
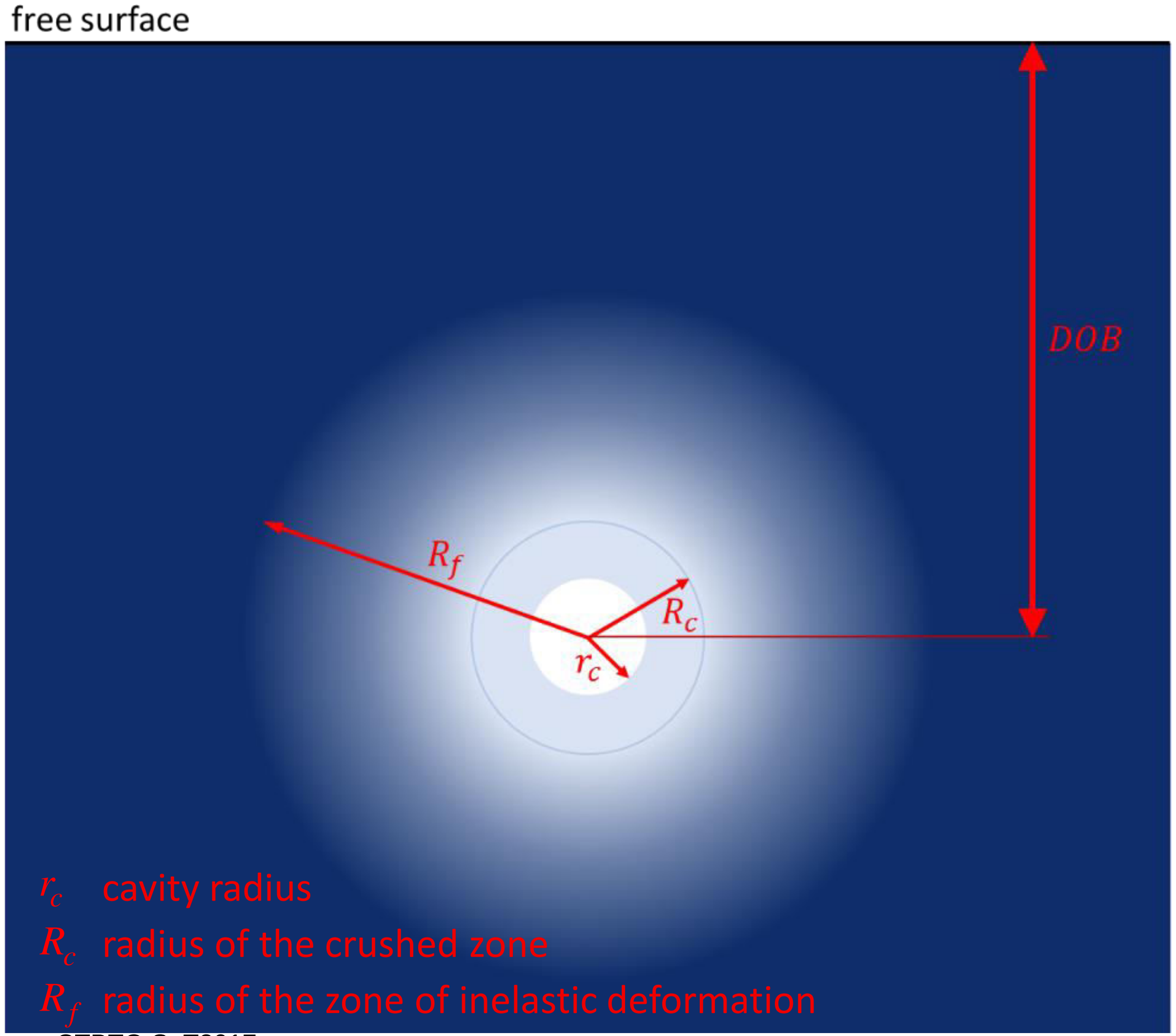


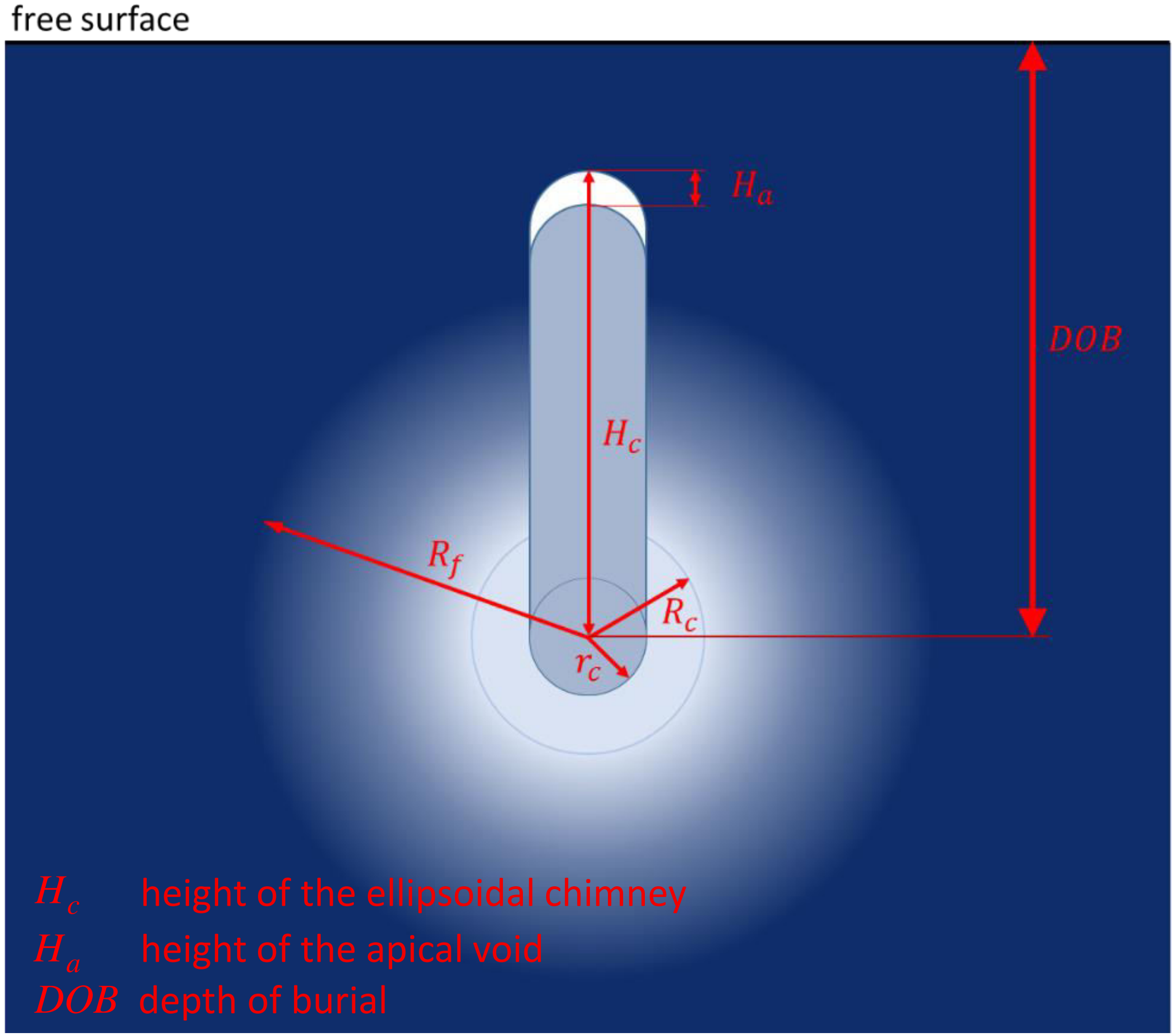
Stage III:
decreasing pressure allows rubble to fill voids which can migrate to the surface

set of structural models
for the vertical emplacement

cavity without chimney (for plastic rock)



cavity with chimney filled with rubble + apical void



set of structural models
for the vertical emplacement

4 essential types of preshot media

- tuff
- alluvium
- rock salt
- granite

2 different yields of explosion

low-yield (1 kt)

high-yield (10 kt)

with **viscoelastic attenuation**

$$Q_S(f) = \frac{V_S}{10}$$

$$Q_\kappa(f) = \infty$$

2 different depth of burial

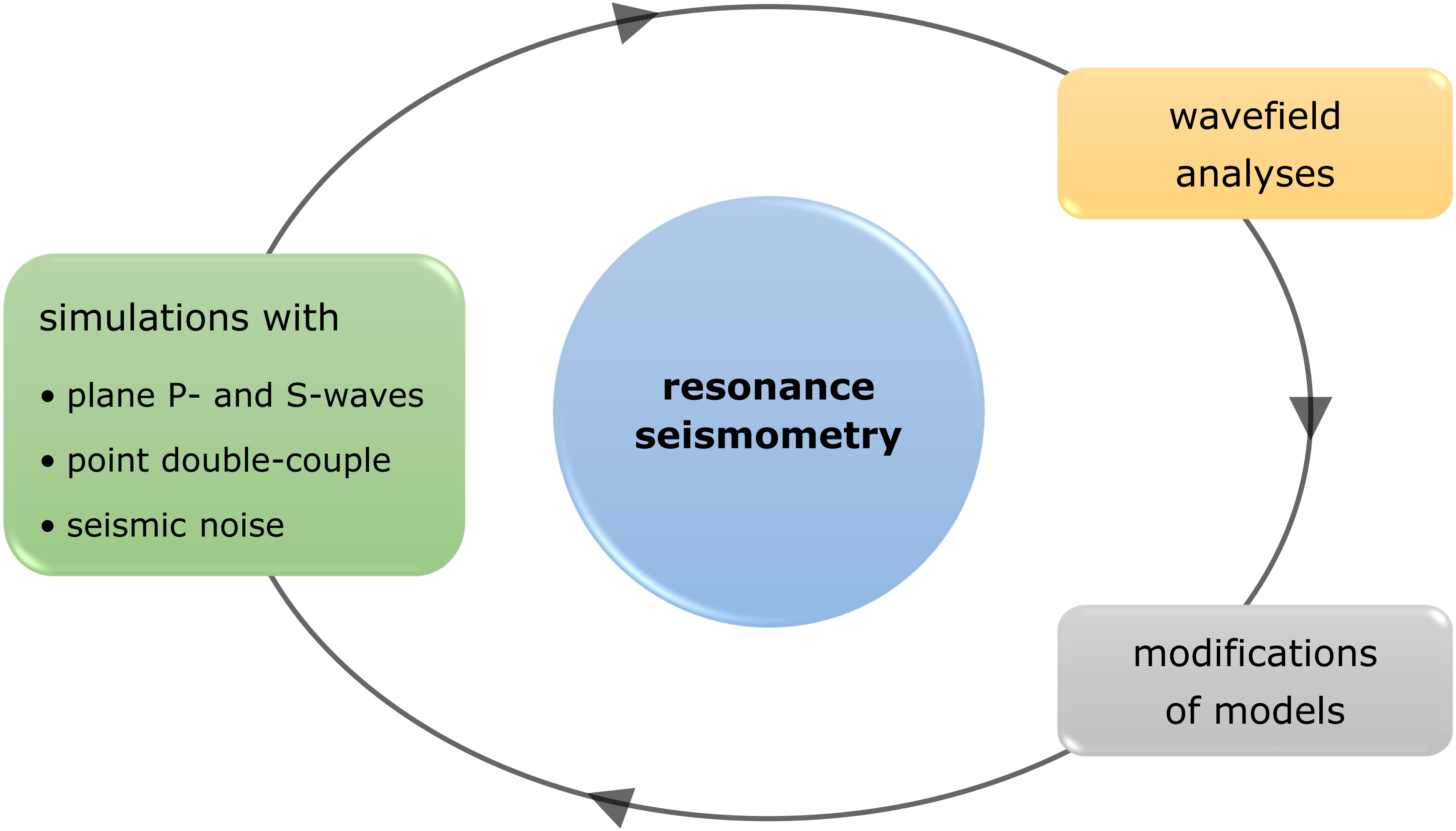
minimal

2 x minimal

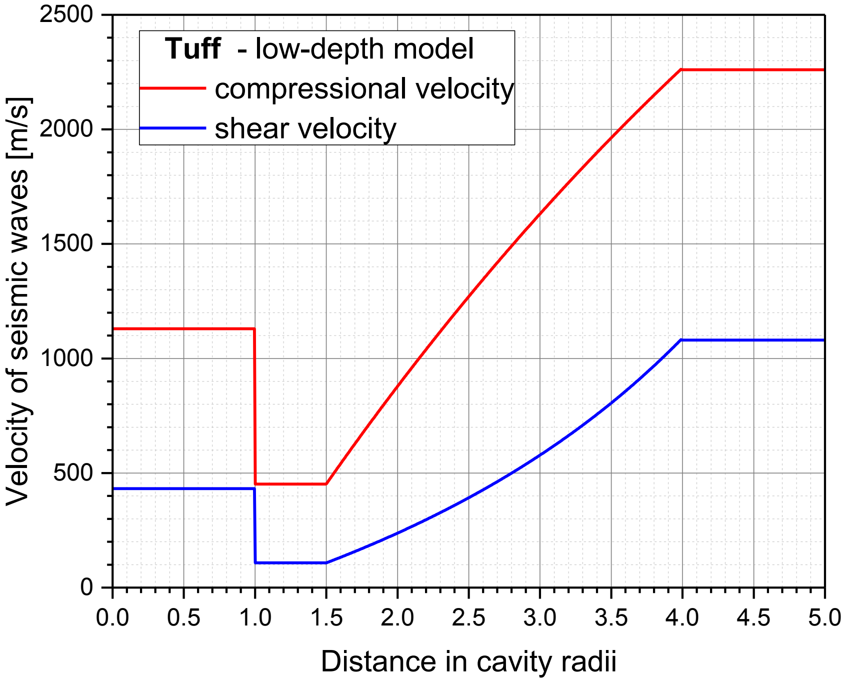
in total: **16 basic structural models**

material	yield	depth of burial	r_c	R_c	R_f	H_c	H_a
tuff	low	180	16.9 ± 0.8	25.4 ± 1.1	67.5 ± 3.0	138 ± 20	9.7 ± 1.4
		360	15.6 ± 1.8	23.4 ± 2.7	56.4 ± 6.5	127 ± 18	8.9 ± 1.3
	high	280	33.4 ± 2.6	50.2 ± 3.9	125.9 ± 9.8	256 ± 16	18.0 ± 1.1
		560	30.9 ± 5.2	46.4 ± 7.8	102 ± 17	237 ± 15	16.6 ± 1.0
alluvium	low	180	14.6 ± 2.2	22.0 ± 3.3	118 ± 18	120 ± 17	8.4 ± 1.2
		360	13.4 ± 1.5	20.1 ± 2.3	88.1 ± 9.9	109 ± 15	7.6 ± 1.1
	high	260	29.0 ± 2.6	43.5 ± 3.8	212 ± 19	222 ± 14	15.6 ± 1.0
		520	26.5 ± 1.4	39.8 ± 2.1	153.6 ± 8.1	204 ± 12	14.2 ± 0.9
granite	low	180	11.5 ± 2.4	22.9 ± 4.8	196 ± 41	75 ± 12	5.2 ± 0.8
		360	10.5 ± 2.1	21.0 ± 4.2	142 ± 28	62 ± 18	4.4 ± 1.3
	high	260	22.7 ± 3.2	45.3 ± 6.5	344 ± 49	173 ± 25	12.1 ± 1.8
		520	20.8 ± 3.0	41.6 ± 6.0	242 ± 35	143.2 ± 8.0	10.0 ± 0.6
rock salt	low	180	14.8 ± 0.9	22.2 ± 1.4	188 ± 12	-	-
		360	13.7 ± 1.7	20.5 ± 2.5	130 ± 16	-	-
	high	260	29.5 ± 2.0	44.3 ± 3.0	323 ± 22	-	-
		520	27.3 ± 4.3	40.9 ± 6.4	219 ± 34	-	-

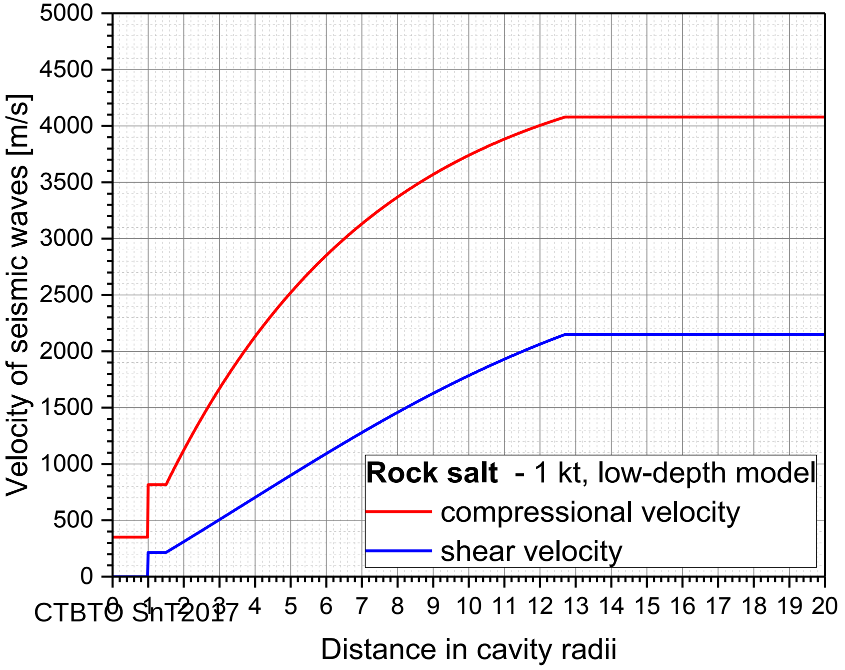
workflow


wavefield analyses
modifications of models
simulations with
• plane P- and S-waves
• point double-couple
• seismic noise
resonance seismometry

illustrative numerical example



Zone	Density [kg/m³]	Velocity compressional [m/s]	Velocity shear [m/s]	Quality factor shear [m/s]	Quality factor bulk [m/s]
cavity + chimney	1542	1130	432	43	∞
apical void	1	350	0	-	∞
crushed zone	1850	452	108	10	∞
zone of inelastic deformations	1850	gradient	gradient	gradient	∞
undeformed zone	1850	2260	1080	108	∞



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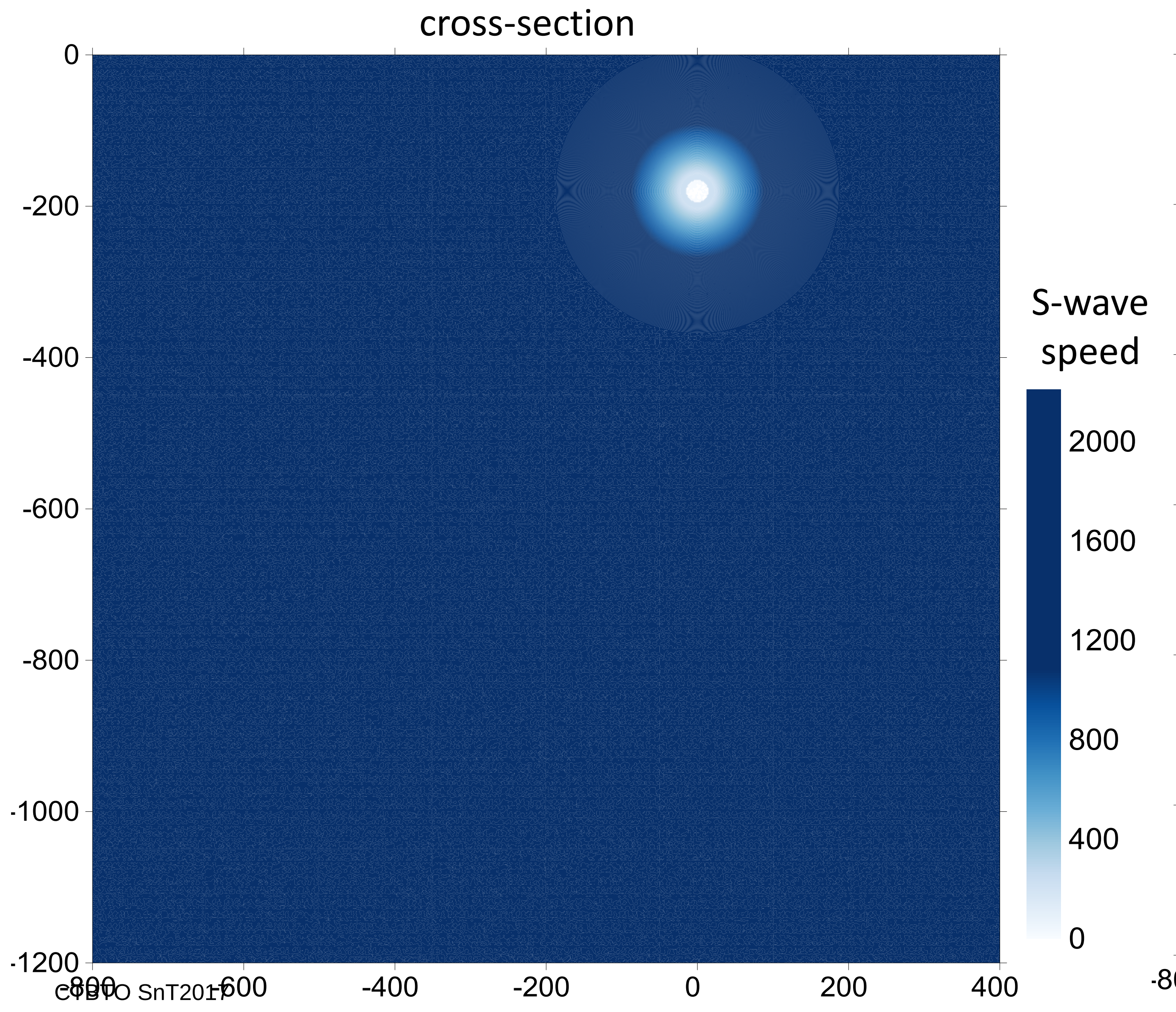
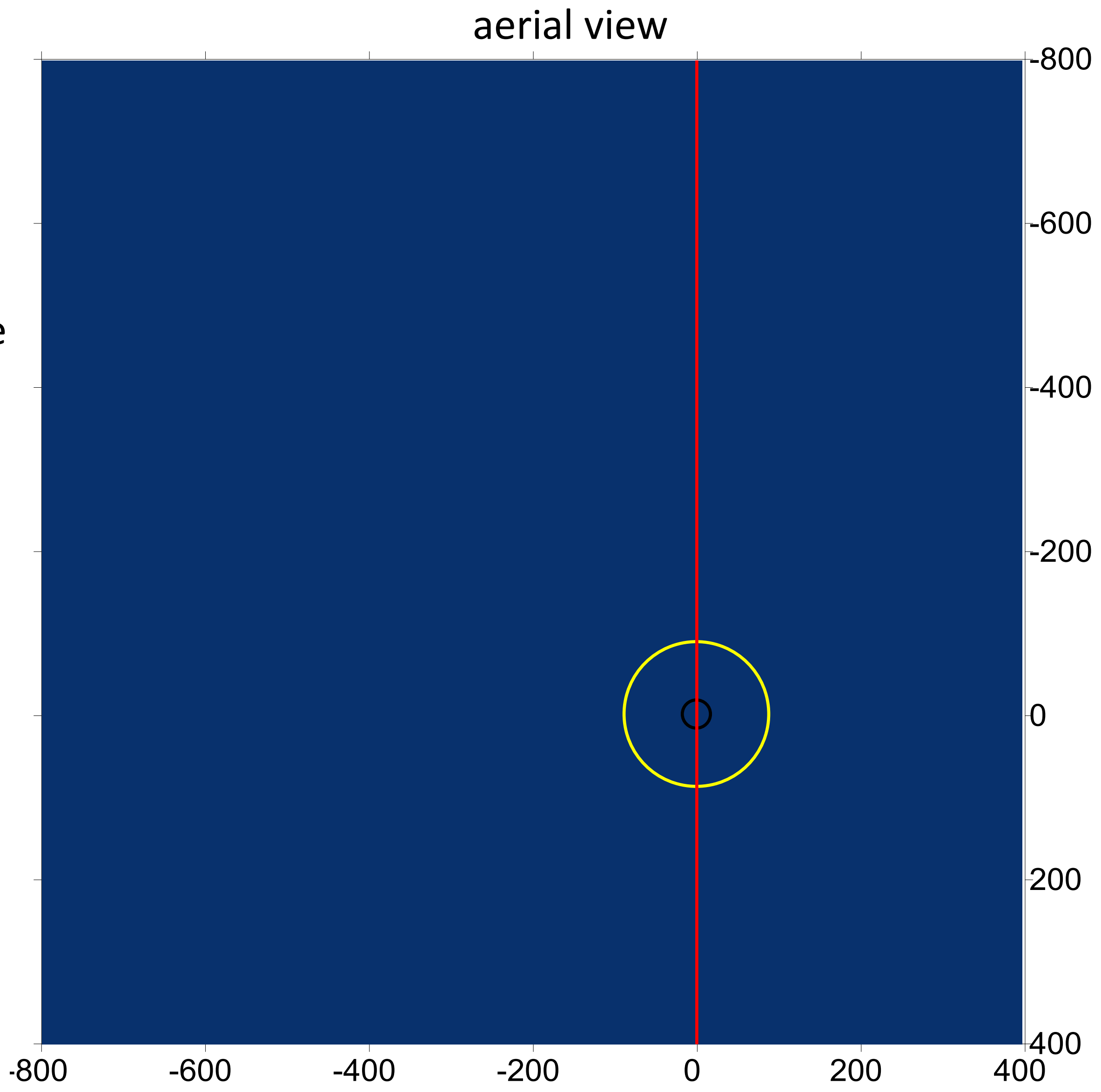
apical void	-	-	-	-	-
crushed zone	2200	816	215	22	∞
zone of inelastic deformations	2200	gradient	gradient	gradient	∞
undeformed zone	2200	4080	2150	215	∞

first results for the plane S-wave incidence

Rock salt, low-yield, minimal depth of burial, delta-like signal up to 20 Hz

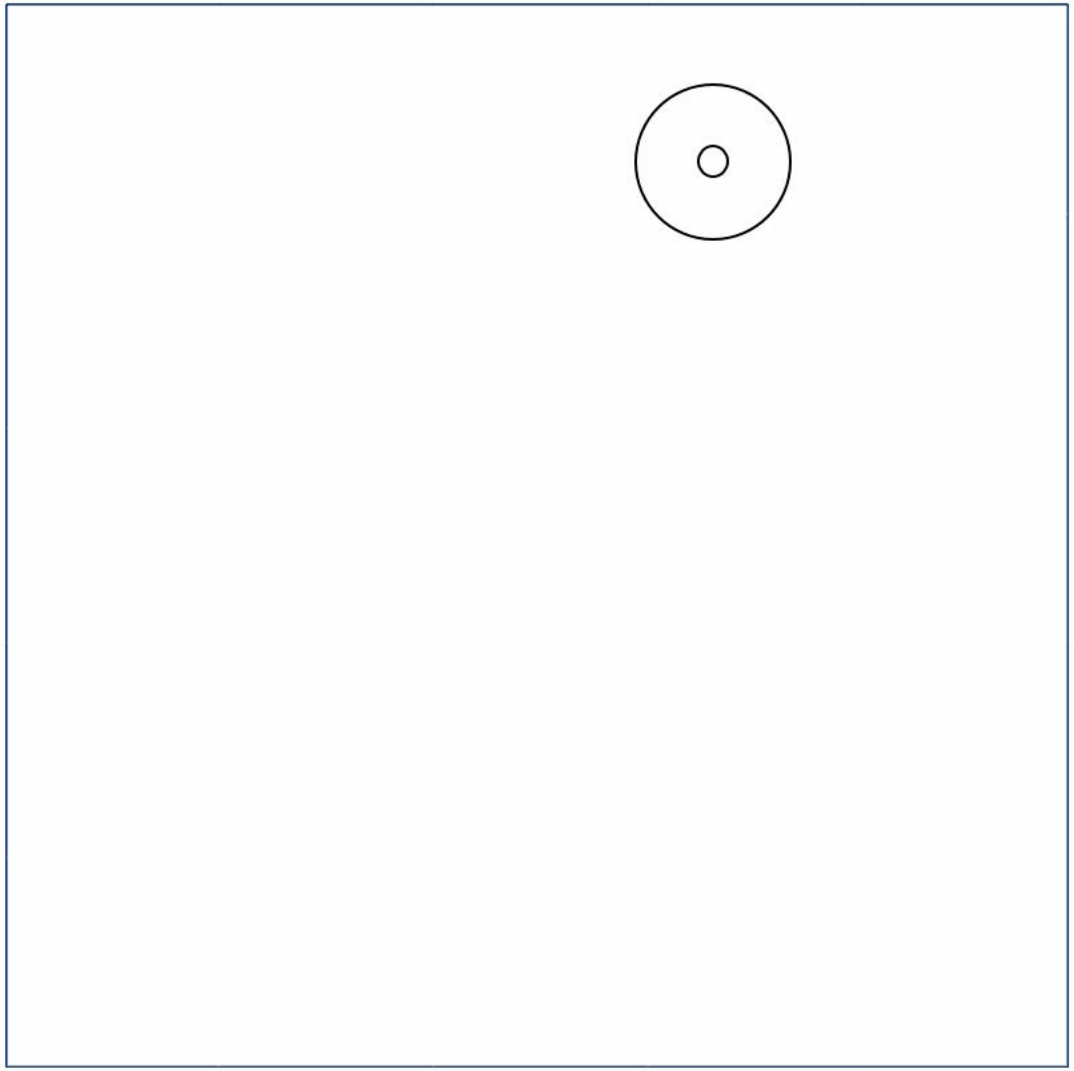




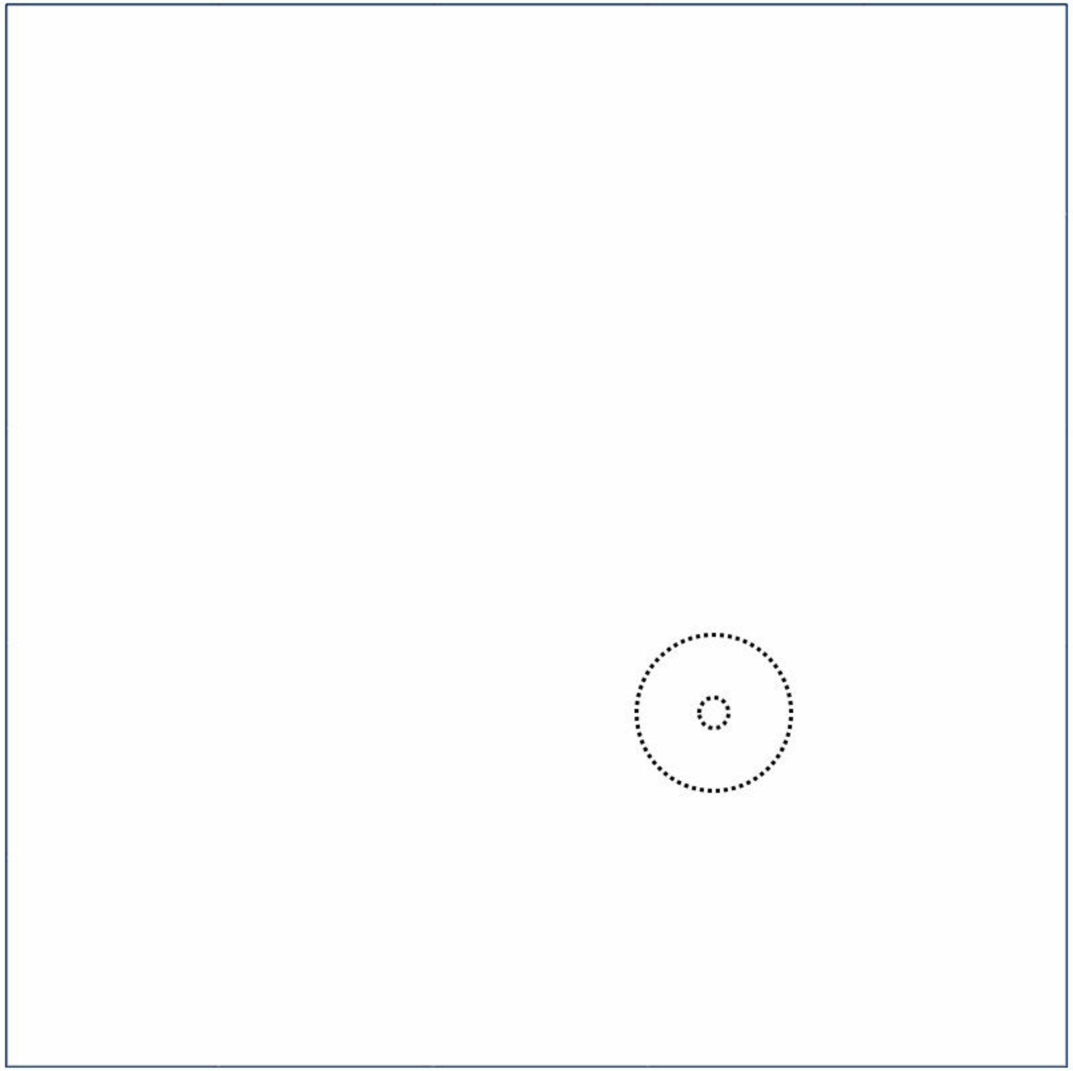
first results for the plane S-wave incidence

Rock salt, low-yield, minimal depth of burial (20-times slower)

cross-section



aerial view



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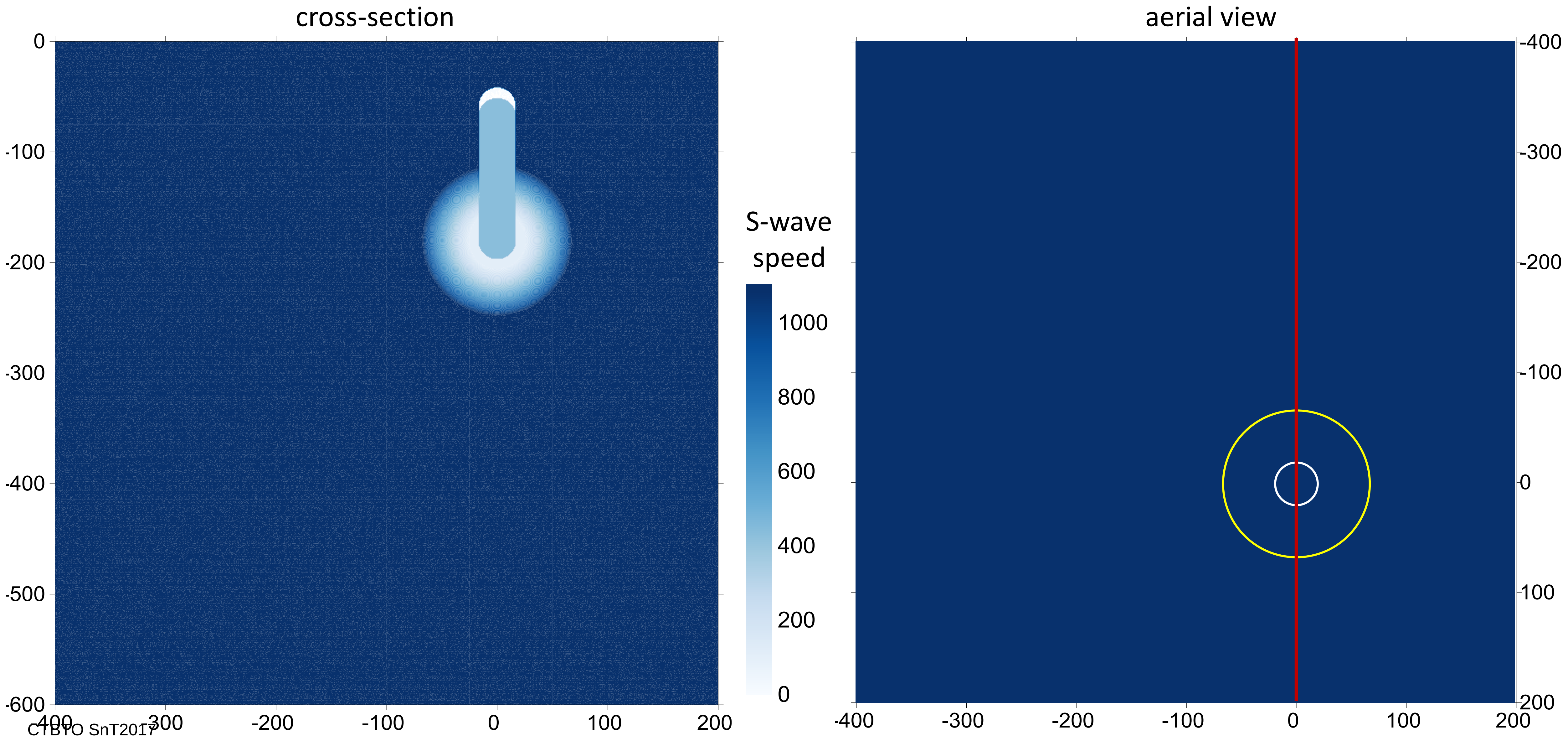
Tuff, low-yield, minimal depth of burial, delta-like signal up to 20 Hz



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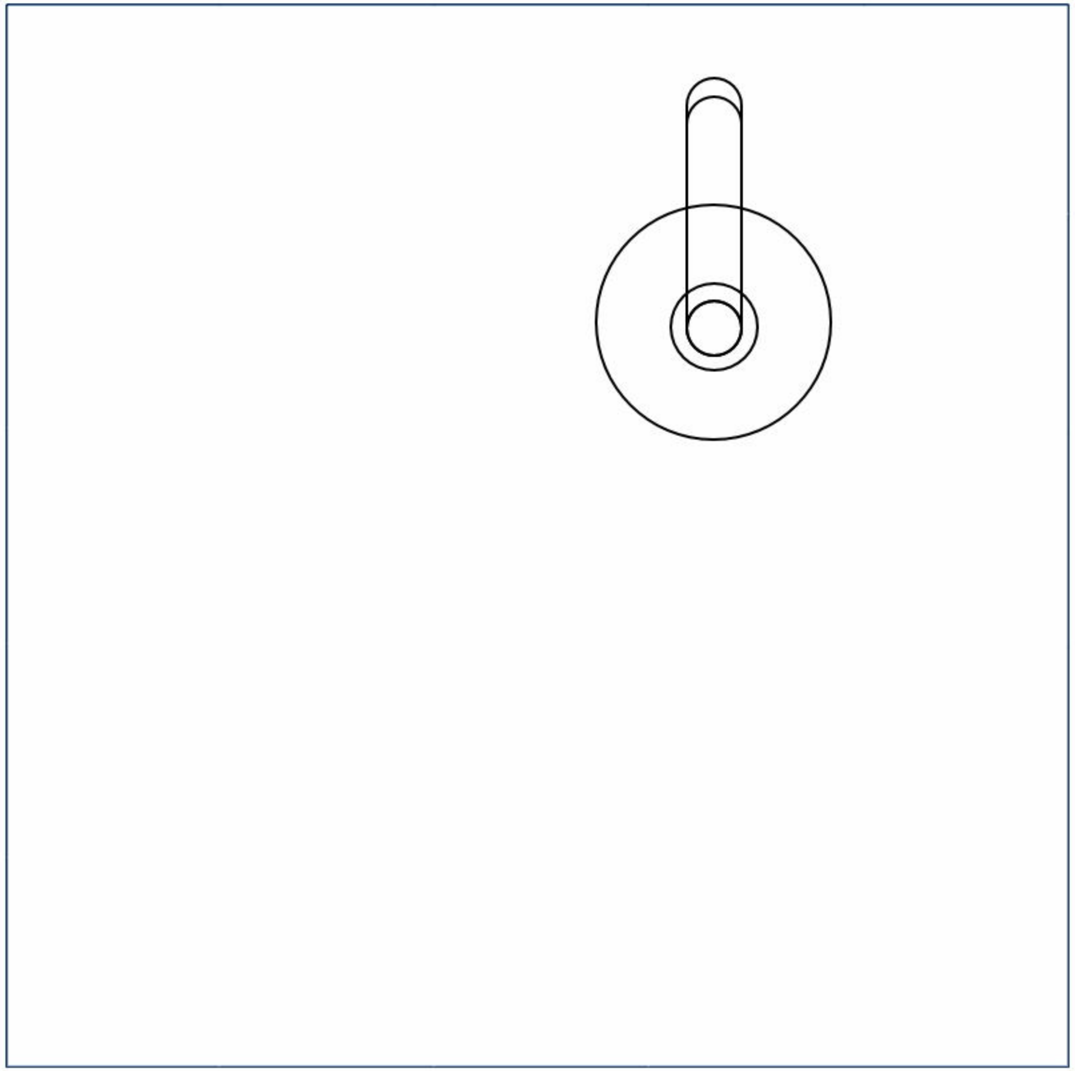

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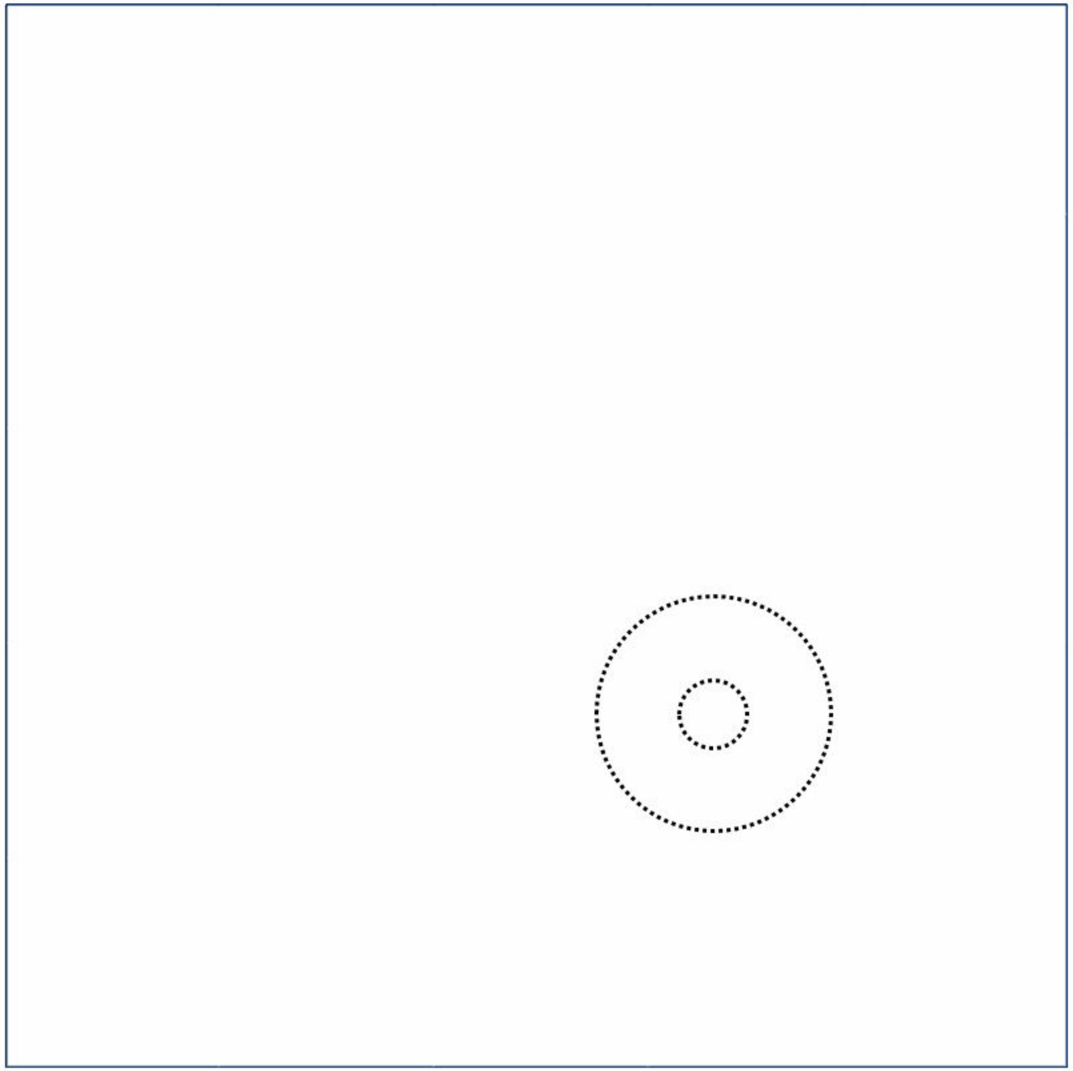
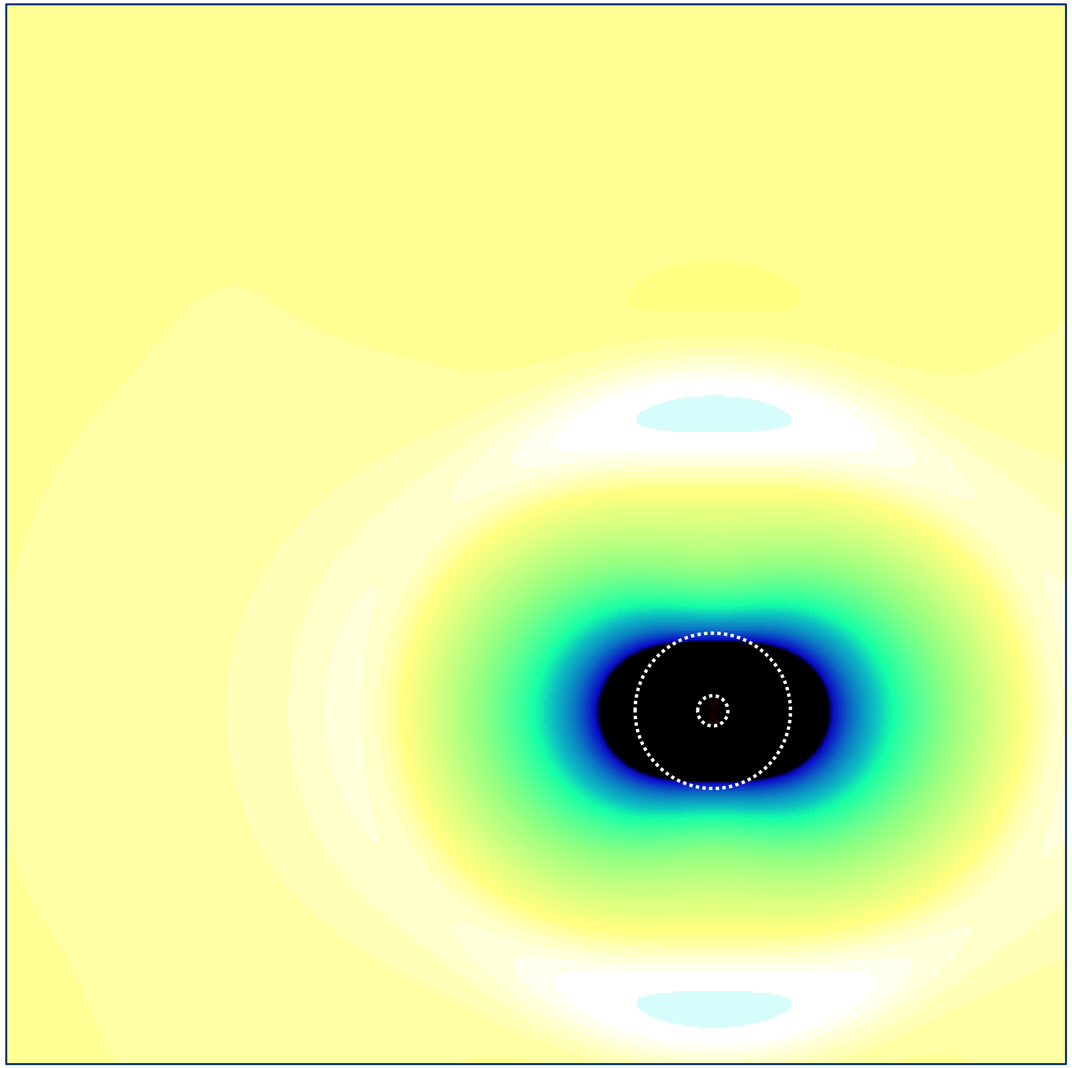


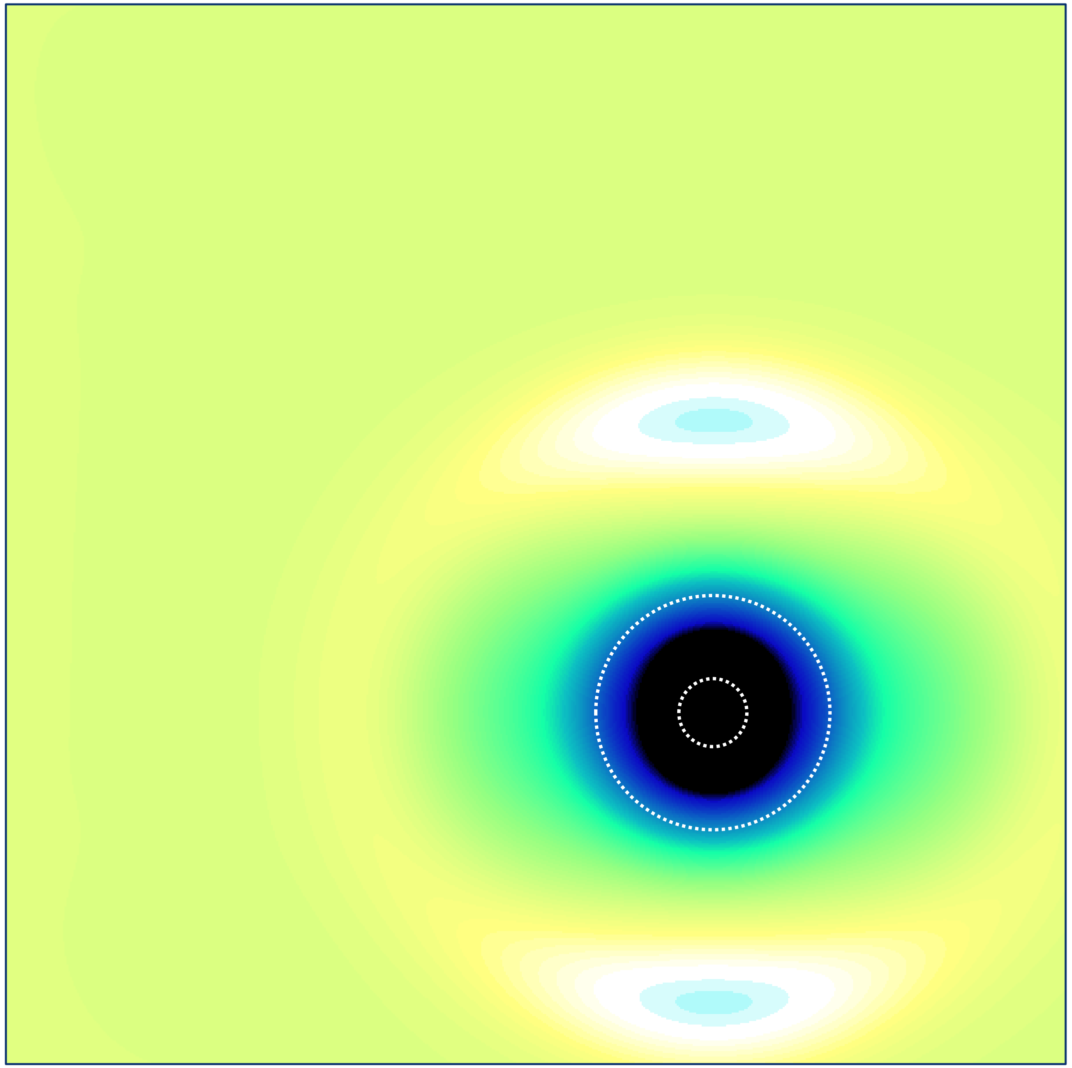
first results for the plane S-wave incidence

aerial view, low-yield, minimal depth of burial

Rock salt – pure cavity



Tuff – cavity + chimney



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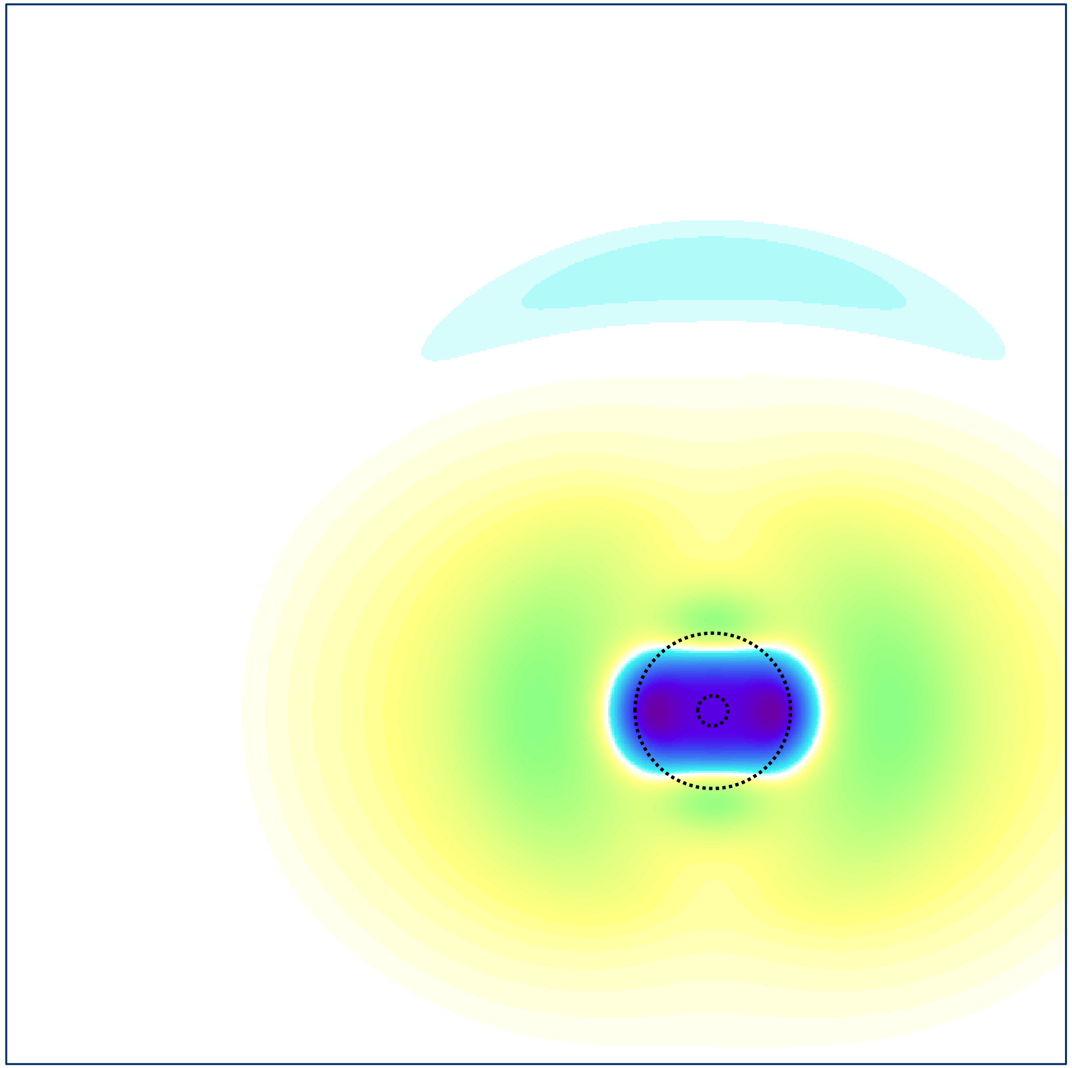

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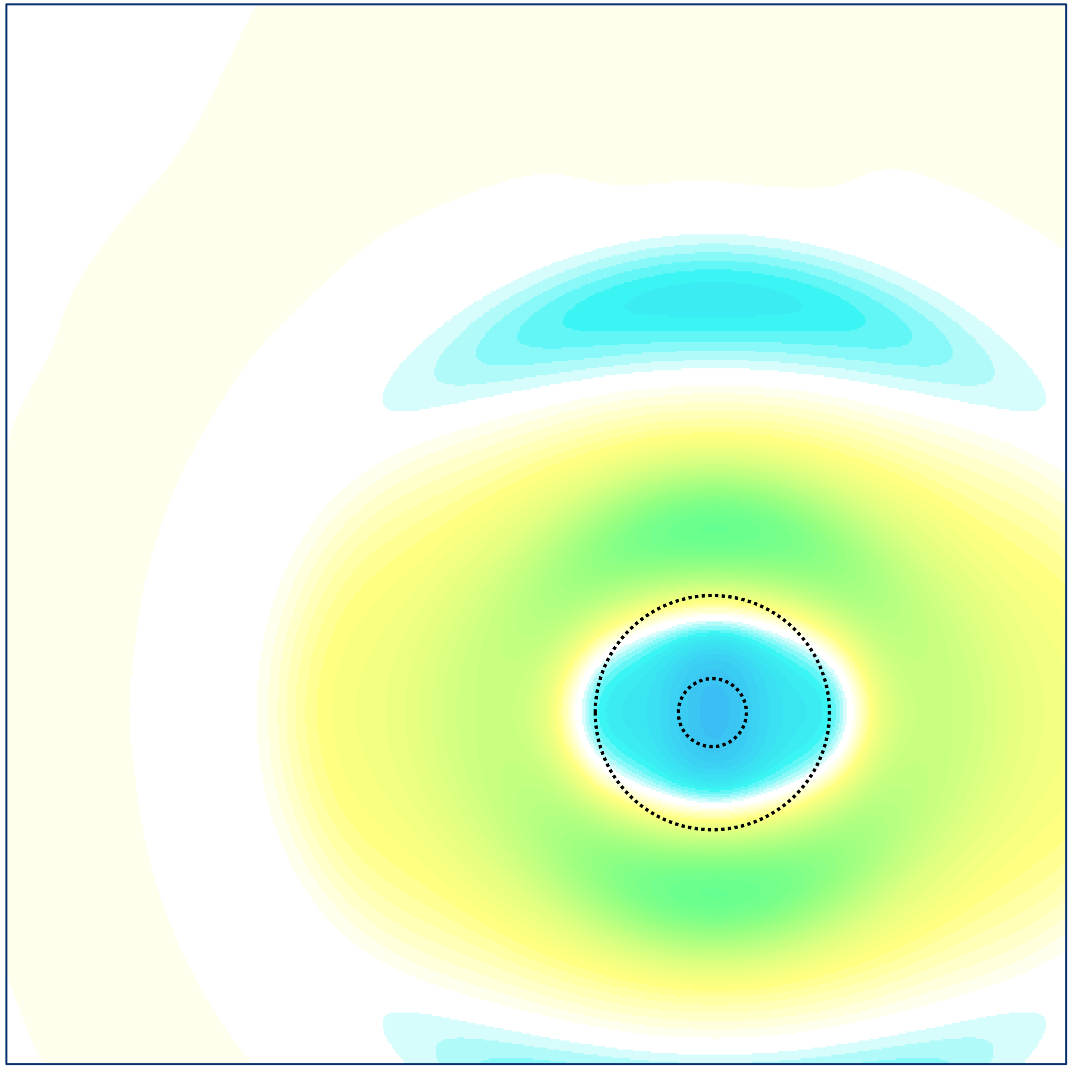

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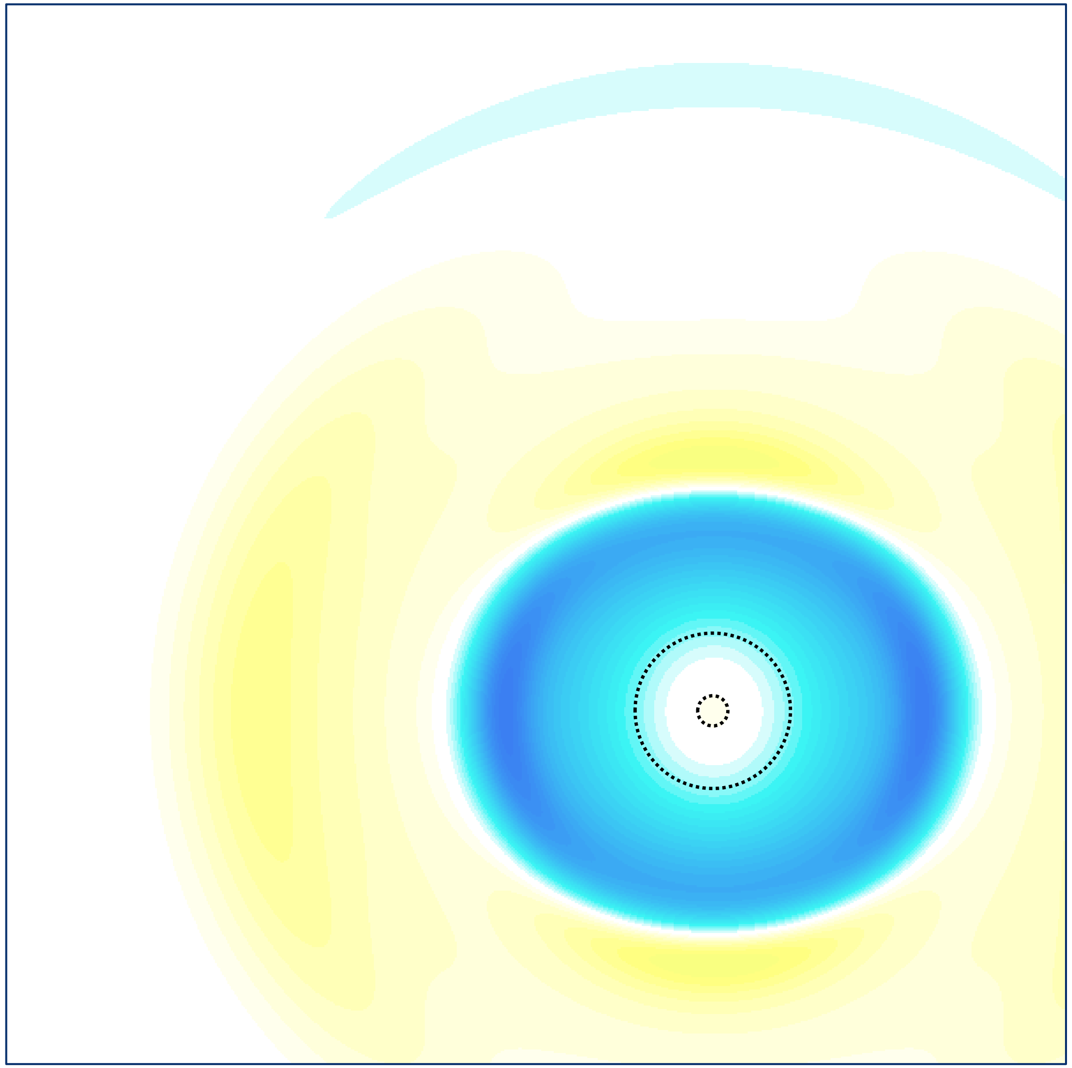

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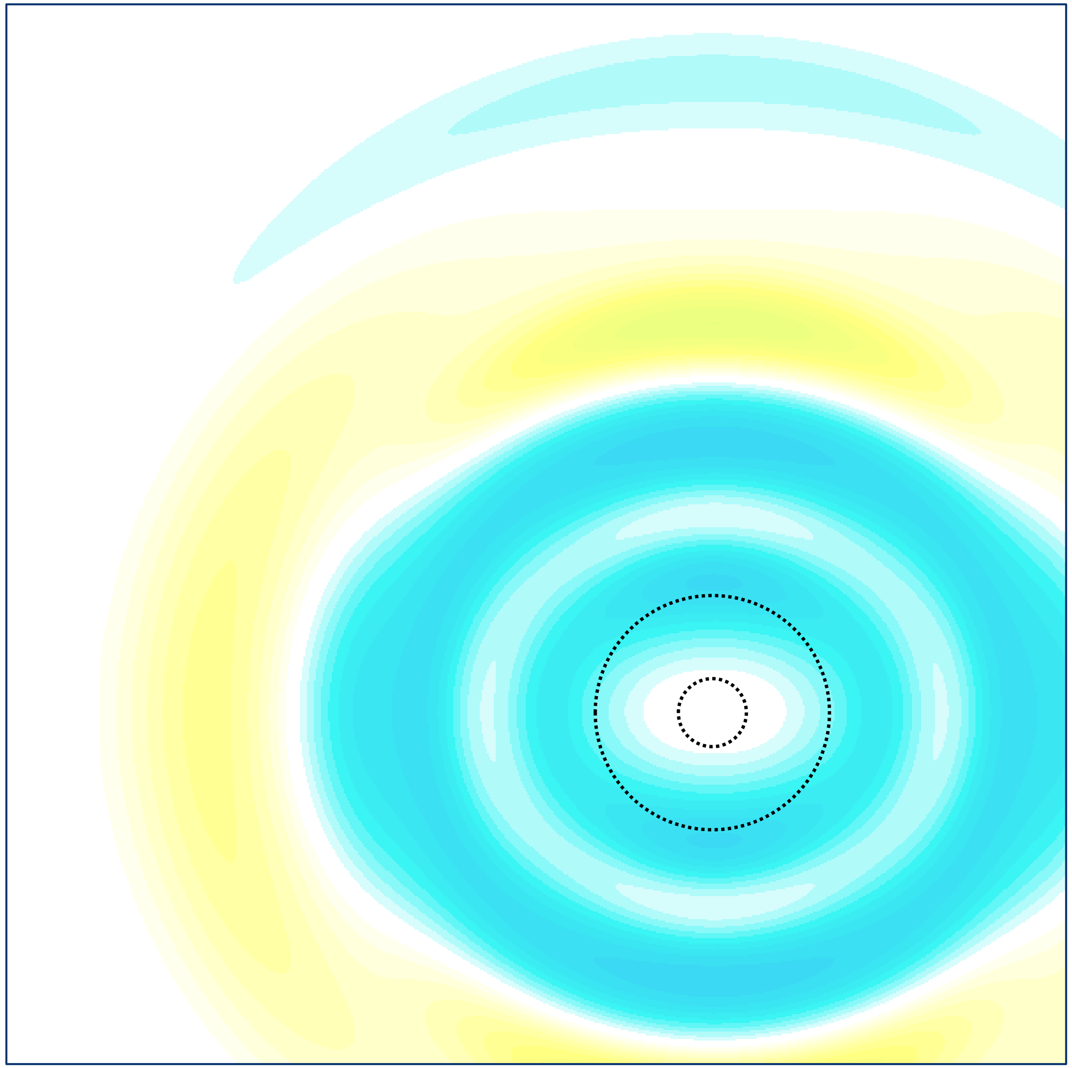

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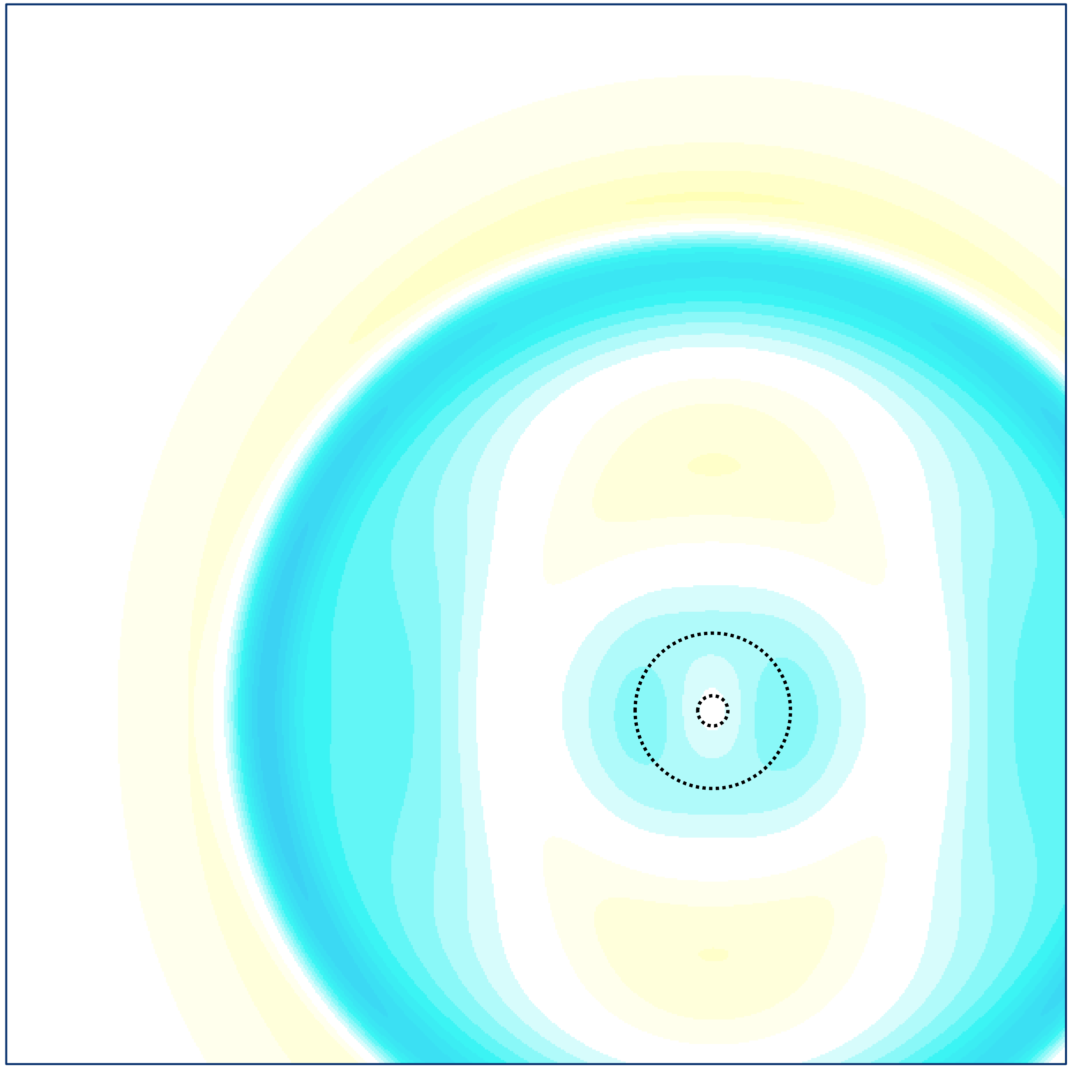

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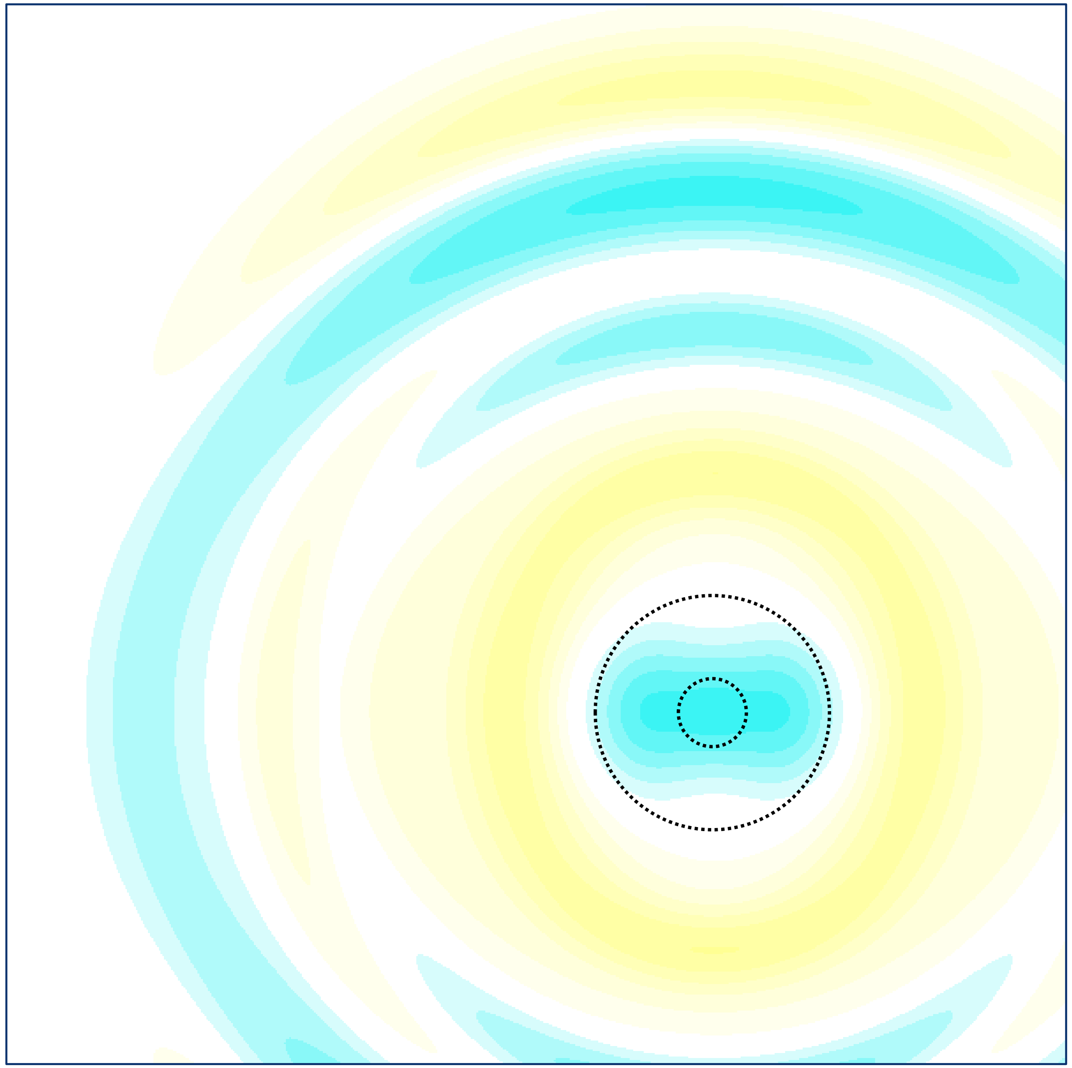

thank you for the attention